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<table>
<thead>
<tr>
<th>PAGES</th>
<th>PAPERS</th>
</tr>
</thead>
</table>
| 343 - 350 | **Modeling of Creep Behavior for Graphene Filled Vinyl Ester Nano-Composites.**  
Ahmad Almagableh, P. Raju Mantena, Ahmed S. Awwad, Mahmoud Rababah. |
| 351 – 358 | **Sliding Wear Response of an Aluminium Metal Matrix Composite: Effect of Solid Lubricant Particle Size.**  
Gajendra Dixit, Mohammad Mohsin Khan |
| 359 – 367 | **On Phase Equilibria of Sn-Sr and Mn-Sn-Sr Systems.**  
Mohammad Aljarrah, Atef Alkhazali, Suleiman Obeidat, Ahmad Almagableh, and Mahmoud Rababah |
| 369 – 375 | **Design, Construction and Evaluation of Chrysanthemum Flower Stem Cleaner Machine**  
Seyed Habib Hashemi Fard Dehkordi, Parvin Jafarhassani Hanjani, Golam Reza Chegini |
| 377 – 384 | **Fixture Designers Guidance: A Review of Recent Advanced Approaches**  
Heidar Hashemi, Awaluddin Mohamed Shaharoun, Izman S. |
| 385 – 392 | **Optimization Studies on Thrust Force and Torque during Drilling of Natural Fiber Reinforced Sandwich Composites**  
Rajamanickam Vinayagamoorthy, Nagamalai Rajeswari, Balasubramanian Karuppiah |
| 393 – 401 | **Statistical Model for Surface Roughness in Hard Turning of AISI D3 Steel**  
Varaprasad Bhemuni, Srinivasa Rao Chalamalasetti |
| 403 – 408 | **Melting Heat Transfer in Boundary Layer Stagnation Point Flow of MHD Micro-polar Fluid towards a Stretching / Shrinking Surface**  
Khilap Singh, Manoj Kumar |
| 409 – 415 | **Fuzzy Rules Extraction Based on Deterministic Data (Case Study: Bank’s Customers Rating)**  
Ramin Sadeghian, Behnam Gholamaliei, Leila Payandeh Peyman |
Modeling of Creep Behavior for Graphene Filled Vinyl Ester Nano-Composites

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Abstract

The creep resistance of thermoset vinyl ester-based nanocomposites is studied by adding different weight percents of exfoliated graphite filler, characterized at different temperatures under constant loading. The creep response of these nanocomposites was analyzed using the TA Instruments Model Q800- DMA. Results showed that the nano-filler at some temperatures may hinder slippage and reorientation of polymer chain that, in turn, shows higher creep resistance for nanocomposites than the neat matrix. At a lower temperature, poor creep resistance was observed for neat matrix as compared to nano materials tested; however, at elevated temperatures (beyond the glass transition temperature), creep resistance in nanocomposites becomes close to that of neat vinyl ester.

To fully understand the complex creep deformation of polymeric based nanocomposites, a physical modeling is conducted to study the structure-property relationship as a function of filler content. Parametric studies for the suggested model, along with variations in the simulated model parameters, illustrate various deformation mechanisms. The predicted results from the models quite well agree with the obtained experimental results.

Keywords: Polymers, Rheology, Nanoparticle.

1. Introduction

Nanoparticles that may be dispersed on nanoscale would outcome in extremely great interaction between these particles and the matrix resin. For example, an interphase of 1 nm wide corresponds to about 30% of the total volume in case of nano-structure as compared to 0.3% of the total volume of polymer in case of micro filler composites [1].

Applications of polymeric-based nanocomposites involve marine composite structures: particularly lightweight glass/carbon polymeric based composites. Sandwich composites with balsa and foam cores are presently being featured in number of navy applications such as in surface ship deck structures, radar mast and boat hulls. Several new and emerging cores have been explored in sandwich construction to provide enhanced mechanical properties.

Many studies on creep performance of various materials were carried out and showed improvements in creep performance associated with filling nanoparticles into various polymer. Creep recovery is particularly noteworthy in engineering applications. Therefore, understanding the creep mechanism of polymer-based nanocomposites requires combined experimental characterization and efficient modeling that help in establishing failure design criteria.

The effect of the clay type, clay content and temperature on creep behavior of polycaprolactone/clay nanocomposites (prepared by melt intercalation) was modeled [2]. The Kelvin-Voight models (4 parameters) along with the power-law were used to establish a correlation between the creep behavior and the nanocomposite morphology. Both, the experimental curves and the models, demonstrated that the incorporation of the clay produces a significant improvement on the creep resistance with respect to the neat matrix.

Several studies have reported both positive and negative influences of fillers on the creep resistance of polymers. For example, improvements in creep performance for multiwall carbon nanotubes/epoxy...
nanocomposite was not as high as anticipated through the use of mixture rule, indicated insufficient dispersion. However, variations in stiffness and creep strain-rate sensitivity obtained using nanoindentation showed quantifiable differences between the MWCNTs nanocomposite and epoxy specimens [3]. On the other hand, a significant improvement in tensile properties of polypropylene composites has been reported in terms of stiffening, strengthening and toughening with a low filled content of about 0.5% [4].

Based on above, modeling and simulating work, becomes a key issue in the future design of nano-based composites for engineering applications. An attempt based on the parameter analysis of the Burgers model had been accomplished [5] to explain the relationship between nanostructure and role of nano-particle toward creep performance of the bulk matrix. Results showed that the nanoparticles at some temperatures may hinder slippage and reorientation of polymer chain.

In the present study, the processed brominated 510A-40 vinyl ester is proposed to be used in the composite sheets of sandwich structures with fire-resistant foam layered in between to decrease flammability combined with enhanced flexural rigidity [6].

A previous investigation on this class of vinyl ester resin systems [7] discussed the effects of nano-filler addition to this resin against dynamic-loading applications. In this article, an attempt is made to model creep performance and the structural long-term durability from molecular structure prospective and establish future design criteria for these nanocomposites.

2. Experimental

2.1. Materials and Creep Measurements

Nanocomposites were prepared by dissolving around 3 kg of vinyl ester resin with various concentrations of graphite platelets in a one gallon container for 4 hours. The above resin-solution was blended for two minutes using FlackTek speed mixer running at 3000 rpm speed. The well-mixed vinyl ester resin solution with graphite nano platelets was discharged into a 0.33 m x 0.33 m x 0.01 m mold, let to rest for 30 minutes at ambient temperature, and then was post cured at 80°C for 3 hours.

Creep tests were conducted in flexural mode under different temperatures using the TA Instruments Model Q800 [8]/ dynamic mechanical analysis (DMA). The specimens for the creep and stress relaxation tests were 35 x 10 x 1.6 mm size. The creep-strain was measured as a function of the time. Prior to the creep tests, the stress level was derived from the proportionate limit in stress-strain diagrams of the tensile tests and was fixed at 3 MPa. Low applied load ensures the creep measurements remained in linear viscoelastic deformation regime.

The testing temperature was in the range of 30–150°C, incremented in 5°C steps, and the isothermal tests were run on each specimen over 30 minutes duration in the DMA. The sample was initially settled at room temperature (30°C) for about 4 minutes.

2.2. Stress-Relaxation Measurements of Nanocomposites

In the stress relaxation mode, the sample was held at a constant strain and the stress level measured as a function of time over the same temperature range. The method segments, executed during the relaxation test, were the same as that used in creep. The sample is initially equilibrated at RT for about 4 minutes, then displaced 0.1 mm for 30 minutes. The temperature is then incremented as in creep test and the process repeated until the final temperature of 150°C.

3. Theory

DMA tests were performed in accordance with ASTM D4065-01: “Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report Procedures” [9]. TA Instruments Mode Q800 DMA is a controlled stress with a Combined Motor and Transducer (CMT) machine in which the motor applies a force and displacement sensors measure strain. Force and amplitude are the raw signals recorded by the machine. The stiffness calculation for single-cantilever clamp type used in the TA Instruments Model Q800 DMA along with the appropriate correction factor is described below. The maximum level of strain occurs at the sample surface, while the centre experiences no strain at all, providing stress and strain are within the linear viscoelastic region.

4. Results and Discussion

4.1. Dynamic Properties

DMA spectra in the form of creep-strain as a function of temperature are plotted and demonstrated in Figures 1-3 for all nano-specimens, respectively. Creep deformation in the initial (pure elastic) segment is observed to be relatively small, associated with twisting and stretching of intermolecular bonds [10]. In the results shown, there was no evidence of creep rupture, which would require a longer time/temperature and maybe a larger load. As expected, these materials are viscoelastic in character, and, therefore, the shape of creep and relaxation curves is totally dependent on temperature. Creep strain increased with temperature, and, at the same time, similar behavior was exhibited by the nanocomposites. It is worth mentioning here that with the temperature rise from 100°C to 125°C the creep strain increases by 300% approximately at t = 1800 s for pure polymer (Figure not shown). Thus, the value of the creep-strain in response toward the temperature change is very sensitive. Moreover, results shown in Figure 3 can also indicate that creep strains of nanocomposites were lower than that of the neat matrix at all test temperatures and this implies that the creep behavior is improved by the addition of nanotubes. For example, the strain values at 82°C were reduced by 17%, and 23% compared to brominated vinyl ester when the contents of xGnP were 1.25 wt.%, and 2.5 wt.%, respectively. In addition, it is also observed that the creep strain rate decreased with the incorporation of xGnP.
Figure 1. Creep-strain versus time for brominated vinyl ester.

Figure 2. Creep-strain versus time for 1.25 wt% graphite platelet vinyl ester.
4.2. Physical Model Formulation

Figure 4 shows the Standard Linear Solid Model that consists of a Maxwell element (linear spring and dashpot in series) and a linear spring in parallel. This model has been selected because it can explain two main deformations of plastics [8]; the spring represents deformations due to twisting and extension of intermolecular bonds, where as the dashpot refers to viscous deformation.

In the proposed viscoelastic model, the total stress at time $t$ can be analyzed into time-rate dependent stress component in the spring $E_2$ and dashpot η (Maxwell element), and constant stress part ($σ_o$) in the spring element $E_1$.

Thus, the total stress as per the Standard Linear Solid model is given as:

$$\sigma_o = E_1 \varepsilon + \frac{\eta}{E_2} (E_1 + E_2) \varepsilon'$$

(1)

Based on the above suggested model, the creep-strain response is:

$$\varepsilon(t) = \frac{\sigma_o}{E_1} \left[1 - \frac{E_2}{E_1 + E_2} \exp(-t \frac{E_1 E_2}{\eta (E_1 + E_2)}) \right]$$

(2)

Where $\varepsilon$ and $\sigma_o$ are creep-strain and the applied stress in the creep experiment, respectively.

To simulate the model elastic parameters, data from the stress-relaxation experiments at a given temperature were accompanied. The relaxation modulus, according to the model, obtained from stress-relaxation data at quite large time, is basically representing $E_1$. $E_1$ alternatively can describe the elastic deformation in the crystalline structure, associated with no amorphous deformation or viscosity effect. In general, a polymer with large value of stiffness, $E_1$, may indicate highly crystalline structure. Accordingly, the neat resin exhibits higher values of $E_1$ with addition of nano-filler under all temperatures.

The total modulus ($E_1 + E_2$), provided in the constitutive model, determines the immediate elastic creep strain (at time equal zero), which could be instantaneously recovered on the removal of creep load. In general, the composites showed greater values of ($E_1 + E_2$) with the addition of filler compared to neat matrix at all temperatures. Among the nanocomposites, 2.25 wt. % appears to be the one with peak total elasticity, second is 1.25 wt. %, and finally is the neat matrix which depicted
that the addition of nanoparticles was helpful in reinforcing the elasticity of the crystalline polymer as shown in Table 1. Moreover, it is worth mentioning that the change in variation of \((E_1 + E_2)\) value from one level of nano-filler loading to another illustrated the diverse reinforcing role of nanoparticle. For example, the total modulus increased by 3\% in response to addition of 1.25 wt.\% xGnP to the resin network, and this figure was magnified to become 22 \% when the level of nano-filler was upgraded from 1.25 to 2.25 wt.\%.

On the other hand, the elasticity dictated from total stiffness \((E_1 + E_2)\) of each specimen showed a decreasing affinity with temperature; it was easy to recognize that the substance materials became softer at higher temperatures and the stiffness was therefore reduced with diminished instantaneous modulus. For example, close to the glass transition temperature, the chain-segments of polymer began to travel and thus the elastic stiffness of substance material was decreased as compared to the one measured at room temperature.

Cross linking density in general restricts the chain-movement from complete segmental motion at high temperatures where deformation is mainly viscous, it is typically given as the mean molecular weight between cross-links, is an important feature governing the mechanical properties of vinyl ester resin. Moreover, cross-linking can be altered by controlling the molecular weight of vinyl ester oligomers, and concentration of nano-filler in the matrix as well.

Cross linking density can be quantitatively evaluated as per Equation (3) which implies that cross-linking density, \(V\), is dependent on Plateau or relaxation modulus in rubbery region, \(G^0\), temperature \(T\), and the universal gas constant \(R\).

\[
V = \frac{G^0}{RT}
\]  

(3)

On comparing the modulus in the rubbery regions for vinyl ester with 2.5 wt.\% and neat matrix as shown in Figure 5 (a, b), no major variation in plateau modulus was observed as opposed to the addition of nano-fillers. The influence of nano-filler addition in cross linking mechanism as per the above equation is not encouraging. As a result, the mechanism of hindering intermolecular slippage appears to be poor within rubbery region, and, therefore, the creep resistance in nanocomposites at elevated temperatures remains unaffected with regard to neat vinyl ester.

\(E_2\) was subsequently developed in the model by subtracting \(E_1\) from \((E_1 + E_2)\), at a specific temperature. The time-dependent \(E_2\) might be associated with the stiffness and viscous deformation due to intermolecular slippage, damage from crystallized polymer or straightening out of the folded amorphous chains which is recoverable but not instantaneously. The retardant spring modulus \(E_2\) and the dashpot viscosity \(\eta\) of each material showed conflicting dependency on temperature, \(E_2\) increases with increasing temperature. The viscosity element \(\eta\) was much more dependent on temperature rather than concentration of nano-filler, unlike \(E_1\) and \(E_2\). Among the tested specimens, the viscosity \(\eta\), showed comparatively slight changes between the neat matrix and the nano-specimens at specific temperature, which accounts that the dashpot viscosity was not much altered by the addition of nano-particles. Rather, viscous deformation as per the model (Maxwell unit) is mainly governed by temperature effect, and the relationship can be correlated as follow:

\[
\eta = \text{constant} \ (T / T_r)^m
\]

(4)

Where \(T_r\) is the reference temperature which is considered here as room temperature, \(m\) is a constant.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temp (°C)</th>
<th>(E_1) (MPa)</th>
<th>(E_1 + E_2) (MPa)</th>
<th>(E_2) (MPa)</th>
<th>(\eta) (MPa.h)</th>
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<td>2929</td>
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<td>454</td>
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<tr>
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<td>82</td>
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<td>2510</td>
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<td>171.4</td>
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<table>
<thead>
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<th>Temp (°C)</th>
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<th>(E_1 + E_2) (MPa)</th>
<th>(E_2) (MPa)</th>
<th>(\eta) (MPa.h)</th>
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<td></td>
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<th>(E_2) (MPa)</th>
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Creep-strain data, at representative temperatures obtained from the creep tests, are plotted in Figure 6 through 8 along with the strain predicted including the modified effect of viscosity in Equation 4. As can be seen from these Figures, the model can predict the strain-time behavior of pure vinyl ester reasonably well except at high temperature (beyond \(80^\circ\)C) where the onset of rubbery region started with complete motion of molecular segments occurred for pure vinyl ester and its nanocomposites at temperature around \(110^\circ\)C. Agreement between model predictions and creep data for all nanocomposites is quite well.
Figure 5. Relaxation modulus versus temperature.

(a) Brominated vinyl ester and

(b) Brominated vinyl ester with 2.5 wt.% graphite.
Figure 6. Predicted and experimental results of creep-strain versus time for brominated vinyl ester at selected temperatures based on the viscoelastic model.

Figure 7. Predicted and experimental results of creep-strain versus time for 1.25 wt% graphite platelet vinyl ester at selected temperatures based on the viscoelastic model.
5. Conclusions

The creep behavior of brominated vinyl ester and its nanocomposites were characterized in creep and relaxation tests using DMA Q800 over various isothermal temperatures. The standard linear solid model was established and developed to understand the relationship of nano-filler/structure property for these nano-materials. The variation in the simulated parameters in the proposed model describes the mechanism of nano-filler toward creep deformation in different regimes. The key findings of the present study are listed below:

- Poor creep resistance was observed for vinyl ester as compared to nanocomposite at low temperatures, while at elevated temperatures, creep resistance in nano-specimens was close in magnitude to that of pure polymer.
- The elastic modulus for the crystalline structure, simulated as \((E_1 + E_2)\) in the model, was observed to increase with nano-filler addition under all temperatures.
- The role of nano-particles toward cross-linking and hindering molecular slippage was found to be insensitive to filler addition at temperatures greater than glass transition temperatures.
- The viscous deformation was totally governed by the predicted model elements: \(E_2\) and \(\eta\), and was strongly dependent on temperature rather than on concentration of nano-filler.
- Analysis of microstructures for different types of nanocomposites and their impact on microscopic creep property can be suggested as a future work.

References

Abstract

The present work investigates the partial lubricated sliding wear behavior of 10 wt% SiC reinforced aluminium composites produced by Vortex method with the help of a pin on disc wear testing machine. The wear tests were conducted at the sliding velocities of 2.1 and 8.4 m/sec and at an applied load of 10 to 200 N in different lubricated environment [oil, oil+ 5wt % graphite (7-10 µm), and oil+ 5wt % graphite (100 µm)]. The influence of changing graphite particle size in the oil lubricant towards controlling the wear behavior of the samples has been studied. The (Aluminium-based) matrix alloy was also characterized under identical conditions to examine the influence of the dispersoid (SiC) phase on the wear behavior. The parameters studied are wear rate, frictional heating and friction coefficient. Results showed a large improvement in wear resistance of the Aluminium-based alloy after reinforcement with SiC particles. The composite experienced a higher frictional heating and friction coefficient than the matrix alloy in all the cases. The wear rate and frictional heating increased with load and speed while friction coefficient was affected in an opposite manner. Test duration influenced the frictional heating and friction coefficient of the samples in a mixed manner.

Keywords: Aluminium Alloy; Composite; Lubricated Sliding Wear Behavior; Solid Lubricant.

1. Introduction

In many engineering applications, aluminium alloys are desirable because of their low density and high strength-to-weight ratio. In several such applications, improved wear resistance of the alloys becomes imperative. Al–Si alloys form an interesting series of the alloy system in this context. Their composites containing hard particles are gaining importance. These materials have properties like high specific strength, high specific stiffness, improved high temperature performance as well as good wear and seizure resistance. The properties of composite materials can be tailored by suitably selecting the matrix alloy and the dispersoid phase. Owing to their versatile properties, composite materials hold a potential for applications in automotive, aerospace, sporting goods and in general engineering.

Available literature posits that the wear behavior of materials depends on a number of operational and material related conditions in a complex manner and even they have synergistic effects on the overall response of materials [1-14]. Chemistry, microstructure and shape, size, content and mode of distribution of the microconstituent, in terms of hardness, strength, cracking tendency, lubricating characteristics, load bearing capability as well as thermal stability are some of the important factors to affect wear behavior [1-14]. The sliding wear behavior is controlled by a number of experimental parameters such as speed, load, conditions, distance, etc. [1-28].

The conditions may be dry, lubricated, high temperature, oxidizing, reducing etc. Lubricants may be liquid, semi-solid, or solid. Nowadays, solid lubricants are added in order to further improve the performance of the liquid lubricants. A variety of solid lubricants are in existence. They are generally lamellar solids with (open) hexagonal structure with c/a ratio larger than that of an ideal close packed hexagonal [29, 30]. This enables them to easily smear along the contacting surfaces producing lubricating effect and thereby to improve wear performance. For the effective working of solid lubricants, the presence of a liquid lubricant is essential and the quantity of solid lubricant to be added to the liquid lubricant that would lead to the best wear performance. This depends on a number of factors like the ones related to material as well as test parameters and need to be determined /optimized for effective utilization of a liquid/solid lubricant. Recent studies have led to a limited understanding of some of the aspects but the role of lubricant's particle size has not practically been studied on the wear behavior of Aluminium based alloys. Moreover, there is a paucity of information pertaining to the influence
of hard particle reinforcement on the partial lubricating wear behavior of the (Aluminium-based) matrix alloy(s).

In light of the above, an attempt has been made in this study to analyze the sliding wear behavior of an Aluminium alloy and its composite reinforced with 10 wt% SiC particles under the influence of varying applied loads and speeds in partial lubricated conditions [oil, oil+ 5wt % graphite (7-10 µm), and oil + 5wt % graphite (100 µm)]. The influence of changing particle size of graphite in the oil lubricant towards controlling the wear behavior of the samples has been studied.

**Table 1. Chemical Composition of the Test Materials**

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Mn</th>
<th>Mg</th>
<th>Cu</th>
<th>Fe</th>
<th>Ni</th>
<th>Al</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC-12</td>
<td>1.29</td>
<td>0.12</td>
<td>0.47</td>
<td>1.98</td>
<td>0.75</td>
<td>0.80</td>
<td>Balance</td>
<td>-</td>
</tr>
<tr>
<td>ADC-12 + SiC Composite</td>
<td>1.29</td>
<td>0.12</td>
<td>0.47</td>
<td>1.98</td>
<td>0.75</td>
<td>0.80</td>
<td>Balance</td>
<td>10</td>
</tr>
</tbody>
</table>

2. Experimental

2.1. Material Preparation

The experimental alloys and composite were prepared by the liquid metallurgy route in the form of 16 mm diameter, 170 mm long cylindrical castings. The composite was synthesized by dispersing 50-100 µm silicon carbide particles at the vortex of the alloy melt. Table 1 shows the chemical compositions of the sample materials.

2.2. Microstructural Examination

Microstructural studies were carried out on 10 mm diameter, 15 mm thick samples. The samples were polished metallographically and etched suitably. Killer reagent was used for etching the samples of the aluminium (matrix) alloy and composite. A microstructural characterization of the samples was carried out using scanning electron microscopy.

2.3. Measurement of Hardness and Density

Hardness measurements were carried out on metallographically polished samples using a Vickers hardness tester. The applied load in this case was 30 kg. The water displacement technique was adopted for density measurement. A Mettlermicrobalance was used for weighing the samples in water and air.

2.4. Sliding Wear Tests

Sliding wear tests were carried out using SAE 20W-40 oil, SAE 20W-40 oil plus (5 Wt %) graphite particles (size 7-10 µm), and SAE 20W-40 oil plus (5 Wt %) graphite particles (size 100 µm) as lubricant using a Magnum Engineers (India) make pin-on-disc machine shown in Figure 1. Cylindrical test pins (8 mm diameter and 30 mm length) were held against a rotating heat-treated En31 steel disc conforming to AISIE 52100 (1.0 % C, 1.4 % Cr, 0.40 % Mn, 0.2 % Si, 0.05 % S, 0.05 % P and balance Fe). Hardness of the disc was HRC 62. The steel disc was polished mechanically up to a roughness (Ra) level of 1-2 µm prior to each test.

Wear tests were conducted over a range of applied loads and sliding speeds. The track diameter of 100 mm enabled the rotational speeds of 400 and 1600 rpm (selected in the present investigation) to attain linear sliding velocities of 2.09 and 8.38 m/s, respectively. The wear testing procedure involved inserting the disk into lubricant/lubricant mixture and allowing it to rotate at a speed of 3.35 m/s for 5 s. The lubricated disk was rotated in order to generate a low and uniform thickness by spinning off the excess lubricant. Thereby, maintaining close to mixed lubrication generally encountered by components in situations dealing with sparse lubrication as well as during starting and stopping operations in the case of fully lubricated sliding. Further sample was fixed in the specimen holder, allowing the disk to rotate at the predetermined sliding speed up to the fixed distance of 2500 m or until specimen seizure, whichever occurred earlier. Specimen seizure was noticed in terms of large material adhesion on to the disc, higher rate of temperature rise of the test pin, and abnormal vibration and noise from the pin-on-disc assembly.

Frictional heating was monitored using a chromel-alumel thermocouple inserted in a 1.5 mm diameter hole on the test pin 1.5 mm away from the sliding surface. Output of the thermocouple is fed into a PC-based data logging system which continuously records the frictional heating of sample during each test. The loads were vertically applied on to the pin sample against the disc. Output from strain gauge is also fed into a PC-based data logging system which continuously records the tangential load on the pin sample during each test.

Coefficient of friction was calculated by dividing the tangential load with the applied normal load. The specimens were thoroughly cleaned in acetone for 10 min using ultrasonic cleaner (34 ± 3 kHZ), dried and weighed prior to and after each test. A Mettler instrument make microbalance was used for weighing the specimens. Weight loss was then converted into volume loss per unit sliding distance to compute wear rate.

![Figure 1. Schematic representation of the wear test configuration.](image-url)
3. Results

3.1. Microstructure

Microstructure of Aluminum alloy (ADC12 alloy) solidified in a cast iron mold shows aluminum dendrites with dendritic arm spacing in the range of 25 microns. The eutectic silicon solidifies in the inter-dendritic region and around the dendrites. The micrograph (Figure 2) depicts plate shaped eutectic silicon and the other intermetallic phases. The plate shaped eutectic silicon is usually 20-30 micron in length and 2-5 micron in width. The composite showed features similar to the matrix alloy except the presence of the dispersoid SiC particles (Figure 3).

3.2. Hardness and Density

Table 2 represents various properties of the specimens. The composite attained somewhat a higher hardness than the corresponding matrix alloy. So far as the density of the specimen is concerned, it was highest for the composite followed by matrix alloy.

<table>
<thead>
<tr>
<th>S No.</th>
<th>Type</th>
<th>Vickers Hardness (HV)</th>
<th>Density g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ADC-12 Matrix Alloy</td>
<td>92.3</td>
<td>2.64</td>
</tr>
<tr>
<td>2</td>
<td>ADC-12 Matrix Alloy +</td>
<td>98.7</td>
<td>2.78</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3. Wear Behavior

3.3.1. Wear Rate

Wear Rate of the samples has been plotted as a function of applied load in Oil + 5% Graphite (7-10 µm), Oil + 5% Graphite (100 µm) & Oil Lubricated environment at sliding velocity of 2.1 and 8.4 m/sec in Figure 4 to Figure 6, respectively. Wear rate increases with the load and sliding velocity for all the sample material and in all environments. Incorporation of SiC significantly reduces the wear rate of the alloy irrespective of the test conditions (Figure 4 – Figure 6). The presence of solid lubricant reduces the wear rate for all the test material. However Oil + 5% Graphite (7-10 µm) is proven to be more effective than the Oil + 5% Graphite (100 µm) {Figure 7-Figure 8}.
3.3.2. Frictional Heating

Temperature near the contacting surface for Alloy and composite at Sliding Velocity of 2.1 & 8.4 m/sec plotted as a function of applied load in various lubricated test environments in Figure 9 to Figure 13, respectively. The temperature increases with increase in load and velocity however the increment is more for the composite than the base alloy (Figure 9-Figure 11). The pattern of temperature is similar in all the environments despite of the fact that the addition of the solid lubricant peculiarly affects the pattern of temperature variation. For all the testing materials, the maximum temperature rise is observed at 8.4 m/sec sliding velocity in Oil + 5% graphite (100 µm) lubricated environment followed by Oil and Oil + 5% graphite (7-10 µm) lubricated environment.
3.3.3. Friction Coefficient

Figure 14 to Figure 16 represent the friction coefficient for Aluminium-Alloy and Aluminium-SiC composite as a function of Applied Load in various lubricated condition at a sliding velocity of 2.1 and 8.4 m/sec. Friction coefficient decreases with the increase in applied load while it varies directly with the sliding speed irrespective of the test material. Incorporation of SiC particle increases the friction coefficient in Oil and Oil + 5wt% graphite (100 µm) lubricated environment however in Oil + 5wt% graphite (7-10 µm) environment it varies in some other manner.
4. Discussion

4.1. Microstructure

From microstructural characteristics point of view, the aluminium based alloy depicts plate shaped eutectic silicon and the other intermetallic phases (Figure 2). Reinforcing the alloy system with thermally stable micro-constituents through alloying with high melting elements and/or incorporation of hard ceramic particles improves its strength (Figure 3). Wear resistance under severe conditions also improves because of improved thermal stability while ambient temperature properties deteriorate over the matrix alloy due to enhanced cracking tendency introduced by the thermally stable micro-constituents [1-10].

4.2. Wear Behavior

4.2.1. Wear Rate

Coming to the sliding wear tests, factors affecting the wear response of materials are applied load, sliding velocity, sliding distance and test environment. Applied load directly influences the wear rate, i.e., the higher the load is the greater the wear rate becomes. Other variables, such as distance and velocity, do not have well defined effects on the wear response of materials [1-10, 31-41]. As far as the environmental (lubricated, oil / oil + graphite) effects are concerned, a lot of complexity exists [1-10, 31-41].

Normally, the use of a lubricant improves the sliding wear characteristics of material because of the formation of a lubricating film consisting of a variety of reaction products [42-44]. The introduction of a solid lubricant into the liquid / semi solid lubricant brings about a further improvement in wear behavior by increasing the stability of the film. It looks logical for an optimum quantity of the (solid/liquid) lubricating constituents to exist in the (lubricant) mixture leading to the best wear performance of materials. The optimum of course may vary with material characteristics as well as operating conditions and, above all, the nature of the lubricating constituents. This is in view of the fact that the lubricant mixture should not lose adherence with the contacting surface and, at the same time, it should have enough lubricating characteristics. The question of losing adherence arises when the mixture become too dry, i.e., when the quantity of the solid lubricating phase in the mixture becomes too much to cause tearing-off the thick and dry lubricating film. Subcritical quantity of the solid lubricating phase reduces the probability of forming a stable lubricating film on the contacting surfaces. Accordingly, either side of the content of the solid lubricant constituent phase in the lubricant mixture may deteriorate the wear response of materials.

Having discussed the role of various material and operating variables on wear behavior, we will be able to better understand the observed wear response of the samples in this investigation.

The addition of graphite to oil lubricants increased the possibility of the formation of a more stable lubricating film causing further in the wear rate. However, this could be realized that for the (7-10 µm) size of graphite particle in the oil, minimum wear rate was obtained.

4.2.2. Frictional Heating

Increasing rate of frictional heating with test duration could be attributed to the increasing effective area of contact thereby reducing the severity of wear condition. A higher rate of temperature rises in some cases towards the end of the tests owing to the sticking/adhering tendency of the specimen material to the disc surface. A more severe wear condition, due to increasing applied load, led to a higher increase in the rate of temperature. The matrix alloy exhibited the generation of least frictional heat due to its excellent lubricating tendency. The abrasion caused by the fragmented dispersoid SiC particles caused larger frictional heating than the matrix alloy [9, 10]. The presence of the lubricant leading to the formation of a more stable lubricating film substantially reduced the temperature increase over dry wear. The addition of graphite further decreased the frictional heating through the formation of a still more stable lubricating film. The matrix alloy was most favorably affected in this case in view of the major constituent being solid lubricating in nature.

4.2.3. Friction Coefficient

The probability of more effective formation of a lubricant film caused the friction coefficient to decrease with an increase in the load. The abrasion caused through the entrapped dispersoid phase after fragmentation during wear led to higher friction coefficient of the composite than matrix alloy. More effective formation of lubricating film in the presence of liquid / liquid + solid lubricant led to a reduced friction coefficient. The lack of cracking tendency in the matrix alloy led to its reduced friction coefficient considerably under identical test conditions. Least friction coefficient in the event of adding graphite particle in the lubricating oil could be attributed to the formation of most stable lubricating film.

An appraisal of the observations made in this study clearly suggests varying effects of parameters like cracking tendency, lubricating characteristics, thermal stability, etc. of material constituents and experimental parameters like load and conditions. The overall effect of the parameters on the wear behavior of the samples seems to be complex in nature.

5. Conclusion

Based on the observations made in this study, the following conclusions could be drawn:

- The Matrix Alloy depicts plate shaped eutectic silicon and the other intermetallic phases while the composite revealed the presence of the dispersed SiC particles in addition to the features of the matrix alloy.
- The density was the least for aluminium-based (matrix) but the composite exhibited the maximum hardness.
- Wear Rate increased with load and speed. Testing the samples in oil plus graphite lubricated conditions led to less wear rate than that in oil alone. Addition of 5 wt% graphite (7-10 µm) to the oil lubricant led to minimum wear rate. The composite exhibited lowest wear rate while it was the maximum for the matrix alloy.
- Frictional heating increased with load and test duration; the frictional heating increased at a higher rate initially.
followed by a lower rate of increase at longer test durations. Testing the samples in oil plus graphite lubricants led to a marginal change in frictional heating.

- The friction coefficient decreased with test duration. Testing the samples in oil lubricated conditions decreased the friction coefficient of the samples especially at low loads. Test duration had a mixed influence on friction coefficient. The addition of graphite to the lubricating oil further reduced the coefficient of friction. No definite influence of the graphite content (to the oil) on friction coefficient of the materials was noted.

References


On Phase Equilibria of Sn-Sr and Mn-Sn-Sr Systems

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Abstract

Sn-Sr system is critically evaluated and the most reliable experimental data are incorporated in thermodynamic modeling. Thermodynamic properties of the binary liquid solution are estimated using the modified quasichemical model (MQM). The optimized Sn-Sr phase diagram and the corresponding thermodynamic properties are found to be in fair agreement with the experimental data in the previous related literature. For all the compounds in Sn-Sr system, a comparison between the calculated enthalpy of formation and that calculated by Miedema and first-principles has been reported. Combining Sn-Sr with the self-established thermodynamic database of Mn-Sr and Mn-Sn was used to calculate liquidus projection of Mn-Sn-Sr ternary system.

Keywords: Modified Quasichemical Model, Magnesium Alloys, Thermodynamic Modeling.

1. Introduction

Magnesium alloys have a great potential for structural applications because of their significant weight savings, superior damping capacity and good castability [1]. Therefore, the automotive industry leads the way in the growing interest in Mg alloys in order to decrease fuel consumption and reduce emissions [1-3]. Recently, research activities have been carried out to improve the elevated temperature properties of the magnesium alloys through precipitation hardening and/or solid solution hardening [4-8]. The most common magnesium alloys for automotive industry contain aluminum as a major alloying element (AZ91 and AM60). Aluminum improves the mechanical properties at room temperature; however the loss of the mechanical strength at service temperature (above 120°C) of Mg alloys is reported due to the discontinuous precipitation of \(\gamma\)-Mg\(_{17}\)Al\(_{12}\) [9-15]. Alloying Mg with Ca, Zn, Sr, Mn and Sn are found to improve the elevated temperature properties of Al containing Mg alloys by delaying or inhibiting the formation of \(\gamma\) and/or precipitating of thermally stable compounds such as Al\(_2\)Ca or Al\(_4\)Sr intermetallic phase [9-19]. Strontium is an important element in multi-component magnesium and aluminum alloys. Alloying magnesium with strontium refines the microstructure and improves the mechanical properties. Moreover, Sr enhances the corrosion resistance of Mg and Al-based alloys [20-23]. On the other hand, tin addition to magnesium based alloys has a potential to improve creep and corrosion resistance of these alloys. Tin is also a reasonably cheap element as compared to RE elements and has a low melting point and is known to improve castability [24-26]. Mn addition to Mg-Sr alloys enhances creep resistance by precipitation of \(\alpha\)-Mn at the interdendritic regions and Mn dissolves in the Mg matrix and Mg\(_{17}\)Sr\(_2\) phase [27, 28].

An understanding of thermodynamic characteristics and equilibrium phase diagram for magnesium and its alloys will allow a better control in developing and designing a new Mg-alloy with desired properties. The present study deals with thermodynamic modeling of the Mn–Sn–Sr system which is one of the important systems in Mg-Mn multi-component systems. Sn-Sr binary system will be critically evaluated and optimized using the available phase equilibria and thermodynamic data. The latest published journal article on thermodynamic modeling of the Sn-Sr system used Bragg-Williams model [29]. In their work [29], the enthalpies of formation for the stoichiometric compounds at 0 K were computed by first-principles calculations. In the present study, this system will be optimized using the modified quasi-chemical model (MQM). The MQM is considered more physically sound than other models such as the associate solution model [30]. Sn-Sr and Mn-Sn binary systems have been optimized using most up-to-date experimental data. Each of the phases in any binary system has been critically assessed based on the thermodynamic properties.
In this research article, the experimental phase diagram and thermodynamic properties of Sn-Sr binary system will be critically evaluated and the most reliable data will be used in optimization. Sn-Sr phase diagram will be optimized and combined with the self-established thermodynamic database of the Mn-Sn and Mn-Sr systems. The optimized parameters of the constituent binary sub-systems will be used to draw liquidus projections of the Mn-Sn-Sr ternary phase diagram.

2. Experimental data

2.1. Sn-Sr phase diagram

Ray [31] tracks the thermal history of twelve tin-strontium alloys within the composition range of 0-29.65 at.% Sr using thermal analysis and optical microscopy. In Ray’s study, alloys were prepared by electrolysis of a mixture of sodium and strontium chlorides over molten tin in an iron crucible. During electrolysis, strontium reacted with iron crucible and the fused salts were rapidly volatilized. Therefore, Ray’s [31] thermal data were in error and will not be used in the current optimization. Phase equilibria of thirteen tin-strontium alloys were investigated by Marshall and Chang [32] using DTA, XRD and optical microscopy from pure tin up to 65 at.% Sn. They reported that SnSr forms peritectically at 598±1° C which is in contrast with the work of Ray who showed that SnSr melted congruently at 607° C and forming a eutectic at 26.5 at.% Sr and 580° C. Marshall and Chang also reported that SnSrSn is in equilibrium with Sn instead of SnSr as reported by Ray [31] and SnSr decomposes peritectically at 334±5°C. They [32] found that Sn3Sr and Sn form an eutectic at 230±2° C and 1 at.% Sr. Widra and Schafer [33] studied Sn-Sr phase diagram in the composition range of 35-100 at.% Sr using DTA and XRD. Five intermetallic compounds, which are Sr5Sn6, Sr3Sn5, Sr5Sn, SrSn3 and SrSn5, were reported in their phase diagram, of which the first four were phases melted congruently. The assessment proposed by Massalski et al. [34] is the summary of the work of Marshall and Chang [32], and Widra and Schafer [33]. In the composition range of 11.6 to 43 at.% Sr, Hoffmann et al. [35,36] tracked phase transformation temperatures during cooling and heating for seven Sn-Sr alloys using DTA. Phase stability of Sr5Sn6 intermetallic compound were shown from the works of Hoffmann et al. [35,36] and Zürcher et al. [37]. The phase equilibria over the whole composition range in the Sn-Sr system were investigated by Palenzona and Pani [38] using XRD, DTA and optical composition. According to their work, five intermetallic compounds were confirmed namely: Sr5Sn6, Sr3Sn5, SrSn3, SrSn5 and SrSn4, where, Sr5Sn6 and SrSn5 melt congruently. In their work, three eutectic reactions were detected in the Sr-Sn system and SrSn4 was confirmed instead of SrSn5 as reported by Ray [31] and Widra and Schafer [33]. Experimental phase diagram data of Palenzona and Pani [38] and Hoffmann and Fassler [37] were in agreement. Those experimental data were the most recent and in good agreement; therefore, they will be used in the current optimization. Crystal structures of the compounds in the Sn-Sr system were reported by [35-37, 39-45].

Limited thermodynamic data for the Sn–Sr system could be found in previous literature. Strontium is highly reactive and, hence, it is very difficult to handle the alloys during high temperature experiments. However, enthalpy of mixing of the Sn-Sr liquid was measured by Esin et al. [46] using high temperature calorimeter at 1773 K within the composition range from 0 – 50 at.% Sr. Enthalpy of mixing from Esin et al. [46] will be used in the current optimization. Morozova et al. [47] estimated the enthalpy of formation of SrSn3 compound to be -82.7±1 kJ/mole atom at 25°C. Zhao et al. [29] calculated the enthalpy of formation for all compounds in the Sn-Sr system using first-principles method and Miedema model and these data will be used only for comparison. Activity of Sr in Sn-Sr system was measured by Klebanov et al. [48] at 900 K.

2.2. Mn-Sr System

Based on the experimental data of Obinata et al. [49], Peng et al. [50] modeled all phases in the Mn-Sr binary system as completely disordered solutions. In order to construct a self-consistent thermodynamic database of the Mn-Sn-Sr ternary system, the optimized parameters of Mn-Sr binary system by Aljarrah et al. [56] will be adopted in the current calculations.

2.3. Mn-Sn-Sr Ternary System

There is no experimental data for Mn-Sn-Sr system could be found in the literature.

3. Thermodynamic Modeling

3.1. Pure Elements

The Gibbs free energy of a pure element with a certain structure $\phi$ is described as a function of temperature as:

$$G_{A}^{\phi}(T) = a + bT + cT \ln T + dT^{2} + eT^{3} + fT^{-1} + gT^{-7} + hT^{-9}$$

The parameters $a$ through $h$ are taken from the SGTE compilation by Dinsdale [51].

3.2. Stoichiometric Compounds

The intermetallic compounds in the Sn-Sr phase diagram are considered stoichiometric and the Gibbs free energy of these compounds is described by the following equation:

$$G_{i}^{\text{phase, } \phi} = x_{i} G_{i}^{\phi} + x_{j} G_{j}^{\phi} + \Delta G_{f}$$

Where $G_{i}^{\phi}$ and $G_{j}^{\phi}$ denote Gibbs free energy of element $i$ and $j$ in their standard state and $\Delta G_{f} = a + bT$ is the Gibbs energy of formation of the stoichiometric compound. Where $a$ and $b$ are the model parameters to be optimized based on experimental data of phase equilibria and thermodynamic properties.
3.3. Liquid Phase

In the present work, the liquid phase is modeled using the MQM where the pair approximation is utilized to describe the short range ordering in the liquid. A detailed description of the MQM for binary and multi-components solutions is available elsewhere [52-54]. Only a brief description will be presented here. The molar Gibbs energy of the liquid phase, derived from the modified quasichemical theory [52], is described by the following equation:

$$ G_{liq} = n_i \cdot G_i^{liq} + n_j \cdot G_j^{liq} - T \Delta S_{config}^{liq} $$

$$ + \frac{1}{2} n_{ij} \Delta S_{pair}^{liq} $$

Where $n_i$ and $n_j$ are the number of moles of the component $i$ and $j$, $n_{ij}$ is the number of $(i-j)$ pairs, $\Delta S_{config}^{liq}$ is the configurational entropy of mixing given for randomly distributing the $(i-i)$, $(j-j)$, and $(i-j)$ pairs.

$$ \Delta S_{config}^{liq} = -R \{ n_i \ln(x_i) + n_j \ln(x_j) \} - R \{ n_{ij} \ln(\frac{x_{ij}}{y_{ij}}) \} $$

$$ + n_{jj} \ln(\frac{x_{jj}}{y_{jj}}) + n_{ij} \ln(\frac{x_{ij}}{y_{ij}}) $$

Where $x_i$ and $x_j$ are the overall mole fractions of the components $i$ and $j$, respectively.

4. Results and Discussions

4.1. Sn-Sr Phase Diagram

Figure 1 shows the calculated Sn-Sr phase diagram in relation with the experimental data from the previous literature. A good agreement with the liquidus line between the calculated values in this work and the experimental values of Palenzona and Pani [38], Marshall and Chang [32], and Hoffman [35] is found in Figure 1.

The calculated invariant points of Sn-Sr phase diagram in comparison with the experimental data are listed in Table 1. The activity of Sr in Sn-Sr liquid reported by Klebanov et al. [48] was used in the optimization of the Sn-Sr system. Comparison between the calculated activity of Sr from Klebanov et al. [48] is shown in Figure 2. The calculated activity shows a good agreement with the experimental data. The optimized model parameters of the stable phases in the Sn-Sr binary system are summarized in Table 2.

The data of enthalpy of mixing by Esin et al. [46] was used in the optimization and matched the calculated enthalpy of mixing curve shown in Figure 3. As can be seen from this figure, the calculated enthalpy of mixing of liquid Sn-Sr is in fair agreement with the experimental data. The lowest point of the curve is located where thermally high stable compounds are formed. This indicates stronger atomic interactions in the liquid at the composition of the intermetallic compounds.

Figure 4 shows a comparison between the calculated enthalpy of formation for all phases in Sn-Sr system and that reported by Zhao et al. [29]. The current enthalpies of formation for intermetallic compounds are in fair agreement with that obtained by Miedema model.

4.2. Mn-Sn-Sr Ternary System

The Gibbs energy of the liquid phase was calculated using the symmetric Kohler-like approximation [55] with no ternary interaction parameters for the liquid phase. The invariant reactions for the Mn-Sn-Sr system are listed in Table 3. The liquidus projection of the Mn-Sn-Sr ternary system is shown in Figure 5. The miscibility gap covers most of the composition triangle, as shown in Figure 5. Since there is no ternary experimental data available for the entire Mn-Sn-Sr system, it is possible that the size of the miscibility gap is over or underestimated by the extrapolation.
Figure 2. Plot of calculated activity of Sr against mole fraction Sn for the Sn-Sr liquid at 900 K in comparison with experimental data of Klebanov et al. [48]

Figure 3. Calculated enthalpy of mixing against mole fraction Sn for the Sn-Sr liquid at 1773 K in comparison with the experimental data of Esin et al. [46]
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<thead>
<tr>
<th>Reaction type</th>
<th>Reaction</th>
<th>Composition (at.%Sn)</th>
<th>T(°C)</th>
<th>Reference</th>
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<tr>
<td><strong>Eutectic</strong></td>
<td>Liquid ↔ Sr$_3$BCC + Sr$_2$Sn</td>
<td>2.22</td>
<td>741</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>2.7</td>
<td>745</td>
<td>[33]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>752 ± 5</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>33.3</td>
<td>1288</td>
<td>This work</td>
</tr>
<tr>
<td><strong>Congruent</strong></td>
<td>L1 ↔ Sr$_2$Sn</td>
<td>3.75</td>
<td>1185</td>
<td>[38]</td>
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<td></td>
<td></td>
<td>1255</td>
<td>1295 ± 5</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1255 ± 5</td>
<td></td>
<td>[33]</td>
</tr>
<tr>
<td><strong>Peritectic</strong></td>
<td>Liquid + Sr$_2$Sn ↔ Sr$_5$Sn$_3$</td>
<td>39.9</td>
<td>1190 ± 5</td>
<td>[38]</td>
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<td></td>
<td></td>
<td>36.7</td>
<td>1170</td>
<td>[33]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>1141</td>
<td>This work</td>
</tr>
<tr>
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<td>L1 ↔ SrSn</td>
<td>50</td>
<td>1140</td>
<td>[33]</td>
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<td></td>
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<td>776</td>
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<td>780</td>
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<td></td>
<td></td>
<td>80</td>
<td>810</td>
<td>[37]</td>
</tr>
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<td><strong>Peritectic</strong></td>
<td>Liquid + SrSn ↔ Sr$_3$Sn$_5$</td>
<td>79.7</td>
<td>598±1</td>
<td>[32]</td>
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<tr>
<td></td>
<td></td>
<td>563</td>
<td>560±5</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>73.5</td>
<td>580</td>
<td>[31]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>320</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>95.1</td>
<td>338</td>
<td>Ray</td>
</tr>
<tr>
<td><strong>Peritectic</strong></td>
<td>Liquid + Sr$_3$Sn$_5$ ↔ SrSn$_4$</td>
<td>95.8</td>
<td>315±5</td>
<td>[38]</td>
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<td></td>
<td></td>
<td>316</td>
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<td>[36]</td>
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<td></td>
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<td>232</td>
<td>[31]</td>
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<td>98</td>
<td>230±2</td>
<td>[32]</td>
</tr>
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<td></td>
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<td></td>
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<td>1100±5</td>
<td>[38]</td>
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<td></td>
<td></td>
<td>46.1</td>
<td>1080</td>
<td>[33]</td>
</tr>
</tbody>
</table>
Table 2: Optimized parameters of all phases in Sn-Sr and Mn-Sr systems.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Thermodynamic parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Liquid</strong></td>
<td></td>
</tr>
<tr>
<td>Sn-Sr Liquid</td>
<td>( Z_{SnSr}^{Sn} = 5; Z_{SnSr}^{Sr} = 5 )</td>
</tr>
<tr>
<td></td>
<td>( \Delta \theta_{SnSr}^{0} = -2127.2 - 1.55T; \Delta \theta_{SrSn}^{10} = -478 - 2.39T )</td>
</tr>
<tr>
<td></td>
<td>( \Delta \theta_{SrSn}^{01} = -1.43T )</td>
</tr>
<tr>
<td><strong>SrSn</strong></td>
<td>( \Delta \theta_{SrSn}^{0} = -2127.2 - 1.55T )</td>
</tr>
<tr>
<td><strong>Sr_{2}Sn</strong></td>
<td>( \Delta \theta_{SrSn}^{10} = -478 - 2.39T )</td>
</tr>
<tr>
<td><strong>Sr_{3}Sn</strong></td>
<td>( \Delta \theta_{SrSn}^{01} = -1.43T )</td>
</tr>
</tbody>
</table>

Table 3. The calculated enthalpies of formation for all the stable compounds in the Sn–Sr system in comparison with literature.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Miedema Model</th>
<th>First-principle method</th>
<th>MQM</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnSr_2</td>
<td>-68.02</td>
<td>-63.40</td>
<td>-66.00</td>
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<tr>
<td>Sn_{3}Sr</td>
<td>-75.47</td>
<td>-64.47</td>
<td>-75.75</td>
</tr>
<tr>
<td>SnSr</td>
<td>-90.55</td>
<td>-68.88</td>
<td>-90.00</td>
</tr>
<tr>
<td>Sn_{3}Sr</td>
<td>-88.83</td>
<td>-57.93</td>
<td>-83.38</td>
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<tr>
<td>Sn_{3}Sr</td>
<td>-67.84</td>
<td>-41.74</td>
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<tr>
<td>Sn_{4}Sr</td>
<td>-55.32</td>
<td>-33.96</td>
<td>-47.88</td>
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</tbody>
</table>

Figure 4. The calculated enthalpy of formation of all intermetallic compounds in comparison with work of Zhao et al. [29].
5. Conclusions

The experimental phase diagram data and thermodynamic properties of the Sn-Sr binary system was evaluated and optimized to obtain self-consistent model parameters for the Gibbs energy of all phases. The calculated liquidus line of Sn-Sr phase diagram was compared with the experimental data and found to be in a good agreement. The calculated thermodynamic properties such as activity and enthalpy of mixing of the Sn-Sr system were in accord with the experimental data in the literature. By combining self-consistent set of optimized parameters of the phases of the constituent binary sub-systems, liquidus projection of the ternary Mn-Sn-Sr phase diagram was obtained.

6. Acknowledgment

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Abstract

The purpose of the present study is to design, construct and evaluate a prototype flower stem cleaner machine. Designing the processing equipments of agricultural products requires information about their physical and mechanical properties. In order to construct the design, the effect of leaf picking velocity and the tensile direction and location were studied on maximum picking force and energy. Results showed that picking force and deformation data ranged from 18 to 61 N and from 4.1 to 8.7 mm, respectively. The mean values of tangent modulus for top and bottom groups were 7.22 MPa and 10.1 MPa, respectively. The effect of the picking velocity, the location and stretch direction on the picking force and the tangent modulus was significant ($P = 0.01$). After measuring the physical and mechanical properties of stems, the machine were designed and constructed. Machine design is based on the use of the rotational axis hit with leaves, which causes leaves to release from the stem. The prototype consists of two axes: rubber fingers that are oriented at angles of 90 degrees on axes, and an axis distance control mechanism and transmission system. After completing the design and construction, the prototype was evaluated to determine the optimum operating conditions. For this purpose, the effects of rotational speed in five levels (200, 350, 500, 650, 800 rpm), axis distance in five levels (-10, -5, 0, +5, +10 mm) and hardness of fingers in two levels (30, 60 shore A) are studied. In the best condition, the machine is able to remove 100% of the leaves. Optimal working conditions happened with 500 rpm for rotational speed, -5 mm for axis distance and 60 shore A for finger hardness. The prototype had the capacity of twenty flower stems cleaning at an average time of 10 s.

Keywords: Cleaner Machine, Chrysanthemum Flower, Picking, Leaf.

1. Introduction

The intersection of art, design and horticulture, represented by the ornamental plant industry, has led to the use of a very wide variety of plant organs, such as cutting flowers for ornamental purposes [1].

Cut chrysanthemum flowers have a longer vase life than most other cut flowers. The loss of quality is mainly due to their leaves wilting [2] because of impeded water transport [3]. The water uptake and the rehydration of chrysanthemum stems have been facilitated by postharvest manipulations, such as immersion into detergent solution and cold water; the addition of antibacterial agents in the holding solution has been recommended [4]. Removing the stem leaves immediately after cutting can lead to retarding flower wilt, and, the subsequence may result in a longer vase life.
A review of the literature revealed a lack in information on mechanical post harvesting system for removing leaves from cut chrysanthemum flowers, but many old research studies have been conducted on removing leaves and thorns from rose flower. Chung invented a rose stem stripper that is accomplished by two metal arms. A rose stem is inserted between the pair of jaws where each jaw has a V-shaped opening, allowing only the rose stem to pass, and thereby removing thorns and foliage [5]. A flower stem cleaning device including a body through which a cleaning opening extends was invented by Richardson. The opening is defined by a flexible surface portion of the body to prevent damage to the plant stems. The stem to be cleaned is pulled through the opening manually to remove thorns and miscellaneous foliage from the stem [6].

Apparatus for bunching flowers including a rotating endless belt defining made by Monic included stem trimming apparatus, stem cleaning apparatus and tying means mounted adjacent the endless belt downstream of the leaf removing apparatus [7]. Maeyer and Huisman [8] used a rotary brush to defoliate hemp. The use of rotary brush to remove the leaf and seed head was partially successful in that less stem was removed but the brush was not sufficiently effective in removing leaf. A device was developed to harvest cereals by stripping based around a rotor with stripping elements of a ‘keyhole’ design made of a stiff polymer. Besides being very effective for removing the seed and grain from a range of crops, the stripping system has also proved to be very effective for defoliating crops, including mint, lucerne and nettles [9].

Without a database of basic and mechanical characteristics, engineers must design plant handling and processing equipments using empirical methods that increase the development time and costs. Information about the physical and the mechanical properties is vital for the proper and effective design of mechanization and automation equipment when the plant material is to be directly handled and manipulated. Equipment, such as transplanters [10], singulation devices [11] and robotic work cells [12], has been developed without benefitting from accurate property data concerning the crop for which the apparatus was intended. To support the mechanization research on flower process, related information is needed on physical (average diameter, specific gravity, and moisture content) and mechanical (bending strength, compression strength, shear strength and leaf picking force) properties of chrysanthemum. Mcrandal and McNulty [13] evaluated the shear strength of grass stems with quasi-static shear test. They studied the effect of bevel angle, oblique angle, shear velocity and blade type on shear strength, and shearing energy of pyrethrum flower stem, tensile strength and energy per unit area for picking up the flowers were evaluated. Chattopadhyay et al. [18] determined shear properties of sorghum stalks with quasi-static shear test. They found that the maximum shear strength increased from 3.74 to 8.18 MPa at the forage stage and from 4.68 to 9.02MPa at the seed stage when the bevel angle was increased from 30 to 70 degree at a 10 mm/min rate of loading. Specific shearing energy was determined for sunflower stalk by Ince et al. [19]. Their results showed that the shearing stress and the specific shearing energy increased as the moisture content increased, also both the shearing stress and the specific shearing energy were found to be higher in the lower region of the stalk due to structural heterogeneity [19].

The objective of this research is to design, construct and evaluate a prototype machine for removing leaves of cut chrysanthemum flowers.

2. Material and Method
2.1. Design and Operation

The method that was developed causes cut chrysanthemum flower stem to be cleaned from foliage as a result of hit the rotating fingers with leaves. The prototype consists of two rotational axes and rubber fingers that are oriented at angles of 90 degrees on axes. Bouquet is entered between two rotational axes as the flower stems are perpendicular to the axes. The axes rotate in opposite directions to each other and fingers strike foliage’s and clean the flower stems. The required outcomes and the principles of this method are as follows: (1) the machine must be cleaned to cut flowers in bouquet without damaging the flower stems; (2) the operating mechanism must be based on impacting the rotating fingers with stationary bouquet; (3) the construction must be compact and portable; (4) the mechanism must be simple, strong and sturdy; (5) the mechanism must be capable of being operated by one person; the prototype comprised two rotational axes, rubber fingers, a distance control, a rotary speed control and a power transmission system (Figure 1).

Finger shaped as a frustum of height 50 mm with main diameter 10 mm and small diameter of 8 mm made from molded rubber, each rotational axe is made of steel bar Ø30mm which drilled and threaded 13 holes with 20 mm distance on each side for finger mounting, an 0.37 kW electromotor with 2980 rpm and four 6006-2z ball bearing has been selected for rotating axes.

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The operating procedure is as follows. First, the cleaning machine is switched on and the axes were rotated. The bouquet which is held with operator in perpendicular direction to axes is entered between two axes slowly. Rubber fingers are impacted through foliage and removed until bouquet was completely cleaned.

2.2. Test Procedure

2.2.1. Determining Physical Properties of Cut Chrysanthemum Flower

The stems of chrysanthemum flower were harvested from Ashian-e-Sabz greenhouse in Tehran, Iran, from healthy mother stock plants by a sharp knife at a height of 10 cm above the soil surface in the morning of each testing date. Harvested stems were covered and transported in an insulated container to a cooling chamber (1°C) to the Tarbiat-modares university biomechanics research laboratory for testing. Testing was completed as rapidly as possible in order to reduce the effects of drying. Two tests were conducted. Test I involved measuring the stem diameter and moisture content. Test II measured bending strength and leaf picking force in relation to variation in load speed. In the first test, the diameter of the stem was measured by a vernier calliper and the specimen was dried in an electric oven (ISOTEMP, USA) to determine its moisture content according to the ASAE Standard [20]. The second test measured specimens from the growth tip end and the root internode end of the stem. A universal testing machine (UTM, HOUNSFIELD H50K-S) with a 500 N load cell was used for measuring the bending and picking force. A three-point loading apparatus with a span of 15 mm was used to support the stem specimens below the UTM probe (Figure 2a) for measuring the bending strength. Support and indenting rods were 3 mm in diameter. Specimens were placed in the three-point loading apparatus under the UTM probe and the force was applied to the centre of the stem at a loading speed of 25 mm/min (ASAE Standard, 1998) until it fractured. For the beam experiment, an apparent modulus of elasticity was computed using equations from Mohsenin (1980, p. 200)

\[
E_a = \frac{f I^3 \cdot 10^6}{48 \pi d c^4 / 64}
\]

(1)

A device similar to the one shown in Figure 2b is constructed for picking force measuring. The device held the leaf and connected it to the UTM crosshead. The end of the stem was also clamped by the lower UTM jaw. Effect of picking velocity at 10, 100, and 500 mm/min, tensile direction, up and down direction and two sample groups were studied on maximum picking force and energy. Each test was replicated 10 times. Analysis of variance and the Duncan Multiple Range Test were applied to determined the influence of factors upon the picking force and determine proper axes rotation speed for prototype machine.

2.2.2. Performance Test of Prototype Cleaning Machine

Before starting the test, the number of leaves from each flower stem was counted, then the axes rotational speed was calibrated with tachometer (Prova). To obtain optimum operating condition of cleaning, machine initial tests were conducted in accordance with the Table 1. Independent affecting factors on machine performance are rotational speed, axes distance and finger hardness (Figure 3). Performance parameters of the cleaning machine, which include the percent of removed leaves, the time required to stem cleaning and cleaned flower vase life were recorded and analyzed. Analysis of variance and the Duncan Multiple Range Test were applied to determine the influence of factors upon the picking performance parameters. For vase life determination and flower stem bases were immersed to a depth of 4 cm in glass vials containing 400 ml of the double-distilled water include 2% ethanol, 2% methanol, 5ppm BA and 5ppm paclobutrazol. Experiments were carried out at 21 ±1°C and 60% RH under continuous fluorescent light (49 mol m⁻² s⁻¹). Wilting of flower was used as the criterion for termination of vase life.
Figure 2a. Apparatus for the strength in bending experiment

Figure 2b. Device to hold and connect the leaf to UTM for picking force measuring

Figure 3. Prototype of the flower stem cleaner machine.

Table 1. Initial test levels of cleaning machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level I</th>
<th>Level II</th>
<th>Level III</th>
<th>Level IV</th>
<th>Level V</th>
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</thead>
<tbody>
<tr>
<td>Rotational speed (rpm)</td>
<td>200</td>
<td>350</td>
<td>500</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>Axes distance (mm)</td>
<td>-10</td>
<td>-5</td>
<td>0</td>
<td>+5</td>
<td>+10</td>
</tr>
<tr>
<td>Finger hardness (shore A)</td>
<td>30</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Replication</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
3. Results and Discussion

3.1. Physical Properties of Cut Chrysanthemum Flower

Samples taken from the bottom of the cutting were significantly larger in diameter than those taken from the top of the cutting. Samples taken from the bottom tended to be lower in the moisture content than those from the top (Table 2). The results of variance analysis showed that the sample group had a significant effect on all the measured physical properties ($P = 0.01$). Observations indicate differences in the woody versus succulent nature of tissue depending upon the physiological age of the stem section (Table 2).

Compiled data from the strength in the parallel plate compression tests can be seen in Table 2. The summarized data are segregated by group. As with the strength in bending tests, differences between groups were primarily in magnitude of force and deformation. Note that the bio-yield “hump” is the dominant and characterizing feature of each force-deformation curve for the compression tests (Figure 4). The nature of the failure of the stem cross-sections versus the resistive loading of the compacted tissue indicates that the data past the bio-yield region is of little value for machine design purposes. Samples from the bottom of the cutting had significantly higher bio-yield forces and deformations than did those from the top. Force and deformation data for calculating the tangent modulus were taken from the point of inflection on the force-deformation curve (Figure 4).

![Figure 4. Typical force-deformation curve for strength in compression experiment.](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>4.44*</td>
<td>3.38</td>
<td>5.37</td>
<td>0.65</td>
</tr>
<tr>
<td>MC (%)</td>
<td>78.17*</td>
<td>74.52</td>
<td>80.81</td>
<td>2.43</td>
</tr>
<tr>
<td>Bio yield force (N)</td>
<td>23*</td>
<td>18</td>
<td>29</td>
<td>4.17</td>
</tr>
<tr>
<td>Bio yield deformation (mm)</td>
<td>5.1*</td>
<td>4.1</td>
<td>6.5</td>
<td>0.65</td>
</tr>
<tr>
<td>Tangent modulus (MPa)</td>
<td>7.22*</td>
<td>5.8</td>
<td>8.1</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Group bottom

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>5.45*</td>
<td>4.19</td>
<td>6.85</td>
<td>0.92</td>
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<tr>
<td>MC (%)</td>
<td>75.99*</td>
<td>72.43</td>
<td>80.15</td>
<td>2.46</td>
</tr>
<tr>
<td>Bio yield force (N)</td>
<td>45.25*</td>
<td>30</td>
<td>61</td>
<td>9.14</td>
</tr>
<tr>
<td>Bio yield deformation (mm)</td>
<td>6.8*</td>
<td>5.4</td>
<td>8.7</td>
<td>1.25</td>
</tr>
<tr>
<td>Tangent modulus (MPa)</td>
<td>10.1*</td>
<td>8.5</td>
<td>12.3</td>
<td>1.14</td>
</tr>
</tbody>
</table>

* significant at 1% and ns not significant.

Picking force increased with the increase in the stem diameter. Based on variance analysis (Table 3), the picking force was affected significantly with the picking velocity ($P = 0.01$).

Results of the Duncan Multiple Range Test show that the mean values for up and down direction were 10.52 N and 1.89 N, respectively. Hag et al. (1971) found that the effect of loading rate on tensile strength of cotton stem was further influenced by the density of the stem. For high density specimens (0.400 g/cm$^3$), the tensile strength increased directly as the rate of loading, but for lower density specimens (0.3759 g/cm$^3$), the tensile strength decreased with an increase in loading rate from 7.6 to 25.4 mm/min and then increased with further increases of loading rate. Results of Kazaie et al. (2002) research showed that the picking velocity has a significant effect on the picking force and energy of pyrethrum flower stem.
Table 3. Analysis of variance of effect of velocity, Location on picking force

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of Freedom</th>
<th>Picking force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>11</td>
<td>163.72*</td>
</tr>
<tr>
<td>Location (L)</td>
<td>1</td>
<td>6.244*</td>
</tr>
<tr>
<td>Tensile direction (D)</td>
<td>1</td>
<td>1353.13*</td>
</tr>
<tr>
<td>Velocity (V)</td>
<td>2</td>
<td>68.12*</td>
</tr>
<tr>
<td>L*D</td>
<td>2</td>
<td>1.34*</td>
</tr>
<tr>
<td>L*V</td>
<td>2</td>
<td>4.05*</td>
</tr>
<tr>
<td>D*V</td>
<td>2</td>
<td>45.41*</td>
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<tr>
<td>L<em>D</em>V</td>
<td>2</td>
<td>3.09*</td>
</tr>
<tr>
<td>Error</td>
<td>48</td>
<td>321.68</td>
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</tbody>
</table>

3.2. Performance of Prototype Cleaning Machine

Table 4 shows the results of the statistical analysis carried out to examine the effect of axes distance, rotational speed and finger hardness on the percentage of the removed leaves for chrysanthemum flower. ANOVA indicated that two independent variables axes distance, rotational speed significantly influenced the percentage of the removed leaves (Table 4). The interaction effects of the independent variable were also significant, except for the interaction between axes distance and finger hardness. Additionally, a difference in the rate of increase in the percentage of the removed leaves was obtained in the interaction between the factors. The data showed that it is possible to remove nearly 100% of the chrysanthemum flower leaves with minimal damage to flower stalk.

Table 4. Analysis of variance of considered parameters on removed leaves.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of Freedom</th>
<th>Sum Squares</th>
<th>F Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>49</td>
<td>14676</td>
<td>18.95</td>
<td>0.0001</td>
</tr>
<tr>
<td>Distance (Di)</td>
<td>4</td>
<td>481.9</td>
<td>7.58</td>
<td>0.0001</td>
</tr>
<tr>
<td>Speed (S)</td>
<td>4</td>
<td>11166</td>
<td>175.6</td>
<td>0.0001</td>
</tr>
<tr>
<td>Hardness (H)</td>
<td>1</td>
<td>1.21</td>
<td>0.07</td>
<td>0.7841</td>
</tr>
<tr>
<td>Di*S</td>
<td>16</td>
<td>1421.1</td>
<td>5.59</td>
<td>0.0001</td>
</tr>
<tr>
<td>Di*H</td>
<td>4</td>
<td>142.4</td>
<td>2.24</td>
<td>0.049</td>
</tr>
<tr>
<td>S*H</td>
<td>4</td>
<td>353.5</td>
<td>5.59</td>
<td>0.0004</td>
</tr>
<tr>
<td>Di<em>S</em>H</td>
<td>16</td>
<td>1201.1</td>
<td>4.72</td>
<td>0.0001</td>
</tr>
<tr>
<td>Error</td>
<td>98</td>
<td>1558.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results of the interaction effects of axes distance and rotational speed on the percentage of the removed leaves are reported in Figures 5 and 6 for finger hardness of 30 and 60 shor A, respectively. With an increase in rotational speed from 200 to 800 rpm, the value of the percentage of the removed leaves for both Fingers 30 and 60 shor A increased. Additionally, with decreasing the axes distance from +10 to -10 mm, the value of the percentage of the removed leaves for finger hardness 30 shor A increased, but for finger hardness 60 shor A, most value of the percentage of the removed leaves related to axes distance -5 mm. For this finger, with an increase in rotational speed from 200 to 650 rpm, the value of the percentage of the removed leaves increased from 91.88 to 100% for axes distance -5mm. Whereas for finger hardness of 60 shor A and axes distance of -5mm, increasing the rotational speed from 200 to 500 rpm caused increases in the value of the percentage of the removed leaves from 94.3 to 100%.

Figure 5. Effect of rotational speed on percentage of removed leaves for hardness 30 shor A.

Figure 6. Effect of rotational speed on percentage of removed leaves for hardness 60 shor A.

Optimal working conditions happened with 500 rpm for rotational speed, -5 mm for axis distance and 60 shor A for finger hardness. Bruce et al. (2001), with the same method, succeeded to remove more than 92% of leaves and flower heads using a rotor fitted with stiff polymer teeth. Also they found that a high rotation speed can increase damage of stems; therefore, from 545, 645 and 770 rpm, they introduced 645 rpm as an optimal speed [22].

4. Conclusion

Testing of a prototype for flower stem cleaning machine resulted in the determination of the optimal operating conditions in terms of rotational speed, axis distance and finger hardness. Subsequent performance tests of the prototype using the selected machine settings indicated that the machine could clean a bouquet with twenty flowers stem at an average time of 10 s. Good levels of cleaning efficiency and consumer acceptance were achieved.
References

Fixture Designers Guidance: A Review of Recent Advanced Approaches

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Abstract

Fixture design is an important issue in the process of manufacturing. Fixture design is a critical design activity process which bridges Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). The present paper presents a literature review of the Computer-Aided Fixture Design (CAFD) approaches performed. The purpose of this research is to give a deep and quick understanding of fixture design, its criteria and approaches used in this field. The significant techniques used in this field along with their applications, criteria and assumptions are also considered. The shortcomings of the existing research studies are stated and some issues pertaining to handling the weaknesses of the current research are suggested to be hopefully taken into account in future research.

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Keywords: Literature Review; Computer Aided Fixture Design; Fixtures Taxonomy; Artificial Intelligence.

1. Introduction

An important type of tooling utilized in assembling, manufacturing, inspecting and other operation processes is known as fixtures. Fixtures are to hold workpieces stable and constraint without any movement during the manufacturing process. They set and secure the orientation and position required by the workpieces based on the specifications of the design [1]. An accurate fixture design is critical for quality of product based on accuracy, precision, and final product of the designed parts. About 40% of the parts that are rejected are mainly rejected because of the dimensioning errors due to poor fixture designs [2]. Fixture design is under the combined influence of workpiece specifications, machining methods, material performances and etc. It demands rich experience of the designers, which leads to a significant increase in the design cycle time and costs. Diminishing the need of potential rework on parts can also lower the time and cost of the manufacturing process [3]. Costs related to fixtureing represents 10-20% of the total costs of a system in manufacturing [4].

To reduce the lead-time and cost of product development in fixture design field, automation and computerization of fixture design are required. Thus, CAFD has been introduced and utilized as an integration of computer-aided designs and computer-aided manufacturing (CAD/CAM) [5]. However, fixture design is still an issue of concern in the present manufacturing field even though many new CAFD techniques have been introduced [2]. Various approaches have been attempted in fixture design, i.e., Case Based Reasoning (CBR), Rule-based expert system, Genetic Algorithm (GA), Multi-agent Approach, Machine Learning, Geometric Analysis, etc.[6, 7].

Although many attempts have been made in the fixture design domain, there still remains some requirements to report and evaluate the used techniques in this area sharply and simply. Therefore, the techniques need to be addressed based on their principles, applications, criteria of use, adapting in fixture design area, and so on. This can help researchers to quickly understand the fields of fixture design and the strengths and weaknesses of each technique(s) in each field. The quick understanding can save time of researchers in fixture design and facilitate boring review process.

This paper is organized as follows: section 2 is about CAFD by focusing on the types of fixtures, design requirements and steps of fixture design. The next step is about aspects of significant techniques that have been used in fixture design. The significance of this study is that it offers a deep, but simplified, understanding of the current and innovative methods of fixture design that are useful and required for fresh researchers in the manufacturing field as a guideline.

2. Computer Aided Fixture Design (CAFD)

CAFD is the use of computers to help in the design of fixtures [8]. CAFDs have grown remarkably since the 1980s, and a lot of work has been done to enhance the
process of fixture designs [9]. Computers have dramatically reduced the design process time. By using a computer, designers are able to design in a virtual atmosphere. This helps the designers identify potential problems and undertake different ideas without actually creating fixtures physically. These programs have the added benefit of keeping a designer from missing steps while designing; and by avoiding mistakes, time and costs can be kept low [8].

However, the contrasting features of the design’s requirements can be rather challenging. For instance, having a heavy fixture can be beneficial to the stability but this would make the material costs to rise exponentially and affect the usability, as the added weight would discourage handling carried out manually. These factors complicate the fixture design further and call for the necessary research of CAFD further [10].

2.1. Taxonomy of Fixtures

Fixtures are utilized as a work-holding device to locate and clamp a part surface that supports the operations of manufacturing. A normal part manufacturing process requires the use of many fixture setups to hold the working part in place as different orientations need to be operated [11]. Many manufacturing processes use fixtures widely, such as welding, testing, inspection, assembly, and machining that include milling, turning, drilling, grinding, etc. Figures 1-4 demonstrate the actual cases of fixture design in the manufacturing field. Based on the fixture’s flexibility, the fixtures would be categorized in modular fixtures, dedicated fixtures and general-purpose fixtures, such as conformable and reconfigurable fixtures [2, 12].

Figure 1. Machining fixture [13]

Figure 2. Assembly fixture [2]

Figure 3. Inspection fixture [2]

Figure 4. Typical pin-array fixture as one type of conformable fixtures [2]
Dedicated fixtures are fixtures that are produced for one specific workpiece and one setup. One of the benefits of the dedicated fixtures is that they have a high stiffness and are generally used for high batch sizes because they are created to perfectly locate and clamp a workpiece [14]. Most dedicated fixtures are, at first, originally at first designed for the purpose of one workpiece only. The dedicated fixtures have many beneficial properties, among which are high tolerances and rigidity; however, they are very expensive [8]. Dedicated fixtures are particularly essential in manufacturing for mass production and for precise, sophisticated, and advanced parts. In comparison to the modular fixtures, dedicated fixtures are carefully designed in accordance with the requirements of manufacturing and the design of the workpiece [15].

Flexible Manufacturing Systems (FMS) are dependent on fixtures that are not particularly fixed to just one workpiece. The fixtures should be reusable and changeable to suit the variations of the workpieces. The variations are inclusive but not limited to the same parts with various dimensions and oddly parts shaped. Therefore, general-purpose fixtures, such as reconfigurable, conformable and modular fixtures, are used as a solution in FMS [16].

Conformable and reconfigurable fixtures can be designed to receive portions of the different sizes and shapes [2]. Specifically, the technology on conformable pin-array fixture is used widely in a lot of fixture designs as certain components consist of internal variables which are adjustable to address the various workpieces and their features [17]. Figure 4 illustrates the typical application of the pin-array fixture. Several precision works in manufacturing utilize the materials-related phase change fixtures. In the aerospace industry, for example, metals with low melting-point are utilized to surround the turbine blades and create surfaces that are well-defined for the parts of locating and clamping the grinding processes [18].

Modular fixture technology is the most widely used type of reconfigurable fixtures. Modular fixturing systems have been looked at as a possible solution for FMS due to the high variability and standard set of parts they contained [8]. They include a base that has extensions that are highlymovable, which helps the configuration changes to take place quickly. CAFD tools can be utilized to make the fixtures quickly and the advantage is that they can be reused in more than one configuration. They are made according to really tight tolerances to make sure that the number of errors is kept to a minimum in the finished product [19]. Most of the CAFD systems are developed based on the use of modular fixture design. This suggests that modular fixtures are the most suitable type of fixture design in terms of a CAFD process, which can be applied to produce a greater computerization impact in the researches [8, 20]. There are several limitations nevertheless [2]:

- These components only result in a limited number of combinations, which means that there is a possibility that no appropriate combination can be designed for some of the workpieces that contain complex or irregular geometries.
- At times, it is hard to maintain the modular fixtures with the structural properties. The modular fixtures’ structural properties include features such as locating accuracy, stability, stiffness, operating speed, loading and unloading, etc. It is commonly known that utilizing modular fixtures may not gain the quality of an optimal fixture.
- It is not appropriate for mass production, such as automotive productions and the manufacturing of their components.

The principles of modular fixturing are used in many documented CAFD studies and applications to design fixture designs given the extensive usage in the present manufacturing and standardized productions [2]. Modular machining and modular assembly fixtures are widely used in the classification of modular fixtures. These kinds of fixtures’ requirements are different but, comparatively, the approach to design them is quite standard [8].

Assembly fixture and welding fixture are mostly similar and they have obvious differences with machining fixture, as shown in the following [2, 6, 21]:

- The workpieces in the process of welding are normally an assembly of a few parts, while the workpieces that go through the machining process have just a single part;
- Normally, the requirements for accuracy in the processes of assembly and welding are less, compared to machining;
- The fixing and machining forces in the processes of assembly and welding are normally smaller, compared to machining; and
- The welding’s thermal reactions should be considered thoroughly.

During the machining operation, the machining fixtures are utilized to locate and constrain the workpieces. The workpieces must be suitably located and clamped to make sure that they are machined based on particular dimensions and tolerances [22].

It is essential to minimize the deflection of the workpiece and fixture tooling caused by the forces of clamping and cutting to enable an accurate and quality production results in the machining process [23]. In general, there are two fundamental functions in a machining fixture [24, 25]: (1) to locate the right position of the component related to the cutting tools; and (2) to secure the components tightly to prevent it from moving in the machining process.

2.2. Steps of Fixture Design

Generally, fixtures contain four components, namely clamps, locators, base plates and supports. Fixture designs commonly assist in placing components onto a workpiece so that it remains immobile and stable in the process of machining or related operations [26].

There are normally four phases in the design process of the fixtures: fixture planning, setup planning, verification and unit design, as demonstrated in Figure 5 [27, 28]. The identification of machining setup by not moving the parts in each setup is known as setup planning. Fixture planning is defined as the physical fixture requirements, layout plan and prevention of collision. Verification is used to ensure that the developed fixture designs meet the requirements of fixturing. Unit design consists of the detailed and conceptual definition of the locating and clamp units of the
fixture made with the base plate. In addition, the design must adhere to the other design issues, which may include the fixture weight, fixture cost, assembly time, etc. [14].

Work piece CAD model
Machining information
Design considerations

Setup planning:
- Identify setups
- Determine locating datums

Fixture planning:
- Define fixturing requirements
- Determine fixture layout plan

Unit design:
- Conceptual unit design
- Detailed unit design

Verification:
- Verify fixture against fixturing requirements

Finished setup plan
Fixture design
Materials listing

Figure 5. Steps of fixture design [27]

These steps can be generalized as: analyze the part, define the suitable locating and clamping points, identify the tooling and environmental requirements, and create a fixture to satisfy the criteria. These steps can be highly individual and can require an exhaustive trial of an error approach until experience is gained [8], which are described below.

In the fixture planning stage, the requirements of fixturing are normally created; these can be divided into six classifications as shown in table 1 [29]. Fixture planning and configuration is mainly an activity that is driven by experience to decide the location and clamping of the workpieces precisely based on the designs of the parts and the requirements of the process. The output of this step configures the fixture layout automatically, which guarantees the stability of the part [11].

The unit design phase is carried out to gain an accurate location and stiffness and to prevent the deformation of the fixture components [30]. For example, the tolerances of the locating units must be in such a way that the accuracy of the location is reached. However, the deformation, as a result of forces from the machining and clamping, must be prevented. It is critical that these requirements are followed as a guideline to design the units for locating and clamping [26].

Fixture design verification is the method of verifying the current fixture design by examining its achieved tolerance, geometric constraint’s ability, fixturing accessibility, and the deformation and stability of the fixture workpiece system. The verification phase also provides the associated suggestions for improving the design [27-29]. Solutions for the verification of a fixture design are required due to the following reasons:

- The design process includes too many factors; it is quite hard to set an accurate model of the analysis in this process;
- The constraints of the design are individually viewed; some of the contrasting constraints may be created when they are regarded altogether; and
- Fixture design is closely linked to other activities such as CAM software, manufacturing systems and Computer-Aided Process Planning (CAPP) [2].

Thus, the CAFDs’ strengths need to be part of the verification approaches that emphasize checking stability and the deformation of the workpieces while machining. A further advantage in this area is the layout planning techniques that aim to minimize the deformation of the workpiece made by the forces during machining [10]. Even though that several research efforts have been undertaken to support all the four phases to overcome the entire process of fixture design activity [31-33], the strength of the provided support differs across each phase and is normally not as good as the research efforts that focus on supporting particular phases only. Joneja and Chang’s [32] ability, for example, to carry out the setup planning is not as impressive as that of Yao et al. [34], who exclusively concentrate on that particular task and consider the tolerance of the stack-ups.

3. Significant Techniques and the Applications in Fixture Design

Fixture design is a process that is complex and experience-based and requires trial-and-error to make the design. Therefore, during the past two decades various approaches have been attempted in fixture design to facilitate and computerize this task. Among these approaches are: Rule-Based Reasoning (RBR), CBR, GA, Neural Network (NN), Finite Element Method (FEM), Geometric Analysis, etc. [6, 35]. Table 2 catalogs the significant approaches used in CAFDs.

As the Artificial Intelligent (AI) technology has gained a greater level of acceptance in manufacturing, expert systems can offer a logical tool in automating the fixture design by utilizing the benefits of the management with the experience-based knowledge [36]. RBR is an experts system approach that utilizes induction rules to decide if a new problem should be further inspected or not [9]. Nnaji [37] and Nee & Kumar [38] typically used this technique. They carried a limited assessment of the likely displacement at each locating point caused by the machining forces and implemented an easy justification module that utilized heuristic rules to decide if a dedicated or modular fixture design should be created.

Fixture designs commonly and heavily depend on knowledge and experience. Simultaneously, fixture design resources and knowledge are required to be suitably retained for reuse in the future [1]. However, CBR [39, 40] includes indexing, representing, and organizing the current design cases as experience and knowledge so that they can be reused, recalled, and modified, for future design conditions. For these reasons, CBR approaches, as one of most effective methods, have been applied in this field [41].
The main assumption in CBR based fixture design methods is Kumar & Nee’s assumption so that similar workpieces would require similar fixtures [18]. Thus, in this kind of system, the workpieces are grouped together into families of parts and an appropriate fixture design is attached to each workpiece. The fixture structures’ similarity relies on the similarity of parts’ structures and process methods where the fixtures are utilized [1, 6, 21, 42, 43]. Now automatically this seems to be a valid and sensible approach.

Applications of GAs to support the fixture planning, fixture layout plan and fixture configuration design are encoded in binary strings. GA has been examined, evaluated, and allowed to go through crossover, mutation, and reproduction. Until an optimal state is derived, the modification continues to develop improved solutions [44, 45]. GA has been interfaced with the FEM for optimization problems in the fixture layout in most cases [22, 46]. Finite element analysis (FEA) is being recognized as a typical platform for simulation and modeling of different manufacturing operations [47]. Normally, deformation testing is utilized by employing a finite element analysis where a workpiece is discretized to generate a node series that reflects the potential points of contact for locating and clamping [48]. FEM and GA are utilized in several fields of fixture design, such as in designing the optimal layouts for fixture configuration [49]. These layouts indicate the optimum points where the fixture should contact the workpiece being machined.

NNs are interconnected networks consisting of simple components. These networks can develop solutions for new problems that are entered into the network. NN techniques have been utilized to support fixture design systems that are case-based, as the similarity evaluator [50] and as the conceptual unit design. Research by Kumar et al. [51] utilized a combination of GA/NN techniques where the NN is trained with selections of past design problems and the possible solutions. The GA creates a possible solution that is assessed utilizing the neural network, which, in turn, works as a guide for the GA.

Geometry is an important aspect of designing individual units where the aim is to choose and to assemble the defined unit elements to offer a unit of appropriate acting heights [25, 52]. Researchers have mainly utilized geometric techniques to design a complete fixture unit [52, 53] in which the fundamental notion is to identify the essential dimensions of specific fixture units, typically being its height and to, later, link all the other dimensions of this component to the essential dimension through mathematical relationships that pre-exist. Typically, a geometry-based system is designed where the dimensions of the individual element are generated in association with the primary dimension of that element (normally the necessary height) through parametric dimension links. This is augmented with a relation knowledge base of how various elements are configured to create one unit [54].

### Table 1. Requirements of fixture design adapted from [29]

<table>
<thead>
<tr>
<th>General requirements</th>
<th>Examples of abstract sub-requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerance</td>
<td>The locating tolerances should meet the design tolerances requirements of the parts</td>
</tr>
<tr>
<td>Physical</td>
<td>The fixture must be capable of physically accommodating the work-piece’s weight and geometry. The fixture must allow access to the features of the work-piece that needs to be machined.</td>
</tr>
<tr>
<td>Affordability</td>
<td>The fixture’s cost should not be more than the desired levels. The fixture’s assembly/disassembly times should not be more than the desired levels. The fixture’s operation time should not be more than the desired levels.</td>
</tr>
<tr>
<td>Constraint</td>
<td>The fixture should guarantee the stability of the work-piece by ensuring that the work-piece’s moment and force equilibrium are kept. The fixture should make sure that the fixture/work-piece’s stiffness is enough to avoid the occurrence of deformation, which could prevent the design tolerances from being reached.</td>
</tr>
<tr>
<td>Usability</td>
<td>The fixture’s weight should not be more than the desired levels. The fixture should not result in damaging the surface at the work-piece/fixture’s interface. The fixture should offer tool guidance to the features of the designated work-piece. The fixture should be error-proof, i.e., the fixture should be able to avoid wrong work-piece insertions into the fixture. The fixture should assist in chip shedding by providing a way to allow the machined chips to flow away from the fixture and the work-piece.</td>
</tr>
<tr>
<td>Collision prevention</td>
<td>The fixture should not result in collisions of the tool path-figure. The fixture should result in work-piece fixture collisions, other than the designated clamping and locating positions. The fixture should not result in fixture-figure collisions besides the designated points for fixture component connection.</td>
</tr>
</tbody>
</table>
Table 2. The significant techniques in CAFD

<table>
<thead>
<tr>
<th>Method</th>
<th>Fundamental Procedure</th>
<th>Applications</th>
<th>To Improve the Performance</th>
<th>Working Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBR</td>
<td>Design based on basic heuristic rules</td>
<td>Setup planning, Fixture planning, unit design, verification</td>
<td>Mostly combined with: CBR</td>
<td>Evaluate and improve design by using some existing and derived basic rules in fixture design</td>
</tr>
<tr>
<td>CBR</td>
<td>Storing and using experiences to solve new problems</td>
<td>Fixture Planning, Unit design, Verification</td>
<td>Mostly used with: RBR</td>
<td>Finding appropriate fixture design for target work-piece in database</td>
</tr>
<tr>
<td>GA</td>
<td>Optimization process by generating possible solutions</td>
<td>Fixture layout configuration, fixture planning, verification</td>
<td>Mostly used with: FEM</td>
<td>Minimizing work-piece deformation by determining minimum forces at the locating and/or clamping points</td>
</tr>
<tr>
<td>FEM</td>
<td>Deformation analysis by meshing the work-piece and examine every single mesh</td>
<td>Fixture layout configuration, fixture planning, verification</td>
<td>Mostly used with: Optimization techniques</td>
<td>Deciding on acceptable candidate regions with minimized deformation of the work-piece</td>
</tr>
<tr>
<td>NN</td>
<td>A set of existing solved problem used to teach the network</td>
<td>Verification, unit design</td>
<td>Mostly combined with: GA</td>
<td>Supporting conceptual unit design and optimal location of units</td>
</tr>
<tr>
<td>Geometric Approaches</td>
<td>Pre-existing mathematical relationships based on parametric dimension relationships</td>
<td>Verification, fixture planning, unit design</td>
<td>Can be combined with: RBR</td>
<td>Determining critical dimensions of fixture units and fixture-work-piece contact points</td>
</tr>
</tbody>
</table>

4. Conclusion

Although many research studies have been conducted in the domain of fixture design, this task is still a blockage in the manufacturing process. A cause of that problem is that most of the CAFD techniques have been examined for simple workpieces, which do not reflect obstacles that are really faced in the industry; hence, the success of the developed methods cannot be confidently stated. Another cause is that there is a requirement to integrate the segmented CAFD techniques cohesively in a framework that includes a comprehensive knowledge of fixture requirements that can be used to drive the process of fixture design. An approach that can be helpful in this case is CBR, so that by combining CBR with other intelligent methods, effective and more comprehensive fixture design systems can be achieved.

Future research could focus on the significance of a more efficient integration of fixture systems to other systems in manufacturing. It is important to place the task of fixture design into the overall process of manufacturing to gain the best performance of each fixture design solution. Regarding the advances in nowadays technology, testing the performance of two approaches would be valuable and efficient in the case of fixture design; these approaches are: (1) placing a multi-sensor network inside the workpiece-fixture system (2) utilizing intelligent online control methods to adjust the fixturing forces and contacts.

References


Optimization Studies on Thrust Force and Torque during Drilling of Natural Fiber Reinforced Sandwich Composites

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Abstract

This research is carried out to investigate thrust force and torque during drilling on the developed bio-degradable sandwich composites. Two natural fibers, namely vetiveria zizaniodes (vetiver) and jute, and one synthetic fiber, namely E-glass, are used as reinforcements with vinyl ester resin to form three composite specimens. The fiber compositions in each specimen are varied while the resin composition is kept as a constant. The vetiver fibers are pre-treated with alkali and followed by furnace heating in order to improve its surface properties. The specimens are subjected to a set of 28 drilling operations during which the machining parameters, like speed, feed rate, tool point angle and work sample, are varied between four levels to form a four-factor mixed level D-optimal factorial design. During each drilling operation, the thrust force and torque are measured as responses by using a kistler make drill dynamometer with an accuracy level of 0.01N. The responses are analyzed by using response surface method, and non-linear regression equations are developed. Optimization on the experimental data resulted in selection of a high level of speed of 2000 rpm, low level feed of 0.1 mm/rev, tool angle between 60\textdegree{} to 90\textdegree{} and selection of sample level I as optimized values with a thrust force of 82.47 N and torque of 4.4 Nm. Confirmatory runs are conducted and the responses are again measured. The average error between the developed model and the confirmatory runs is found to be minimal and hence the optimization is highly satisfactory.

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Keywords: Vetiver, Jute, Glass, Thrust, Torque, Optimization.

1. Introduction

In recent days, composites have been developing in the shape of a final component during their manufacturing stage in order to reduce the machining operations. They still need machining operations for producing holes and slots, finishing the holes, slots, edges and exterior surfaces. The damage of the hole is measured by using delamination factor. During the drilling of carbon fiber reinforced composites, it was observed that the delamination decreases with the increase in speed. Also, it was concluded that a low feed rate and a low point angle are found to be the optimum conditions for drilling [1]. During turning of carbon reinforced cylindrical rods, using cubic boron nitride and polycrystalline diamond tools, surface roughness increases with the increase in feed rate, but decreases as the cutting speed is increased [2, 3]. Drilling induced thrust force and torque on work sample. Drilling of unidirectional glass fiber reinforced plastics revealed that both thrust force and torque have a major influence on delamination on the material and the residual strength decreases with the increase in delamination [4]. Optimization studies on surface roughness during end milling of aluminium metal matrix composites concluded that the feed rate has a predominant influence on surface roughness [5, 6].

Machinability is also influenced by the selection of resin, fiber, additives and their proportions used in composites. An investigation drilling of glass fiber reinforced composite reported that the type of chip formed, thrust force and surface roughness depend upon the type of resin used. It was concluded that the thrust force and surface roughness are found to be larger for a composite made of polyester resin when compared to that of composites made of the polypropylene composite [7]. Extensive research has been done in machinability associated issues by using different synthetic fibers as

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reinforcements in composites. In the few recent years, many natural fibers like jute, vetiver, bamboo, sisal, licuri etc. have been introduced into composites. Studies on their mechanical properties showed that, by careful selection of fiber proportions in composites, they could serve as a possible alternative for synthetic fibers [8-11].

Studies on drilling of natural coir reinforced plastics reported that the feed rate has a major influence on thrust force and torque. It was concluded that a medium feed rate of 0.2 mm/rev, a high speed of 1503 rpm and a medium drill diameter of 8 mm are found to be optimum conditions for machinability [12]. Investigations during the drilling of Medium Density Fiberboards (MDF) reported that the delamination factor increases when the feed rate is increased and decreases when the cutting speed is increased [13]; such results are similar to the results obtained during the machining of synthetic fiber reinforced composites. In another study, commercially woven jute fibers are reinforced with polyester in the form of plates and the developed composites are subjected to end milling operations. Analysis of thrust force and torque showed that three factors, namely speed, feed rate and depth of cut, predominantly affect the responses [14]. Extensive studies have been done to analyze the behavior of natural fiber reinforced plastics and only few research works have evolved during the recent years to perform machining and machinability associated investigations.

In an earlier research, Vinayagamourthy et al. [8] developed the nine new composites and made an extensive analysis on properties like tensile, flexural, compressive and impact strengths. It was concluded that, by a proper selection of reinforcement and resin proportions and by giving a suitable chemical treatment to natural fibers, natural fibers served as an alternative to synthetic fibers. As an extension of this work, three composites samples, showing best mechanical properties, were taken for the present machining studies. The samples are subjected to a 28 drilling operations according to mixed level D-optimal design methodology. The responses, namely thrust force and torque, are measured and the data are analyzed and optimized using response surface methodology. This resulted in the selection of the best levels for the factors. Confirmatory runs are conducted and the responses are compared with the model.

2. Material and Methods

Vetiveria zizanioides is a perennial grass whose roots can grow up to a maximum length of 12 meters. It is used as an aromatic agent in perfumes and as an agent for treatment of rheumatism in Indian traditional medicines. These roots have a tensile strength of 723 MPa and modulus of 49.8 GPa with strain at break of 2.4%. In the present study, the composite samples are prepared by using the hand layup method in the form of slabs, each of the size 300 mm x 300 mm x 12 mm. The hand layup method uses a table over which the resin is spread and a fiber layer is placed over it. Again, a layer of resin is applied over the fiber layer and this procedure is repeated until the proportions of fiber and resin are satisfied. Finally, a load is applied over it for about 24 hours for the uniform bonding of resin with fibers. The composition of vetiver fibers and E-glass fibers are varied in each sample to form 34 wt% in total and vinyl ester resin is maintained as 66 wt% in all samples. The composition of fiber and resin in the samples are presented in Table 1. The samples preparation method and the chemical treatment of the fibers were extensively discussed in the earlier study by the authors [8], and the mechanical properties of the developed samples are presented in Table 2.

### Table 1. Composition of samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fiber Proportions (wt %)</th>
<th>Resin proportions (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Vetiver: 13</td>
<td>Jute: 13</td>
</tr>
<tr>
<td>III</td>
<td>Vetiver: 10</td>
<td>Jute: 10</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tensile strength (MPa)</th>
<th>Tensile modulus (MPa)</th>
<th>Tensile strain at break (%)</th>
<th>Flexural strength (MPa)</th>
<th>Flexural modulus (MPa)</th>
<th>Flexural strain at break (%)</th>
<th>Compressive strength (MPa)</th>
<th>Impact energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>71.73</td>
<td>1736</td>
<td>9.5</td>
<td>133.11</td>
<td>2894</td>
<td>7</td>
<td>122.21</td>
<td>11</td>
</tr>
<tr>
<td>II</td>
<td>74.14</td>
<td>2105</td>
<td>7.5</td>
<td>131.9</td>
<td>3358</td>
<td>6.67</td>
<td>121.81</td>
<td>15.33</td>
</tr>
<tr>
<td>III</td>
<td>70.96</td>
<td>2318</td>
<td>7.5</td>
<td>137.6</td>
<td>2950</td>
<td>7</td>
<td>128.23</td>
<td>18.33</td>
</tr>
</tbody>
</table>
Table 3. Factors and levels

<table>
<thead>
<tr>
<th>Factors</th>
<th>Type</th>
<th>Level</th>
<th>Level</th>
<th>Level</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (n)</td>
<td>Numeric</td>
<td>500</td>
<td>1000</td>
<td>1500</td>
<td>2000</td>
</tr>
<tr>
<td>Feed (f) mm/rev</td>
<td>Numeric</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Tool angle (α) degree</td>
<td>Numeric</td>
<td>60</td>
<td>90</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>Work sample</td>
<td>Categorical</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>-</td>
</tr>
</tbody>
</table>

3. Statistical Design

Response surface method is one of the important statistical tools during designing an experiment. It helps in analyzing and optimizing the statistical data having responses that are affected by multiple factors. It provides three dimensional plots and contour plots for responses against the input factors through which the influence of various factors on the responses could be analyzed. D-optimal design is another important tool for analyzing responses under the influence of factors with different levels. In this design method, the variance of regression coefficients in the model equation is minimized. In general, factors are classified as numeric factors and categorical factors. Numeric factors are varied between any numerical value as per the system requirement or of the interest of researcher. Categorical factors cannot be varied between any ranges but they are of particular importance. D-optimal design is a technique for analyzing the influence of either or both the numeric and the categorical factors on the responses [18]. The significance and contribution of each factor on the response are analyzed using analysis of variance (ANOVA). The runs and responses are presented in Table 4.

Table 4. Experimental runs and responses

<table>
<thead>
<tr>
<th>Run</th>
<th>Input Parameters</th>
<th>Output Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed (n) rpm</td>
<td>Feed (f) mm/rev</td>
</tr>
<tr>
<td>1</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>500</td>
<td>0.4</td>
</tr>
<tr>
<td>9</td>
<td>500</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>0.4</td>
</tr>
<tr>
<td>11</td>
<td>500</td>
<td>0.4</td>
</tr>
<tr>
<td>12</td>
<td>1000</td>
<td>0.1</td>
</tr>
<tr>
<td>13</td>
<td>1000</td>
<td>0.4</td>
</tr>
<tr>
<td>14</td>
<td>1000</td>
<td>0.4</td>
</tr>
<tr>
<td>15</td>
<td>1500</td>
<td>0.1</td>
</tr>
<tr>
<td>16</td>
<td>1500</td>
<td>0.3</td>
</tr>
<tr>
<td>17</td>
<td>2000</td>
<td>0.1</td>
</tr>
<tr>
<td>18</td>
<td>2000</td>
<td>0.1</td>
</tr>
<tr>
<td>19</td>
<td>2000</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>2000</td>
<td>0.2</td>
</tr>
<tr>
<td>21</td>
<td>2000</td>
<td>0.2</td>
</tr>
<tr>
<td>22</td>
<td>2000</td>
<td>0.3</td>
</tr>
<tr>
<td>23</td>
<td>2000</td>
<td>0.3</td>
</tr>
<tr>
<td>24</td>
<td>2000</td>
<td>0.4</td>
</tr>
<tr>
<td>25</td>
<td>2000</td>
<td>0.4</td>
</tr>
<tr>
<td>26</td>
<td>2000</td>
<td>0.4</td>
</tr>
<tr>
<td>27</td>
<td>2000</td>
<td>0.4</td>
</tr>
<tr>
<td>28</td>
<td>2000</td>
<td>0.4</td>
</tr>
</tbody>
</table>
4. Discussion

4.1. Thrust Force (F)

Drilling operation involves the penetration of a tool through the work piece during its rotation; as a result, thrust force is impressed on the working zone. The magnitude of thrust force depends upon various machining parameters. ANOVA analysis for thrust force is presented in Table 5. The model F-value of 115.68 and lack of fit F-value of 4.57 indicate that the model is significant and the lack of fit is non-significant relative to pure error. A P-value less than 0.05 indicates that the terms are significant. $R^2$ and adj $R^2$ values of 0.995 and 0.986, respectively, are closer to each other, which gives the indication of a maximum model adequacy. It was observed that work sample, feed and tool angle predominantly affect the thrust force with a contribution of 55.24% for work sample, 14.5% for feed and 4.64% for tool angle. Also, it was noticed that speed has no influence on the thrust force. A 55.24% contribution of work sample indicates that the selection of natural and synthetic fibers and their composition in the composite plays an important role in reducing the thrust force.

Interaction plots between the thrust force and input factors and the normal probability plot are presented from Figures 1a to 1d. It was observed that variation of speed from 500 rpm to 2000 rpm does not have much influence on the thrust force, whereas thrust force increases when feed and tool angle are increased. This is because the tool, at higher feed rates, penetrates the work piece more quickly than during the low feed rates. Faster penetration leads to an increase in the thrust force [12]. Also, as the tool angle increases the contact area between the cutting edge and the work surface increases leading to an increase in thrust force. These behaviors are commonly seen in all the samples but sample I shows a least thrust force followed by samples II and III. This indicates that the inclusion of glass fibers increases the thrust force and the increase in glass fiber composition also increases the thrust force [19]. This behavior is seen because hardness of glass fibers are greater than that of vetiver fibers. Hence, sample I is suitable for machining under reduced thrust force. The normal probability plot is a graphical representation for checking the adequacy of the model. If the distribution of points follows a straight line, then the model is adequate and can be effectively used for predicting the responses [20]. Figure 1d clearly follows a straight line which is a symbol of good model adequacy.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Degrees of freedom</th>
<th>Mean square</th>
<th>F value</th>
<th>P value</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2803.5</td>
<td>17</td>
<td>164.91</td>
<td>115.68</td>
<td>&lt;0.0001</td>
<td>-</td>
</tr>
<tr>
<td>Speed (n)</td>
<td>6.12</td>
<td>1</td>
<td>6.12</td>
<td>4.29</td>
<td>0.0651</td>
<td>0.22</td>
</tr>
<tr>
<td>Feed (f)</td>
<td>408.03</td>
<td>1</td>
<td>408.03</td>
<td>286.22</td>
<td>&lt;0.0001</td>
<td>14.5</td>
</tr>
<tr>
<td>Tool angle (α)</td>
<td>130.82</td>
<td>1</td>
<td>130.82</td>
<td>91.77</td>
<td>&lt;0.0001</td>
<td>4.64</td>
</tr>
<tr>
<td>Work sample (D)</td>
<td>1556.5</td>
<td>2</td>
<td>778.22</td>
<td>545.89</td>
<td>&lt;0.0001</td>
<td>55.24</td>
</tr>
<tr>
<td>n*f</td>
<td>0.035</td>
<td>1</td>
<td>0.035</td>
<td>0.035</td>
<td>0.025</td>
<td>0.0012</td>
</tr>
<tr>
<td>n*α</td>
<td>0.74</td>
<td>1</td>
<td>0.74</td>
<td>0.52</td>
<td>0.4876</td>
<td>0.026</td>
</tr>
<tr>
<td>n*D</td>
<td>2.95</td>
<td>2</td>
<td>1.48</td>
<td>1.04</td>
<td>0.3902</td>
<td>0.104</td>
</tr>
<tr>
<td>f*α</td>
<td>1.79</td>
<td>1</td>
<td>1.79</td>
<td>1.26</td>
<td>0.2883</td>
<td>0.0635</td>
</tr>
<tr>
<td>f*D</td>
<td>39.6</td>
<td>2</td>
<td>19.8</td>
<td>13.89</td>
<td>0.0013</td>
<td>1.4</td>
</tr>
<tr>
<td>α*D</td>
<td>14.26</td>
<td>2</td>
<td>7.13</td>
<td>5</td>
<td>0.0312</td>
<td>0.5</td>
</tr>
<tr>
<td>n^2</td>
<td>0.16</td>
<td>1</td>
<td>0.16</td>
<td>0.11</td>
<td>0.748</td>
<td>0.0056</td>
</tr>
<tr>
<td>f^2</td>
<td>26.77</td>
<td>1</td>
<td>26.77</td>
<td>18.78</td>
<td>0.0015</td>
<td>0.95</td>
</tr>
<tr>
<td>α^2</td>
<td>3.67</td>
<td>1</td>
<td>3.67</td>
<td>2.57</td>
<td>0.1398</td>
<td>0.13</td>
</tr>
<tr>
<td>Residual</td>
<td>14.26</td>
<td>10</td>
<td>1.43</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>11.7</td>
<td>5</td>
<td>2.34</td>
<td>4.57</td>
<td>0.0605</td>
<td>Not significant</td>
</tr>
<tr>
<td>Pure error</td>
<td>2.56</td>
<td>5</td>
<td>0.51</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>2817.7</td>
<td>27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$R^2 = 0.995$; Adj $R^2 = 0.986$
4.2. Torque (T)

During drilling, the drill tool is subjected to rotation at various speeds set by the operator. Hence, torque is developed and its magnitude depends on various machining parameters. The ANOVA table for torque is presented in Table 6. The model and lack of fit F-values of 13.16 and 1.17, respectively, indicates that the model is significant and the lack of fit is non-significant relative to pure error. $R^2$ and $\text{adj } R^2$ values of 0.95 and 0.88, respectively, are closer to each other, which gives the indication of a maximum model adequacy. It was observed that all the factors, namely speed, feed, tool angle and work sample, predominantly affect the torque with a contribution of 3.35% for speed, 9.29% for feed 3.77% for tool angle and 55.35% for work sample. A 55.35% contribution of work sample indicates that the selection of natural and synthetic fibers and their composition in the composite play an important role in reducing the thrust force. This contribution is almost equal to that of the contribution of work sample with thrust force. Hence, work sample has a major influence on thrust force and torque.

The influence of each factor on the response is analyzed by using interaction plots. These plots present the behavior of the response under the influence for a combination of two input factors, namely speed-work sample, feed-work sample and tool angle-work sample. Interaction plots between the torque and input factors and the normal probability plot are presented in Figures 2a to 2d. It was observed that the increase in speed and feed increases the torque, whereas the increase in tool angle decreases the torque. The torque is found to be low for sample I between the ranges of speed, feed and tool angle. This is followed by sample II and sample III. This clearly indicates that the presence of glass fibers increases the torque and the increase in glass composition also increases the torque. Hence, sample I may be selected for machining under minimum torque conditions. This behavior is similar to the observations during thrust force and, hence, the overall performance of sample I was found to be satisfactory when compared to that of other samples. The normal probability plot as shown in Figure 2d which clearly follows a straight line, which is a symbol of a good model adequacy.
Table 6. ANOVA table for Torque

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Degrees of freedom</th>
<th>Mean square</th>
<th>F value</th>
<th>P value</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>20.82</td>
<td>17</td>
<td>1.22</td>
<td>13.16</td>
<td>&lt;0.0001</td>
<td>-</td>
</tr>
<tr>
<td>Speed (n)</td>
<td>0.73</td>
<td>1</td>
<td>0.73</td>
<td>7.88</td>
<td>0.0185</td>
<td>3.35</td>
</tr>
<tr>
<td>Feed (f)</td>
<td>2.02</td>
<td>1</td>
<td>2.02</td>
<td>21.7</td>
<td>0.0009</td>
<td>9.29</td>
</tr>
<tr>
<td>Tool angle (α)</td>
<td>0.82</td>
<td>1</td>
<td>0.82</td>
<td>8.84</td>
<td>0.014</td>
<td>3.77</td>
</tr>
<tr>
<td>Work sample (D)</td>
<td>12.04</td>
<td>2</td>
<td>6.02</td>
<td>64.64</td>
<td>&lt;0.0001</td>
<td>55.35</td>
</tr>
<tr>
<td>n*f</td>
<td>0.11</td>
<td>1</td>
<td>0.11</td>
<td>0.12</td>
<td>0.7339</td>
<td>0.05</td>
</tr>
<tr>
<td>n*α</td>
<td>0.25</td>
<td>1</td>
<td>0.25</td>
<td>2.7</td>
<td>0.1316</td>
<td>1.15</td>
</tr>
<tr>
<td>n*D</td>
<td>0.35</td>
<td>2</td>
<td>0.18</td>
<td>1.9</td>
<td>0.1998</td>
<td>1.6</td>
</tr>
<tr>
<td>f*α</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
<td>1.12</td>
<td>0.3143</td>
<td>0.46</td>
</tr>
<tr>
<td>f*D</td>
<td>0.22</td>
<td>2</td>
<td>0.11</td>
<td>1.18</td>
<td>0.3465</td>
<td>1.01</td>
</tr>
<tr>
<td>α*D</td>
<td>0.28</td>
<td>2</td>
<td>0.14</td>
<td>1.49</td>
<td>0.2715</td>
<td>1.29</td>
</tr>
<tr>
<td>n²</td>
<td>3.43x10⁻⁶</td>
<td>1</td>
<td>3.43x10⁻⁶</td>
<td>3.68x10⁻⁵</td>
<td>0.9953</td>
<td>0.000015</td>
</tr>
<tr>
<td>f²</td>
<td>0.17</td>
<td>1</td>
<td>0.17</td>
<td>1.82</td>
<td>0.2074</td>
<td>0.78</td>
</tr>
<tr>
<td>α²</td>
<td>3.7x10⁻⁴</td>
<td>1</td>
<td>3.7x10⁻⁴</td>
<td>3.97x10⁻³</td>
<td>0.951</td>
<td>0.0017</td>
</tr>
<tr>
<td>Residual</td>
<td>0.93</td>
<td>10</td>
<td>0.093</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>0.5</td>
<td>5</td>
<td>0.1</td>
<td>1.17</td>
<td>0.433</td>
<td>Not significant</td>
</tr>
<tr>
<td>Pure error</td>
<td>0.43</td>
<td>5</td>
<td>0.086</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>21.75</td>
<td>27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

R² = 0.95; Adj R² = 0.88
4.3. Optimization

Design Expert 7 software is used in this study for statistical analysis and optimization. Multi-response optimization is carried out aiming to minimize the thrust force and torque. The optimized values of factors and responses are presented in Table 7. Seven runs are selected based on the desirability factor closer to unity. The first five runs show that a high level speed, a low level feed rate, sample I and a tool angle from 60° to 90° would be suitable for reducing the thrust force and torque with a desirability of 0.95. The sixth and the seventh runs show that a low level speed, a low level feed rate, sample I and a tool angle from 90° to 100° would be the optimum conditions with desirability of 0.85. Tools are ground to new tool angle values of 70°, 80° 90° and 100° and confirmatory runs are conducted. The average percentage of error between the model and confirmatory runs are 0.74% for thrust and 1.07% for torque. As the error percentages are minimal, the optimization is satisfactory and the model could be used to accurately predict the responses.

5. Conclusions

The present study focused on designing and optimizing thrust force and torque during the drilling of three new hybrid polymeric composites. The influence of various fibers in each composite on thrust and torque are investigated and optimization is carried out aiming to reduce the responses. The conclusions are as follows:

- The influence of work sample, feed and tool angle are predominant on thrust force and it was noticed that speed has no influence on the thrust force as presented in Table 5.
- All the factors, namely speed, feed, tool angle and work sample, affect the torque.
- A 55% contribution of work sample with both thrust force and torque indicates that the selection of natural and synthetic fibers and their composition in the composite plays an important role in reducing the thrust force.
- Presence of glass fibers and the increase in their content increase the thrust force and torque. Hence, a composite sample without the presence of glass fibers would be suitable for improving the machinability.
- Optimization of the model seems good with an overall desirability factor of 0.95, and the results of confirmatory runs are closer to the developed model with average errors of 0.74% for thrust force and 1.07% for torque.

Improving machinability is a primary objective of all manufacturers irrespective of the nature of the material. This exhaustive research helps end users to appropriately select the best machining conditions in order to improve the machinability.

Table 7. Optimization and confirmation

<table>
<thead>
<tr>
<th>S. No</th>
<th>Speed n (rpm)</th>
<th>Feed f (mm/rev)</th>
<th>Tool angle α (degree)</th>
<th>Sample</th>
<th>Desirability factor</th>
<th>D-Optimal Model</th>
<th>Confirmatory runs</th>
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<td>Thrust F (N)</td>
<td>Torque T (Nm)</td>
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<td>82.47</td>
<td>4.4</td>
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<tr>
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<td>2000</td>
<td>0.1</td>
<td>60</td>
<td>I</td>
<td>0.95</td>
<td>82.47</td>
<td>4.4</td>
</tr>
<tr>
<td>2</td>
<td>1975</td>
<td>0.1</td>
<td>60</td>
<td>I</td>
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<td>82.74</td>
<td>4.41</td>
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<tr>
<td>3</td>
<td>2000</td>
<td>0.1</td>
<td>90</td>
<td>I</td>
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<td>84.08</td>
<td>4.56</td>
</tr>
<tr>
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<td>2000</td>
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<td>70</td>
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<tr>
<td>5</td>
<td>2000</td>
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<tr>
<td>6</td>
<td>570</td>
<td>0.1</td>
<td>90</td>
<td>I</td>
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<td>85.86</td>
<td>4.05</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
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<td>100</td>
<td>I</td>
<td>0.85</td>
<td>86.03</td>
<td>4.05</td>
</tr>
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Error between model and confirmatory for Thrust force = 0.74%
Error between model and confirmatory for Torque = 1.07%

References


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Statistical Model for Surface Roughness in Hard Turning of AISI D3 Steel

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Abstract

In the present experimental work, the effects of cutting speed, feed rate and depth of cut on surface roughness are investigated in hard turning of AISI D3 steel. AISI D3 steel is hardened to 62 HRC and is machined using a mixed ceramic tool. Mathematical models for surface roughness are developed using the Response Surface Methodology (RSM). Central Composite Design (CCD) is applied as an experimental design. Al2O3/TiC mixed ceramic tool with corner radius of 0.8 mm is employed to accomplish 20 tests with six centre points. The range of each parameter is set at three different levels, namely low, medium and high. The main effects of the factors and their interactions were considered in the present study using Analysis of variance (ANOVA). Various graphs and plots are drawn to evaluate the influence of the process parameters on surface roughness. Feed rate is the most influencing factor on surface roughness. Results revealed that the use of lower feed, lower depth of cut and higher cutting speed, while hard turning of AISI D3 hardened steel, ensures a better surface roughness.

Keywords: Hard Turning, Surface Roughness, AISI D3, RSM, Main Effect Plots and ANOVA.

1. Introduction

Hard turning is the process of single point cutting of hardened ferrous material with hardness more than 45HRC in order to obtain finished work pieces directly from hardened parts [1-5]. This process was developed as an alternative to grinding process in a bid to reduce the number of setup changes, process flexibility, compatible surface roughness, higher material removal rate, and less environment problems, which leads to a reduction in machining costs, an elimination of cutting fluids, an increase in the flexibility and efficiency, a reduction in part-handling costs and, finally, a decrease in the set-up times [1, 4]. Many industrial steel components, under the influence of critical loads from automotive and aerospace parts to bearing and forming tool, are made of hardened steel. These parts are produced by a series of sequential operations like turning, grinding and polishing, which are time consuming and costly. Therefore, hard turning is gaining importance to replace operations by single setup and single operation [6, 7]. The growth of hard turning process is indebted to the advent of new advanced cutting tools such as Cubic Boron Nitride (CBN), Poly Crystalline Boron Nitride (PCBN) and Ceramics since 1970 [4].

The surface quality is an index to evaluate the productivity of machine tools as well as the machined components. The surface roughness is used as a major quality indicator for the machined surfaces, which is the result of process parameters such as cutting conditions and tool geometry. In today’s manufacturing industry, a special attention is being paid to the dimensional accuracy as well as surface finish and, hence, measuring and characterizing the surface finish can be considered as a machining performance index. Achieving a better surface quality, tool life and dimension accuracy are the crucial concerns in turning of hardened steels [4]. The cutting tool is one of the most critical elements in hard turning and the development of newer cutting tool materials has been characterized by an increase in wear resistance. Much work has been done on various hardened steels with CBN and PCBN cutting tools. According to the recent research, few studies have been reported on hard turning of AISI D3 with mixed ceramic (CC 6050).

Zou et al. [8] used Al2O3/TiN-coated tungsten carbide tools for finish turning of NiCr20TiAl nickel-based alloy under various cutting conditions and the cutting forces, surface integrity and tool wear are investigated and the inter diffusing and transferring of elements between Al2O3/TiN-coated tungsten carbide tool
and NiCr-0.5TiAl nickel-based alloy are studied. Fahad et al. [9] investigated the cutting performance of tungsten carbide tools with restricted contact length and multilayer chemical vapor deposition coatings, TiCN/Al<sub>2</sub>O<sub>3</sub>/TiN and TiCN/Al<sub>2</sub>O<sub>3</sub> TiN in dry turning of AISI 4140 and the results show that the coating layouts and cutting tool edge geometry can significantly affect heat distribution into the cutting tool. Hamdan et al. [10] presented an optimization method of the machining parameters in high-speed machining of stainless steel using coated carbide tool to achieve minimum cutting forces and better surface roughness using Taguchi’s technique and pareto ANOVA and found that the feed rate is found to be more significant followed by the cutting speed and the depth of cut.

Suhail et al. [11] developed a method to identify surface roughness based on measurement of workpiece surface temperature and root mean square for feed vibration of the cutting tool during turning mild steel using grey relational analysis. Gopalsamy et al. [12] studied the machinability of hardened steel using grey relational approach and ANOVA to obtain optimum process parameters considering MRR, surface finish, tool wear and tool life for both rough and finish machining. Ahilan et al. [13] performed a multi-response optimization of turning parameters and nose radius over surface roughness and power consumed using Taguchi based grey relational approach and found that the main influencing parameter is cutting speed followed by feed rate and depth of cut. In turning operations, for a multi-response optimization Taguchi based grey relational approach is used [14, 15] to identify the optimum conditions that obtain better results. Prediction of flank wear and surface roughness during hard turning is performed using uncoated carbide inserts of various tool geometries [16].

Fnides et al. [17] investigated the productivity in terms of volume chip carved of six cutting tools for two different cutting conditions in straight hard turning of X38CrMoV5-1 (50 HRC). They found that, for the first set of cutting parameters ($Vc=120$ m/min, $Doc =0.15$ mm, and $f=0.08$ mm/rev), the productivity of the uncoated cermets CT5015, the coated cermets GC1525, the uncoated carbide H13A, the reinforced ceramic CC670, the coated car-bide GC3015, and the mixed ceramic CC650 are 2,160; 1,440; 6,480; 11,520; 23,040; and 70,560 mm<sup>3</sup>, respectively. Their results prove that the mixed ceramic Al<sub>2</sub>O<sub>3</sub>+TiC (CC650) is more efficient than the other tools used in terms of productivity.

The main scope of the present work is the experimental investigation of the effect of machining parameters (i.e., cutting speed, feed rate, depth of cut) on surface roughness in hard turning process of AISI D3 which is widely used in manufacturing. ANOVA is used on the results obtained from experimentation to determine the main effect of parameters and their interactions. Moreover, RSM and regression analysis are used to establish the correlation between factors and responses.

### 2. Experimental Procedure

#### 2.1. Material, Work piece and Tool

The work piece material used for experiments is AISI D3. The bar of diameter 68 mm x 360 mm long is prepared. Test sample is trued, centred and cleaned by removing a 2 mm depth of cut from the outside surface, prior to actual machining tests. A new insert was employed for each run of experiments in order to provide completely identical cutting edge conditions for each test. The chemical composition of the work piece material is given in Table 1. The workpiece is oil-quenched from 980°C (1800°F), hardened, followed by tempering at 200°C to attain 62HRC. Figure 1 shows the image of cutting insert CC6050. Experimental set up is shown in Figure 2.

The lathe used for machining operations is Kirloskar; model Turn Master-35, spindle power 6.6KW. Surface roughness is measured using Mitutoyo Surftest SJ 210 as shown in Figure 3 having measuring range of 17.5 mm and skid force less than 400 mN. Four readings with a sample length of 0.8 mm are recorded after each experiment and an average value is taken as the surface roughness. These values are obtained without disturbing the assembly of the work piece in order to reduce uncertainties.

#### Table 1 Chemical composition of AISI D3 (wt %)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Al</th>
<th>Cu</th>
<th>Zn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.06</td>
<td>0.55</td>
<td>0.449</td>
<td>0.036</td>
<td>0.056</td>
<td>11.09</td>
<td>0.277</td>
<td>0.207</td>
<td>0.0034</td>
<td>0.13</td>
<td>0.27</td>
<td>85</td>
</tr>
</tbody>
</table>

![Figure 1. Image of ceramic cutting insert CC6050](image1.png)

![Figure 2. Experimental setup](image2.png)
The cutting insert used is a mixed ceramic removable, of square form with eight cutting edges and having designation SNGA 120408 T01020 Sandvik make CC6050 is a mixed ceramic grade based on alumina with an addition of titanium carbide. The high hot-hardness and the good level of toughness make the grade suitable as first choice for hardened steel (50 – 65HRC) in applications with good stability or with light interrupted cuts. The inserts are mounted on a commercial tool holder of designation PSBNR 2525 M 12 (ISO) with the geometry of active part characterized by the following angles: $\chi = 75^\circ; \alpha = 6^\circ; \gamma = -6^\circ; \lambda = -6^\circ$.

2.2. Experiments Design

RSM is a modelling approach for determining the relationship between the various factors and the responses with the desired criteria and searching the significance of these parameters on the responses. The RSM is useful for developing, improving and optimizing the processes, which provides an overall perspective of the system response within the design space [18]. In order to know surface quality values in advance, it is necessary to employ empirical models making it feasible to do predictions as a function of operational conditions. Using the design of experiments and applying the regression analysis, the relationship between the various factors and the responses can be obtained. The RSM is utilized to describe and identify the influence of the interactions of different process parameters on the performance characteristics when these are varied simultaneously. In the present investigation, the second-order RSM-based mathematical models for surface roughness ($Ra$) are developed with cutting speed ($V_c$), feed rate ($f$), and depth of cut (Doc) as the process parameters.

The experimental plan is developed to assess the influence of the interactions of process parameters on the performance of cut (Doc) developed with cutting speed ($V_c$), feed rate ($f$) and depth of cut (Doc) as the process parameters. The response surface equation for three factors is given by [18]:

$$Y = a_0 + a_1V_c + a_2f + a_3a_p + a_{12}V_cf + a_{13}V_ca_p + a_{23}fa_p + a_{11}V_c^2 + a_{22}f^2 + a_{33}a_p^2$$

(2)

Where $Y$ is the desired response and $a_0$ is the free term of the regression equation, the coefficients $a_1$, $a_2$, $a_3$ and $a_{11}$, $a_{22}$, $a_{33}$ are the linear and quadratic terms, respectively, while $a_{12}$, $a_{13}$, $a_{23}$ are the interacting terms. The experimental plan is developed to assess the influence of cutting speed ($V_c$), feed rate ($f$), and depth of cut (Doc) on the surface roughness ($Ra$), regression coefficients to be determined for each response. The regression coefficients of linear, quadratic, and interaction terms of RSM-based mathematical models are determined by [18].

Three levels are defined for each cutting variable, as given in Table 2. The variable levels are chosen within the intervals recommended by the cutting tool manufacturer. Three cutting variables at three levels led to a total of 20 tests. The factors to be studied and the attribution of the respective levels are indicated in Table 3.

### Table 2. Assignment of the levels to the variables

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/min)</td>
<td>-1 0 1</td>
</tr>
<tr>
<td>Feed (mm/rev)</td>
<td>0.05 0.075 0.1</td>
</tr>
<tr>
<td>Depth of cut (mm)</td>
<td>0.3 0.6 0.9</td>
</tr>
</tbody>
</table>

3. Results and Discussion

Table 3 presents the experimental results of surface roughness ($Ra$) for various combinations of cutting conditions (cutting speed, feed rate and depth of cut) as per the design matrix.

The experimental data presented in Table 3, for which analysis has to be graphically done and represented. The following sections present the detailed discussion.

3.1. Statistical Analysis

The estimated regression coefficients for surface roughness $Ra$ are shown in Table 4 and scatter plot is shown in Figure 4.

It can be observed from Figure 4 that, as the residuals are located on a straight line, the errors are distributed normally. Hence, the developed empirical models can represent the process significantly. Scatter plots identifies the relationship between two variables whether the relationship is positive, negative, or no relationship can be easily detected. Therefore, these models can be further used for the optimization of process parameters.
Table 3. Experimental results for surface roughness

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Coded Form</th>
<th>Un-Coded Form</th>
<th>Surface Roughness (Microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed (m/min)</td>
<td>Feed (mm/rev)</td>
<td>Doc (mm)</td>
</tr>
<tr>
<td>1</td>
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<td>-1</td>
<td>-1</td>
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<tr>
<td>2</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
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<td>10</td>
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<td>0</td>
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<td>0</td>
<td>1</td>
<td>0</td>
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<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>14</td>
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<tr>
<td>15</td>
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<tr>
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<td>0</td>
<td>0</td>
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<tr>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<tr>
<td>20</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

Table 4. Estimated regression coefficients for surface roughness Ra (microns)

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>Constant</td>
<td>0.814091</td>
<td>0.02647</td>
<td>30.752</td>
<td>0.000</td>
<td>Significant</td>
</tr>
<tr>
<td>Speed(m/min)</td>
<td>-0.028900</td>
<td>0.02435</td>
<td>-1.187</td>
<td>0.263</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Feed(mm/rev)</td>
<td>0.063000</td>
<td>0.02435</td>
<td>2.587</td>
<td>0.027</td>
<td>Significant</td>
</tr>
<tr>
<td>Doc (mm)</td>
<td>0.100900</td>
<td>0.02435</td>
<td>4.143</td>
<td>0.002</td>
<td>Significant</td>
</tr>
<tr>
<td>Speed(m/min)* Speed(m/min)</td>
<td>-0.015227</td>
<td>0.04644</td>
<td>-0.328</td>
<td>0.750</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Feed(mm/rev)* Feed(mm/rev)</td>
<td>0.001273</td>
<td>0.04644</td>
<td>0.027</td>
<td>0.979</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Doc (mm)* Doc (mm)</td>
<td>0.019773</td>
<td>0.04644</td>
<td>0.426</td>
<td>0.679</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Speed(m/min)*Feed(mm/rev)</td>
<td>-0.063750</td>
<td>0.02723</td>
<td>-2.342</td>
<td>0.041</td>
<td>Significant</td>
</tr>
<tr>
<td>Speed(m/min)*Doc (mm)</td>
<td>0.062500</td>
<td>0.02723</td>
<td>2.0296</td>
<td>0.045</td>
<td>Significant</td>
</tr>
<tr>
<td>Feed(mm/rev)* Doc (mm)</td>
<td>-0.054000</td>
<td>0.02723</td>
<td>-1.983</td>
<td>0.075</td>
<td>Insignificant</td>
</tr>
</tbody>
</table>

S = 0.0770070  R-Sq = 80.07%  R-Sq(adj) = 62.14%

Figure 4. Scatter plot of Ra (actual Vs predicted)
3.2. Analysis of Variance

The ANOVA has been applied to check the adequacy of the developed models. The ANOVA table consists of a sum of squares and degrees of freedom. The sum of squares is performed into contributions from the polynomial model and the experimental value, and was calculated by the following equation:

$$SS_f = \frac{N}{N_{a_f}} \sum_{i=1}^{N} (\bar{y}_i - \bar{y})^2$$

The mean square is the ratio of the sum of squares to degrees of freedom; it was calculated by the following equation:

$$MS_i = \frac{SS_i}{DF_i}$$

F-value the ratio of mean square of regression model to the mean square of the experimental error, was calculated by the following equation:

$$F-value = \frac{MS_i}{MS_{error}}$$

This analysis was out for a 5% significance level, i.e., for a 95% confidence level. The percentage of each factor contribution (Cont. %) on the total variation, which indicates the degree of the influence on the result, was calculated by the following equation:

$$cont.\% = \frac{SS_i}{SS_{mod}} \times 100$$

A low P-value indicates a statistical significance for the source on the corresponding response. It is clear from the results of ANOVA that the depth of cut is the dominant factor affecting surface finish $Ra$. The second factor influencing $Ra$ is cutting speed *feed rate. To understand the hard turning process in terms of surface roughness $Ra$, a mathematical model is developed using a multiple regression method. $Ra$ model is given by equations 1 and 2. Its coefficient of correlation $R^2$ is 80.07%.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>9</td>
<td>0.238291</td>
<td>0.238291</td>
<td>0.026477</td>
<td>4.46</td>
<td>0.014</td>
</tr>
<tr>
<td>Speed (m/min)</td>
<td>1</td>
<td>0.008352</td>
<td>0.008352</td>
<td>0.008352</td>
<td>1.41</td>
<td>0.263</td>
</tr>
<tr>
<td>Feed (mm/rev)</td>
<td>1</td>
<td>0.03969</td>
<td>0.03969</td>
<td>0.03969</td>
<td>6.69</td>
<td>0.027</td>
</tr>
<tr>
<td>Doc (mm)</td>
<td>1</td>
<td>0.101808</td>
<td>0.101808</td>
<td>0.101808</td>
<td>17.17</td>
<td>0.002</td>
</tr>
<tr>
<td>Speed (m/min)*Speed (m/min)</td>
<td>1</td>
<td>0.000034</td>
<td>0.000038</td>
<td>0.000038</td>
<td>0.11</td>
<td>0.75</td>
</tr>
<tr>
<td>Feed (mm/rev)*Feed (mm/rev)</td>
<td>1</td>
<td>0.000242</td>
<td>0.000004</td>
<td>0.000004</td>
<td>0</td>
<td>0.979</td>
</tr>
<tr>
<td>Doc (mm)*Doc (mm)</td>
<td>1</td>
<td>0.001075</td>
<td>0.001075</td>
<td>0.001075</td>
<td>0.18</td>
<td>0.679</td>
</tr>
<tr>
<td>Speed (m/min)*Feed (mm/rev)</td>
<td>1</td>
<td>0.032512</td>
<td>0.032512</td>
<td>0.032512</td>
<td>5.48</td>
<td>0.041</td>
</tr>
<tr>
<td>Speed (m/min)*Doc (mm)</td>
<td>1</td>
<td>0.03125</td>
<td>0.03125</td>
<td>0.03125</td>
<td>5.27</td>
<td>0.045</td>
</tr>
<tr>
<td>Feed (mm/rev)*Doc (mm)</td>
<td>1</td>
<td>0.023328</td>
<td>0.023328</td>
<td>0.023328</td>
<td>3.93</td>
<td>0.075</td>
</tr>
<tr>
<td>Residual Error</td>
<td>10</td>
<td>0.059301</td>
<td>0.059301</td>
<td>0.00593</td>
<td>0.37</td>
<td>0.70</td>
</tr>
<tr>
<td>Total</td>
<td>19</td>
<td>0.297592</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3. Main Effect Plots and Interaction Plots for Surface Roughness

The effect of process parameters on performance characteristic is easy to explain with the help of the main effects plot. In Figure 5, the main effects for average surface roughness ($Ra$) is plotted.

It is clearly observed that the feed strongly changes the surface roughness. The feed rate has an increasing effect. It is known that the theoretical geometrical surface roughness is primarily a function of the feed for a given nose radius and changes with the square of the feed rate value. The cutting speed has an important and a decreasing effect. Surface roughness is improved by increasing cutting speed, though the improvement is very limited at higher cutting speed (155-165 m/min). Producing a better surface finish at higher cutting speed is well known in metal cutting.

During experimentation, where hardened steel is machined, the cutting speeds are higher than those favouring BUE formation. The higher the velocity is, the less significant the plastic behaviour becomes. The lateral plastic flow of the workpiece material along the cutting edge direction may increase the peak-to-valley height of the surface irregularity. If the material presents less plasticity by increasing cutting speed and, hence, deformation velocity, the surface finish can be improved as a result of less significant lateral plastic flow and, thus, less additional increase in the peak-to-valley height of the machined surface.

For the depth of cut ($Doc$), the influence value is the second statistical significance on surface roughness. However, low depth of cut should be used in order to reduce the tendency to chatter. The depth of cut ($Doc$) has a little direct influence on the surface roughness; however, with the increases in $Doc$, above nose radius of tool values (0.8 mm), a chatter may result causing degradation of the workpiece surface. Therefore, if the tool work system is not very rigid, such as in cutting slender parts, very fine depth of cut should be employed to avoid chatter. In this
way, very good surface finish can be obtained. For all machining tests, the $Ra$ values observed are in the range of 0.561-0.999 microns, indicating that Ceramic tool is able to produce parts with surfaces equivalent to those resulting from grinding and other finishing processes.

3.4. Contour Plots for Surface Roughness Vs Speed, Feed and Depth of cut.

Contour plots play a very important role in the study of the response surface. By creating contour plots using software for response surface analysis, the optimum is located by characterising the shape of the surface. Circular shaped contour represents the independence of factor effects and elliptical contours may indicate factor interaction. The contours of the responses are shown in Figures 6a, 6b & 6c. The surface roughness clearly showed that the minimum roughness is at low value of feed, because feed is the most influencing factor for surface roughness. $Ra$ is minimum at low depth of cut and low speed.

![Main Effects Plot for Ra(microns)](image1)

**Figure 5.** Main effect plots for mean Surface roughness against speed, feed and depth of cut.

![Contour Plot of Ra(microns) vs Feed(mm/rev), Speed(m/min)](image2)

**Figure 6a.** contour plot of $Ra$ vs Feed and Speed
3.5. 3D Surface Plots

3D Surface plots of $Ra$ vs. different combinations of cutting parameters are shown in Figures 7a, 7b, 7c, and these figures obtained by RSM. Figure 7a presents the influences of cutting speed ($V_c$) and feed rate ($f$) on the surface roughness, while the depth of cut ($Doc$) is kept at the middle level. Figure 7b shows the estimated response surface in relation to the cutting speed ($V_c$) and depth of cut ($Doc$), while feed rate ($f$) is kept at the middle level. The effects of the feed rate ($f$) and depth of cut ($Doc$) on the cutting force components are shown in Figure 7c, while the cutting speed ($V_c$) is kept at the middle level. For each plot, the variables not represented are held at a constant value (the middle level). These 3D plots confirm the notes observed during the principal effects plots analysis.
4. Conclusions

The tests of hard turning, carried out on AISI D3 steel having 62 HRC which is machined with a mixed ceramic tool (insert CC6050), enabled us to develop statistical models of surface roughness criteria.

- These models are obtained using a multiple regression method in Minitab16 software. The results revealed that the feed rate seems to influence the surface roughness more significantly than the cutting speed.

- The depth of cut is found to be the second significant parameter after feed; thus, to get a good surface finish with a higher chip removal rate, the proposed process parameters are cutting speed at 165 m/min, feed rate at 0.05 mm/rev and depth of cut of 0.3 mm.

- The statistical models developed illustrate the degree of influence of each machining condition on surface roughness. These models can also be used for the optimization of hard cutting process.
This study confirms that dry hard turning of AISI D3 steel for the chosen cutting conditions shows the surface roughness to be close to that obtained in grinding.

References


Abstract

The present study investigates the fluid flow and heat transfer characteristics occurring during the melting process due to a stretching / shrinking surface in micropolar fluid. A uniform magnetic field is applied normally to the surface. The governing equations representing fluid flow were transformed into nonlinear ordinary differential equations using similarity transformation. The equations thus obtained were solved numerically using the Runge–Kutta–Fehlberg fourth-fifth order method with shooting technique. The effects of the magnetic parameter on the fluid flow, couple stress coefficient and heat transfer characteristics, are illustrated graphically and discussed in detail. Significant changes were observed in the fluid flow, couple stress coefficient and heat transfer with respect to magnetic parameter.

1. Introduction

The micropolar fluids are those which contain micro-constituents that can undergo rotation, the presence of which can affect the hydrodynamics of the flow. It has many practical applications, like, for example, analyzing the behaviour of exotic lubricants, colloidal suspensions, solidification of liquid crystals, extrusion of polymer fluids, cooling of metallic plate in a bath, animal blood, body fluids, among others. Eringen [1] introduced the theory of micropolar fluids that is capable to describe those fluids by taking into account the effect arising from local structure and micromotions of the fluid elements. Gamal and Rahman [2] studied the effect of MHD on thin films of a micropolar fluid and they observed that the rotation of the microelements at the boundary increase the velocity when compared with the case when there is no rotation at the boundary. Das [3] investigated the effect of the first order chemical reaction and thermal radiation on hydro-magnetic free convection heat and mass transfer flow of a micropolar fluid through a porous medium. Satya Narayana et al. [4] investigated the effects of Hall current and radiation absorption on MHD free convection mass transfer flow of a micropolar fluid. Srinivasacharya [5] analyzed the heat and mass transfer characteristic of the forced convection on a vertical wall temperature and concentration in a doubly stratified micropolar fluid. Das [6] studied the effect of partial slip on steady boundary layer stagnation point flow of an electrically conducting micropolar fluid impinging normally through a shrinking sheet in the presence of a uniform transverse magnetic field. The unsteady MHD boundary layer flow of a micropolar fluid near the stagnation point of a two-dimensional plane surface through a porous medium was studied by Nadeem et al. [7]. Ishak et al. [8] investigated the heat transfer over a stretching surface with variable heat flux in micropolar fluid. Wang [9] investigated the shrinking flow where the velocity of boundary layer moves toward a fixed point and he found an exact solution of Navier–Stokes equations. A good list of references for micropolar fluids is available in Łukaszewicz [10]. Tien and Yen [11] investigated the effect of melting on forced convection heat transfer between a melting body and surrounding fluid. Epstein and Cho [12] analyzed the melting heat transfer of the steady laminar flows over a flat plate. The steady laminar boundary layer flow and heat transfer from a warm, laminar liquid flow to a melting surface moving parallel to a constant free stream has been studied by Ishak et al. [13]. Rosali et al. [14] studied micropolar fluid flow towards a permeable stretching/shrinking sheet in a porous medium numerically. Yacob et al. [15] investigated a model to study the heat transfer characteristics occurring during the melting process due to a stretching/shrinking sheet and they studied the effects of the material parameter, melting parameter and the stretching/shrinking parameter on the velocity, temperature, skin friction coefficient and the local Nusselt number. Cheng and Lin [16] analyzed the melting effect on transient mixed convective heat transfer from a vertical plate in a liquid saturated porous medium.
In the present work, we consider the boundary layer stagnation-point flow and melting heat transfer of a MHD micropolar fluid towards a stretching / shrinking surface. To the best of our knowledge, this problem has not been considered before, so that the results are new.

2. Mathematical formulation

![Figure 1: Flow configuration and Coordinate system](image)

The graphical model of the problem is given along with flow configuration and coordinate system. The system deals with two dimensional stagnation point steady flow of micropolar fluids towards a stretching / shrinking surface subject to a constant transverse magnetic field \( B_0 \). The velocity of the external flow is \( u_e(x) = ax \) and the velocity of the stretching surface is \( u_w(x) = cx \), where \( a \) is a positive constant and \( c \) is a positive (stretching surface) or a negative (shrinking surface) constant, \( x \) is the coordinate measured along the surface. It is also assumed that the temperature of the melting surface and free stream condition is \( T_m \) and \( T_{∞c} \), where \( T_{∞c} > T_m \). The viscous dissipation and the heat generation or absorption has assumed to be negligible. Under these assumptions, the governing equations representing flow are as follows:

\[
\begin{align*}
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} &= 0 \quad (1) \\
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} &= u \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial N}{\partial y} - \frac{k}{\rho} \frac{\partial v}{\partial y} = \frac{\partial}{\partial y} \left( \frac{\mu \partial u}{\partial x} \right) \quad (2) \\
\frac{\partial N}{\partial x} + v \frac{\partial N}{\partial y} &= \frac{\gamma}{\rho} \frac{\partial^2 N}{\partial y^2} - \frac{k}{\rho} \frac{\partial u}{\partial y} \frac{2N + \partial u}{\partial y} \quad (3) \\
\frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} &= \frac{\alpha}{\rho} \frac{\partial^2 T}{\partial y^2} \quad (4)
\end{align*}
\]

with the following boundary conditions:

\[
\begin{align*}
u = u_e(x) &= cx \land N = n \frac{\partial u}{\partial y} \land y = 0 \\
u = u_w(x) &= ax \land N = 0 \land T = T_m \quad \text{at} \quad y \to \infty \quad (5)
\end{align*}
\]

and \( \kappa \left( \frac{\partial x}{\partial y} \right)_{y=0} = \rho \left[ \lambda + c \left( T_m - T_0 \right) \right] v(x, 0) \)

here \( u \) and \( v \) are the velocity component along the \( x \) and \( y \) axis, respectively. Further, \( \mu \) is dynamic viscosity, \( k \) is vortex viscosity, \( \sigma \) is electrical conductivity of the fluid, \( \rho \) is fluid density, \( T \) is fluid temperature, \( j \) is micro inertia density, \( \gamma \) is spin gradient viscosity, \( \alpha \) is thermal diffusivity, \( \kappa \) is the thermal conductivity, \( \lambda \) is the latent heat of the fluid and \( C_s \) is the heat capacity of the solid surface. We note that \( n \) is a constant such that \( 0 \leq n \leq 1 \). The case when \( n = 0 \), is called strong concentration which indicates that no microtation near the wall. In case \( n = 1 / 2 \) it indicates that the vanishing of anti-symmetric part of the stress tensor and denote weak concentration and the case \( n = 1 \) is used for the modeling of turbulent boundary layer flows by Yacob et al. [15].

\[
\gamma = \left( \mu + \frac{k}{2} \right) l = \mu \left( 1 + \frac{K}{2} \right) l, \quad \text{where} \quad K = \frac{\kappa}{\mu} \quad (6)
\]

\[
\psi = (a \nu)^{1/2} x \frac{f^\prime}{\eta} \quad \text{and} \quad N = a \frac{\nu}{\nu} g(\eta) \quad (6)
\]

\[
\theta = \frac{T - T_m}{T_{∞c} - T_m}, \quad \eta = \left( \frac{a \nu}{\nu} \right)^{1/2} y \quad (6)
\]

The transformed ordinary differential equations are:

\[
(1 + K) f'' + f' + K f + M (1 - f') = 0 \quad (7)
\]

\[
(1 + K / 2) g'' + fg' - f'g + K (2g + f'') = 0 \quad (8)
\]

\[
\theta'' + Pr f' \theta' = 0 \quad (9)
\]

where primes denote differentiation with respect to \( \eta \) and \( Pr = \nu / \alpha \) is Prandtl number. The boundary conditions (5) become:

\[
f'(0) = \epsilon, \quad g(0) = -nf''(0), \quad \text{Pr} f(0) + m \theta'(0) = 0, \quad \theta(0) = 0 \quad (10)
\]

\[
f'(\infty) = 1, \quad g(\infty) = 0, \quad \theta(\infty) = 1.
\]

where \( \epsilon = c / a \) is the stretching (\( \epsilon > 0 \)) or shrinking (\( \epsilon < 0 \)) parameter, \( m \) is the dimensionless melting parameter and \( M \) is magnetic parameter which are defined as:

The total spin \( N \) reduces to the angular velocity.
\[ m = \frac{c_f (T_w - T_m)}{\lambda + c_f (T_m - T_0)} \]
\[ M = \frac{\sigma B_0^2}{a \rho} \]

The physical parameters of interest are the skin friction coefficient \( C_f \), local couple stress coefficient \( C_m \), and the local Nusselt number \( \text{Nu}_c \), which are defined as:
\[ C_f = \frac{\tau_w}{\rho u_T^2} \]
\[ C_m = \frac{C_n}{x \rho u_T^2} \]
\[ \text{Nu}_c = \frac{x q_w}{\kappa (T_w - T_m)} \]

where \( \tau_w \), \( C_m \) and \( q_w \) are the surface shear stress, the local couple stress and the surface heat flux respectively, which are given by:
\[ \tau_w = \left( \mu + k \right) \left( \frac{\partial u}{\partial y} \right)_{y=0} \]
\[ C_m = \gamma \left( \frac{\partial u}{\partial y} \right)_{y=0} \]
\[ q_w = -\kappa \left( \frac{\partial u}{\partial y} \right)_{y=0} \]

hence using (6), we get:
\[ \text{Re}^{1/2} C_f = \left[ 1 + \left( 1 - n \right) K \right] f''(0) \]
\[ \text{Re} C_m = \left[ 1 + \frac{K}{2} \right] g'(0) \]
\[ \text{Re}^{1/2} \text{Nu}_c = -\theta'(0) \]

where \( \text{Re} = u_c (x) x / \nu \) is the local Reynolds number.

4. Results and discussion

The transformed equations (7) - (9), subject to boundary conditions (10), were solved numerically using the Runge-Kutta-Fehlberg fourth-fifth order method with shooting technique to obtain the missing values of \( f''(0) \), \( g'(0) \) and \( \theta'(0) \) for some values of the magnetic parameter \( M \), micropolar parameter \( K \), melting parameter \( m \) and the stretching / shrinking parameter \( \varepsilon \), while the Prandtl number \( Pr \) is fixed to unity and we take \( n=0.5 \) (weak concentration).

In order to validate the numerical results obtained, we compared our results with those reported by Ishak et al. [8], Wang [9], and Yacob et al. [15], as shown in Table 1; and they are found to be in a favorable agreement.

Figures 2, 3 and 4 show the variations of the skin friction coefficient \( f''(0) \), the local couple stress coefficient \( g'(0) \) and the local Nusselt number \( \theta'(0) \), respectively with \( \varepsilon \) for different values of \( M \) when \( m=1, K=1 \). It is also seen from these figures that for the shrinking case \( (\varepsilon < 0) \), the solution exists up to a critical value of \( \varepsilon \) (say \( \varepsilon_c \)) beyond which no solution exists. The values of \( f''(0) \) are positive when \( \varepsilon < 1 \), and become negative when \( \varepsilon > 1 \). Physically, positive value of \( f''(0) \) means the fluid exerts a drag force on the solid surface and negative value means the solid surface exerts a drag force on the fluid. The zero skin friction when \( \varepsilon = 1 \), since for this case the stretching velocity is equal to the free stream velocity. However, for this case, the heat transfer rate at the surface - \( \theta'(0) \neq 0 \) means there is a heat transfer between the fluid-solid interfaces (even when the friction is zero). The couple stress coefficient \( g'(0) \) (Figure 3) shows similar behaviour as that of skin friction coefficient for the variation of the magnetic parameter \( M \) with the stretching parameter \( \varepsilon \). The negative value of \( -\theta'(0) \) (Figure 4), presented in Figure 4, shows that the heat is transferred from the warm fluid to cool solid surface. It is evident from Table 2 and Figure 2 that an increase in magnetic parameter \( M \) leads to a decrease in the value of \( f''(0) \) absolute sense. It is clear from Table 2 and Figure 3 that the value of local couple stress coefficient \( g'(0) \) decreases with the increase in the value of magnetic parameter \( M \) for \( \varepsilon < 1 \), whereas the value of local couple stress coefficient \( g'(0) \) increases with increasing value of magnetic parameter \( M \) for \( \varepsilon > 1 \). This result in the decreasing manner of the heat transfer rate at the fluid-solid interface \( -\theta'(0) \) for \( \varepsilon < 1 \), but opposite behaviours are observed for \( \varepsilon > 1 \).

It is observed from velocity profiles \( f'(\eta) \) in Figure 5 that the value of \( f'(\eta) \) decreases as \( M \) increases and from the angular velocity profiles \( g(\eta) \) in Figure 6 show that the value of \( g(\eta) \) initially increases as \( M \) increases and then changing the behaviour for large \( g \) the value of \( g(\eta) \) decreases with \( M \), thus due to the increase in magnetic parameter \( M \) the boundary layer thickness increases. For temperature (Figure 7), the change in magnetic parameter \( M \) is a small change in the temperature \( \theta(\eta) \). Consequently, thermal boundary layer undergoes negligible change with \( M \). Finally, from all the figures (Figures 5–9) above, it can be easily seen that the far field boundary conditions are satisfied asymptotically and it signifies the correctness of the numerical scheme used.
Table 1. Comparison between $f''(0)$ and $-\theta'(0)$ calculated by the present method, Ishak et al. [8], Wang [9] and Yacob et al. [15] for various values of $m$, $\varepsilon$, $K$ when $M=0$.

<table>
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<tr>
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Table 2. The values of Skin friction coefficient $f''(0)$, local couple stress coefficient $g'(0)$ and local nusselt number $-\theta'(0)$ for various values of $M$, $\varepsilon$ when $m=1$ and $K=1$.

<table>
<thead>
<tr>
<th>$M$</th>
<th>$\varepsilon$</th>
<th>$f''(0)$</th>
<th>$g'(0)$</th>
<th>$-\theta'(0)$</th>
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**Figure 2.** Skin friction coefficient $f''(0)$ with $\varepsilon$ for several value of $M$ when $m=1$, $K=1$.

**Figure 3.** Local Couple stress coefficient $g'(0)$ with $\varepsilon$ for several value of $M$ when $m=1$, $K=1$. 
Figure 4. Heat transfer coefficient $-\theta'(0)$ with $\varepsilon$ for several value of $M$ when $m=1, K=1$.

Figure 5. Velocity profiles $f'(\eta)$ for several value of $M$ when $m=1, K=1$ and $\varepsilon =0.75$.

Figure 6. Angular velocity profiles $g(\eta)$ for several value of $M$ when $m=1, K=1$ and $\varepsilon =0.75$.

Figure 7. Temperature profiles $\theta(\eta)$ for several value of $M$ when $m=1, K=1$ and $\varepsilon =0.75$.

Figure 8. Velocity profile $f'(\eta)$ for different values of $\varepsilon$ when $M=0.5, K=1$ and $m=1$.

Figure 9. Temperature profile $\theta(\eta)$ for different value of $\varepsilon$ when $M=0.5, K=1$ and $m=1$. 
5. Conclusions

We have studied the effects of the magnetic parameter on skin friction coefficient, couple stress coefficient and local Nusselt number (which represents the heat transfer rate at the surface) for the steady laminar boundary layer stagnation point flow and heat transfer from a warm micropolar fluid to a melting solid surface of the same material. It has been found that the skin friction coefficient, the couple stress coefficient and the heat transfer coefficient decreases with increase in magnetic parameter.

References

Fuzzy Rules Extraction Based on Deterministic Data (Case Study: Bank's Customers Rating)

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Abstract

Financial institutions and banks are the type of organizations whose customer rating is very valuable. In the present paper, two algorithms are proposed and compared that can extract some fuzzy rules from deterministic data. Each fuzzy rule may be used as a class of customers. In the first algorithm, a method is proposed based on both experiment and fuzzy theory. In the second algorithm a heuristic approach is proposed. Additionally, for more explanations a case study in a real bank is presented.

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Keywords: Bank's Customers Rating, Fuzzy Rules Extraction, Deterministic Data Clustering, Linguistic Labels.

1. Introduction

The knowledge acquisition from the existing data and information is essential for today's complicated world. The data mining and rules extraction from the raw data can be one method for knowledge acquisition [1]. In this paper, two algorithms are proposed to extract some fuzzy rules from the raw data. The extracted rules may be used in each field and situation. For instant, each rule may show a class of customers and consequently a service level of them.

The extracted rules can be applied for rating the customer of a specific bank. The customer rating can be very valuable for both customers and servicers. For example, top customers are considered as the customers of service level (1). These customers can receive the special services, while the service of other levels may be limited. However, the results of the present paper may also be used in any field, other than banking.

In many cases, banks use a set of raw and uncategorized information, which has been taken from the accounts of their customers. The information can be applied more effectively by processing.

By utilizing data mining methods, researchers and users will be able to extract some guidance from the given information. Of course, if there is a considerable ambiguity in the existing data, the deterministic data cannot be very helpful. Therefore, two proposed heuristic algorithms are able to extract fuzzy rules from the deterministic data. It is noteworthy that fuzzy rules and relations can describe uncertainty cases better than deterministic data [2-4].

Extracting the database of fuzzy rules from numerical data can be obtained by both tabling and clustering [5]. In the tabling approach, the input and output data are divided into several ranges, so a linguistic label is assigned to each range. Therefore, a table is shaped and the rules are determined [4]. Figure (1) shows a sample of tabulation of two-dimensional data.

![Figure 1: A sample of tabulation of two-dimensional data](image)

The second approach utilizes clusters. The clustering approach places elements into a group based on some similarities and into different groups based on some dissimilarities [6].

In this approach, the data can be clustered by some specified clustering techniques, and each cluster may be considered as a rule. One of the advantages of this approach, of which the previous approach lacks, is that the fuzzy membership functions can be calculated easier [7-9]. Figure (2) shows a sample of two-dimensional deterministic data clustering.
The main idea of the present paper is that the placed similar data in a cluster may be described as a rule.

For this purpose, a suitable clustering algorithm (for example k-means) is used to cluster the existing data. Next, the steps of the proposed algorithms (one of proposed algorithms) are done to find the extracted fuzzy rules. It is clear that the left hand side of the rules has \( n-1 \) variables and the right hand side of the rules has one variable only. So, according to Eq. (2), an \( n \)-dimensional space is obtained. Hence, when clustering is done, each cluster shows an \( n \)-dimensional sphere.

Since the obtained rules are formed from the set of linguistic labels, the rules can be defined as a Cartesian product similar to Eq. (3):

\[ R: L_1 \times L_2 \times \cdots \times L_n \times T \]

Where \( L_i \) is a set of labels used for the input variables and \( T \) is a set of labels used for the output variable.

Due to the nature of the data and clusters, the clustering techniques can be divided into four general categories:

- Deterministic data, deterministic clusters
- Deterministic data, fuzzy clusters
- Fuzzy data, deterministic clusters
- Fuzzy data, fuzzy clusters

In a clustering technique, if an element belongs to several clusters with different membership degrees, there is a fuzzy clustering. The fuzzy clustering methods can be performed by deterministic or fuzzy data. In this paper, two algorithms are presented to cluster the deterministic data as several fuzzy clusters.

3. Algorithms

3.1. Algorithm (I)

- Step 0: Begin
- Step 1: Determine the linguistic variables and labels for any data by experts - (in this case study by the bank's experts).
- Step 2: Use a suitable clustering technique to cluster the existing data.
- Step 3: Assign a fuzzy number to each member of clusters.
- Step 4: Compare the fuzzy numbers with their corresponding linguistic labels; and then select the label that is closest to the number.
- Step 5: According to the assigned labels in Step 4, extract and rewrite a fuzzy rule for each cluster.
- Step 6: End

The steps of the above algorithm are explained below.

Step 1: Define the linguistic variables

As mentioned in previous sections, fuzzy rules can be obtained using a set of linguistic labels. The definition of linguistic variables and labels may affect the efficiency of the algorithm. The arguments of linguistic variables are described by fuzzy numbers. Generally, a linguistic variable may be defined in four levels. In the first level, "variable name" (e.g., account balance), in the second level, "linguistic labels" (e.g., high, medium and low), in the third level, "membership function" of linguistic labels, and in the fourth level, "universal set."
Assume that the data are arranged using a table whose rows and columns represent the elements (e.g., bank customers) and the attributes of elements (e.g., customer account information), respectively. A linguistic variable is defined for each column. The first and second levels of linguistic variables may be defined by modeler, while their third and fourth levels should be defined by experts (e.g., expert in banking).

If you are not able to find an expert, you may use some another data or software similar to the report of Baturone et al. [5]. Table (1) shows a sample of the assignment of linguistic labels to fuzzy numbers.

<table>
<thead>
<tr>
<th>Linguistic Variables</th>
<th>Fuzzy Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample1</td>
<td>Sample2</td>
</tr>
<tr>
<td>Very Low</td>
<td>(0.0, 0.0, 0.1, 0.2)</td>
</tr>
<tr>
<td>Low</td>
<td>(0.0, 0.0, 0.2, 0.4)</td>
</tr>
<tr>
<td>Medium</td>
<td>(0.2, 0.5, 0.5, 0.8)</td>
</tr>
<tr>
<td>High</td>
<td>(0.6, 0.8, 1.0, 1.0)</td>
</tr>
<tr>
<td>Very High</td>
<td>(0.8, 0.9, 1.0, 1.0)</td>
</tr>
</tbody>
</table>

**Table 1.** The assignment of linguistic labels into fuzzy number[23]

---

**Step 2: Data clustering**

A cluster is a set of objects; its objects are similar to each other in some attributes, and are different from other objects in another attributes. For example, in the case of bank's customers, a cluster can include a set of customers whose account information have similarities, but are different from other customers. A good clustering technique may keep the mentioned feature. By utilizing this feature, the bank's managers may identify and forecast the behavior of customers to obtain better results [1]. A successful clustering is achieved through the execution of existing clustering algorithms. The use of different algorithms leads to different results, but there is not any approach for selecting the best algorithm [24]. In this paper, the K-means technique is used for clustering [1].

Despite that fact that the K-means technique was proposed for the first time over 50 years ago, it is still widely used for clustering. Simplicity, efficiency and empirical success are the main reasons for its popularity [25].

Definitely, any other clustering technique could also be used in this step. Clustering algorithms for high dimensional data were investigated in [26, 27]; time series data clustering were reviewed in [28]; the clustering problem in the data stream domain were studied in [29, 30]; and an overview of the approaches to clustering mixed data were given in [31].

Identifying the number of clusters in a data set (often labeled as $k$) is a fundamental issue in clustering analysis. To estimate the value of $k$, many studies have been presented and discussed in the literature [32].

Sun et al. [33] presented an algorithm based on the fuzzy k-means to determine the number of clusters automatically. It consists of a series of fuzzy k-means clustering procedures with the number of clusters varying from 2 to $k$. By investigating the clustering results for different values of $k$, the exact number of clusters is obtained in a given data set. The same approach for determining $k$ is also used in the present paper.

![Figure 3. The assignment of linguistic labels into fuzzy numbers](image-url)
Step 3: Determining the fuzzy numbers for the attributes of placed objects within clusters

Suppose the data is written in a table. The rows and columns of the table indicate the information of the bank's customers and the customer's accounts, respectively. Each attribute can be shown by a fuzzy number. In this paper, the triangular fuzzy numbers are used. In this step, for determining the fuzzy numbers the mean (μ) and standard deviation (σ) of data (data in each column) are applied. Hence, a triangular fuzzy number, such as (μ-σ, μ, μ + σ), can be defined (see Figure (4)). Similarly, determine a triangular fuzzy number for each attribute (each column of table) and cluster.

Step 4: Select the appropriate label

In this step, you have to select the best label for any determined fuzzy number. A suitability criterion for a label means that its membership function is close to the desired fuzzy number. For measuring the closeness between two fuzzy numbers, there are several methods. In this paper two criteria as "Degree of Similarity" (DOS) and "Degree of Inclusion" (DOI) are applied [1]. The criteria can be defined as follows:

\[
S(N, L) = \frac{\|N \cap L\|}{\|N \cup L\|} \quad (4)
\]

\[
I(N, L) = \frac{\|N \cap L\|}{\|N\|} \quad (5)
\]

Where the symbol \(\|\|\) shows the cardinality of a set, also \(N\) is an obtained fuzzy number in step (3) and \(L\) is the membership function of a linguistic label. \(S(N, L)\) (degree of similarity between \(N\) and \(L\)) is used to determine the best \(L\) (as a linguistic label). \(L\) is selected if its DOS is the greatest. If the DOS of several linguistic labels are equal, DOI may be used to determine the best \(L\). In this state, \(L\) is selected if its DOI is the greatest. Therefore, a linguistic label is assigned to each attribute.

Step 5: Rewriting the rules

In this step, the extracted rules can be rewritten like if–then rules. The number of rules may be equal to the number of clusters. For instance, a rule for cluster \(h\) can be written as follows:

\[
R_h: \text{if } x_i \text{ is } A^i_h \text{ and } \cdots \text{ and } x_p \text{ is } A^p_h \text{ then } y \text{ is } B^i_h
\]

Where \(x_i, x_2, ..., x_p, y\) are linguistic variables and \(A_i^h, B_h\) are the assigned labels in step (4). By rewriting the rules for all clusters, a rule base is obtained which can describe the behavior of the system in any conditions.

3.2. Algorithm (II)

- Step 0: Begin
- Step 1: Define a linguistic label and variable for each data by experts.
- Step 2: Cluster the deterministic data by an appropriate technique.
- Step 3: Calculate the “Degree of Dependency” to the cluster (DoD) for each attribute of objects within a cluster separately.
- Step 4: Find the equation of DoD changes in terms of “attribute values” for each attribute within a cluster separately.
- Step 5: Modify the obtained equations in step (4) according to the data concentrations.
- Step 6: Assign the suitable labels to the obtained equations in step (5).
- Step 7: Extract and rewrite the rules.
- Step 8: End.

Below, the above mentioned steps are explained.

Step 1: Defining linguistic variables

It is similar to step (1) in the first algorithm.

Step 2: Data clustering

It is similar to step (2) in the first algorithm.

Step 3: Calculating DoD

Each cluster includes a number of customers and their accounts have several attributes. A DoD can be calculated for each customer and attribute. If the number of customers is \(m\) and the number of attributes is \(n\), the number of DoDs can be equal to \(m \times n\). A DoD may be determined by equation (7):

\[
DoD_{ijh} = 1 - \frac{\left| x_{ijh} - m_{ijh} \right|}{m a x_{i} (x_{ijh} - m_{ijh})}
\]

Where \(DoD_{ijh}\) is the degree of dependency to cluster \(h\) for each attribute \(j\) and customer account \(i\). Also \(X_{ijh}\) is the value of attribute \(j\) and customer account \(i\) in cluster \(h\) and also \(m_{ijh}\) is the median of attribute \(j\) in cluster \(h\). The symbol \(\|\|\) shows an absolute function too.

Step 4: Finding the equation of DoD changes in terms of changes in the value of attributes

In discrete cases, the value of the attributes can be represented by fuzzy sets that include a number of ordered pairs, where the first element shows the value of an attribute and the second element shows DoD.
In the present paper, the values are continuous, so the horizontal axis shows the values of an attribute and the vertical axis shows DoD. A regression equation may be fitted for the existing data. This curve can be considered as a fuzzy number to assign the best linguistic label to the data (see Figure 5).

![Figure 5. A sample of fitting a curve on data](image)

**Step 5: Improving the obtained equations according to the data concentrations**

Generally, the values of attributes are concentrated in specified areas of domain (Figure 5). Also the existence of some useless data in first and end of domain can widen the domain and curve. The widened domain and curve can lead to some errors in the selection of appropriate linguistic labels and a reduction in the accuracy of the results. For this purpose, exclude a range of data from the beginning and end of domain. If the length of the old domain is \( d_1 \) and the length of the new domain is \( d_2 \), the multiplying proportion \( d_2/d_1 \) in the length of the graph horizontal axis may reduce the width of the chart and increase its focus on areas where the density of data is higher. This action will increase the accuracy of linguistic labels selection.

**Step 6: Find the appropriate labels**

Select a label that is closer to the obtained equation in step (5). The current step is similar to step (4) of the first algorithm, so you can implement it by equations (4) and (5).

**Step 7: Rewriting the rules**

This step is similar to step (5) of the first algorithm.

### 4. Case Study

The customer relationship management and customer requirements management in banks and financial institutions are very important. So rating customers based on the analyzed criteria can help organizations to present more favorable services. Data mining [14] and the presented algorithms in previous sections can be used as tools for evaluating, predicting customer behavior and customers rating in terms of some criteria. In this paper, it is shown how to implement the proposed algorithms. For this purpose, the information of 2500 accounts from a bank in Iran is studied [34]. The afore-mentioned information is clustered by the \( k \)-means method and is considered 5 clusters corresponding to 5 levels of customers rating.

In this case study, the following criteria of customers account information are considered:

1. **average**: The average of daily balance for each customer during one year.
2. **val-cheq**: The average amount of returned checks for each customer during one year.
3. **tran-bed**: Total debtor turnover of each customer during one year.
4. **tran-bes**: Total creditor turnover of each customer during one year.
5. **rem-bes**: The sum of the creditor balance of each customer during one year.
6. **remained**: The remaining creditor balance of each customer at the end of year.

The criterion "tran-bed" can be considered as a consequent of other criteria, so it is located in right hand side of the rules. The steps of the first algorithm can be performed as follows:

**Step 1** Defining the linguistic variables (see Figures (6) to (11)).

**Step 2** Clustering data by \( k \)-means method: since 5 clusters have less error, so 5 clusters are considered.

Steps (3-5) Selecting appropriate labels, their calculations, rules extraction and their rewriting.

Finally the five rules are obtained as follows:

- **R1**: If \( (\text{remained} = \text{VL}) \) and \( (\text{tran_bes} = \text{L}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{VL}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{L}) \)

- **R2**: If \( (\text{remained} = \text{VL}) \) and \( (\text{tran_bes} = \text{S}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{VL}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{S}) \)

- **R3**: If \( (\text{remained} = \text{VL}) \) and \( (\text{tran_bes} = \text{M}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{VL}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{M}) \)

- **R4**: If \( (\text{remained} = \text{M}) \) and \( (\text{tran_bes} = \text{VS}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{M}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{VS}) \)

- **R5**: If \( (\text{remained} = \text{VL}) \) and \( (\text{tran_bes} = \text{M}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{VL}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{M}) \)

Third and fifth rules are similar, so the fifth rule is removed, so only the first four rules can be considered.

Also by the second algorithm, five rules are obtained as following:

- **R6**: If \( (\text{remained} = \text{VL}) \) and \( (\text{tran_bes} = \text{L}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{VL}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{L}) \)

- **R7**: If \( (\text{remained} = \text{L}) \) and \( (\text{tran_bes} = \text{S}) \) and \( (\text{rem_bes} = \text{L}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{L}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{S}) \)

- **R8**: If \( (\text{remained} = \text{VL}) \) and \( (\text{tran_bes} = \text{M}) \) and \( (\text{rem_bes} = \text{L}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{L}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{M}) \)

- **R9**: If \( (\text{remained} = \text{M}) \) and \( (\text{tran_bes} = \text{VS}) \) and \( (\text{rem_bes} = \text{S}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{M}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{VS}) \)

- **R10**: If \( (\text{remained} = \text{VL}) \) and \( (\text{tran_bes} = \text{M}) \) and \( (\text{rem_bes} = \text{L}) \) and \( (\text{val_cheq} = \text{VS}) \) and \( (\text{average} = \text{VL}) \) \( \Rightarrow \) \( (\text{tran_bed} = \text{L}) \)

Note that the extracted fuzzy rules from each of the two algorithms are different.

By extracting the fuzzy rules according to the needs of each bank, the customers can be rated into several levels. A bank can present services to its customers based on the
determined levels. For example, the customers of the first cluster can be considered as high level customers (first level) because their account balance and turnover is large and their returned check rate is low; these customers can be useful for a bank. Therefore, a bank can prepare more services for this level of customers. The reward and punishment can also be applied similarly for other levels.

5. Conclusions

In this paper, two algorithms were presented to extract fuzzy rules from deterministic data. The proposed algorithms were performed in a case study on bank customers. One of the applications of fuzzy rules for banks may be rating their customers. Each customer in each level can receive some services depending on its level.

For investigating the validity of the algorithms, the information of 300 new customer accounts was extracted. The data were compared with the obtained rules from previous algorithms. The criteria values as input data and the value of “tran-bed” as output data were considered. The calculations show that the first algorithm 95.7% and the second algorithm 92.7% confirm the views of experts. Of course the confirmation of both algorithms is acceptable.

The advantage of the above methods over the other methods is that they can reduce the time and the required effort for extracting rules.

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