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An Application of Finite Element Method and Design of Experiments in the Optimization of Sheet Metal Blanking Process

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Abstract

Metal blanking is a widely used process in high volume production of sheet metal components. The main objective of this paper is to present the development of a model to predict the shape of the cut side. The model investigates the effect of potential parameters influencing the blanking process and their interactions. This helped in choosing the process leading parameters for two identical products manufactured from two different materials blanked with a reasonable quality on the same mold. Finite Element Method (FEM) and Design of Experiments (DOE) approach are used in order to achieve the intended model objectives. The combination of both techniques is proposed to result in a reduction of the necessary experimental cost and effort in addition to getting a higher level of verification. It can be stated that the Finite Element Method coupled with Design of Experiments approach provide a good contribution towards the optimization of sheet metal blanking process.

Keywords: Blanking process; Finite Element Method; Design of Experiments; Optimization; Burrs height;

1. Introduction

Metal blanking is a widely used process in high volume production of metal components. General guidelines for this process exist but they are not sufficient to overcome the difficulties in designing blanking processes, where requirements for less cycle time and accurate product dimensions become more demanding. The design of blanking processes in industrial practice is still based largely on experimentations and it is often governed by time-consuming and expensive trial and-error iterations caused by limited, mostly empirical, knowledge of these processes. There is a need for a new method that allows for the reduction of trial and error option in designing a blanking process. Therefore, appropriate modeling and understanding of the blanking process could be beneficial to reduce the lead-time and to control the product specifications, especially the shape of a blanked (sheared) edge.

Current research on the control of blanking operations aims to improve the monitoring and control of the quality of components. The motivation is the reduction of reject volume, the reduction of manual quality control, and the high cost of replacing tools after catastrophic failure [1]. Optimizations of manufacturing processes and parameters control are known to have direct impact on the production line maintenance and operations [2]. Among the most important tools for manufacturing processes optimization are the design of experiments (DOE) approach and the finite element method (FEM).

In this paper, a combination of both techniques is used in order to achieve a higher level of verification and to reduce the cost of the necessary experimental effort. Design of experiments will aid in guiding the selection of the proper combination of the process parameters at their specified levels in such a way that costly dies will not be manufactured until the finite element method shows the best set of the process parameters.

1.1. The Blanking Process

Blanking is a manufacturing operation as old as the technology itself. Its applications range from components of very light to heavy appliances and machineries [3]. Blanking is defined as the cutting of a work piece between two die components to a predetermined contour [4]. During blanking, the part is subjected to complex solicitations such as deformation, hardening and crack initiation and propagation. The theoretical modeling of such processes is very difficult due to the complexity in describing the different stages of the whole shearing process starting with the elastic stage and ending with the total separation of the sheet metal [5].

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The behavior of the blank material during the blanking process can be divided into five stages. During the start of the process, the sheet is pushed into the die and the blank material is deformed, first elastically. The process continues and the yield strength of the blank material is reached, first at the outer fibers and later at all the fibers in the zone between the punch and the die. Normally, the material underneath the punch is subjected to thinning. The plastic deformation causes rounding of the edge of the blank. During this stage, or possibly as early as during the plastic deformation stage, damage initiation followed by the nucleation and growth of cracks takes places. In most of the conventional blanking situations, ductile fracture occurs after shear deformation. This causes rough, dimpled rupture morphology on the fractured surface of the product. Finally, the work due to friction is dissipated when forcing (pushing) the slug through the die hole [6].

1.2. Finite Element Method (FEM) and Design of Experiments (DOE)

Numerical methods provide a general tool to analyze arbitrary geometries and loading conditions. Among the numerical methods, Finite Element Analysis (FEA) has been extensively used with success; however, this kind of analysis requires the generation of a large set of data in order to obtain reasonably accurate results and consumes large investment in engineering time and computer resources [7]. FEM is a good choice for the analysis of sheet metal processes since it helps in eliminating the need for time-consuming experiments to optimize the process parameters [3]. The FEM simulations are increasingly used for investigating and optimizing the blanking processes. Many time-consuming experiments can be replaced by computer simulations. Therefore, highly accurate results of sheet metal forming may be obtained by using the FEM simulation [8]. The finite element method gives an approximate solution with an accuracy that depends mainly on the type of element and the fineness of the finite element mesh.

In the manufacturing area, Design of Experiments (DOE) is found to be an efficient statistical technique that can be used for various experimental investigations. The design of experiments is one of the powerful tools used to investigate deeply hidden causes of process variation [9]. It is a systematic, rigorous approach to engineering problem solving that applies principles and techniques at the data collection stage to ensure the generation of valid, defensible, and supportable conclusions. In the blanking process, experimental design is considered a powerful approach for product and process development, and for improving the yield and stability of an ongoing process. Hambli *et al.*, [10] found that the design of experiments technique is an efficient and cost-effective way to model and analyze the relationships that describe process variations.

The sheet metal industry is highly interested in knowing if two identical products manufactured of two different materials, can be blanked with a reasonable quality without the need to build two separate setups. This will increase the efficiency of the production processes and reduce the level of wasted materials, time, cost, and effort involved in the production stages. In addition, the industry needs a suitable model to overcome the long cycle time in developing a particular blanking process. This can be achieved by combining the Finite Element Method and Design of Experiments techniques aiming at identifying opportunities to increase efficiency and productivity as well as eliminating waste and reducing production cost associated with the blanking process. The main objective of this paper is to construct a finite element model to predict the shape of the cut side of a blanked product, and to investigate the effect of potential parameters influencing the blanking process and their interactions using the design of experiments approach in order to choose the process leading parameters in an optimal way.

2. Relevant Literature

Numerical simulation of the problems associated with sheet metal forming using the Finite Element Method (FEM) can help in process design by reducing the number of trial steps. Although process modeling using FEM simulation is already used in industry in a wide variety of forming operations, no commercially available FEM code is capable of simulating, with the required degree of precision, the blanking process, and fracture formation [11]. Hambli [5] presents industrial software called BLANKSOFT dedicated to sheet metal blanking processes optimization. Several researches have emphasized different aspects of the blanking process. Through literature, it is clear that many methods are used to study the blanking process to achieve the optimal combination of its parameters. This includes analytical approaches [6, 12]; Finite Element Method [13, 14, and 5]; Design of Experiments [10, 15] and Neural Networks Modeling [15, 16]. Literature shows that the mechanical characteristics of the blanking process and the geometrical aspect of the sheared edge are affected by different parameters. These parameters include clearance, wear state of the tool, tool radii and geometry, thickness of the sheet, blank geometry, or layout, material prosperities such as hardness and ductility, friction, tools surface finish or lubricant type, sheet metal coating, and stroke rate or blanking speed [10-16].

Using a combination of techniques in analyzing the blanking process and its parameters and conducting comparisons are widely common in literature. Klingenberg and Singh [6] have compared two existing analytical models of blanking while Biglari *et al.* [13] have performed a comparison between fine and conventional blanking. Hambli [15] has combined predictive finite element approach with neural network modeling of the leading blanking parameters in order to predict the burr height of the parts for variety of blanking conditions. Brokken *et al*. [17] presented a set of interrelated numerical techniques resulting in a finite element model of the metal blanking process, focusing on the prediction of the shape of the cut edge of the blanked product. In addition, Rachik *et al*. [18] presented a comprehensive experimental and numerical study of the sheet metal blanking process.

The clearance impact on the blanking processes has consumed a significant amount of research. This concern about the clearance factor is because the structure of the blanked surfaces is influenced by both the tooling (clearance and tool geometry) and the properties of the work piece material (blank thickness, mechanical properties, microstructure, etc.). The selection of the clearance influences the life of the die or punch, the blanking force, the unloading force and the dimensional precision [19]. Hambli and Guerin [16] have developed a methodology to obtain the optimum punch–die clearance for a given sheet material by the simulation of the blanking process. The proposed approach combined predictive finite element and neural network modeling of the leading blanking parameters. Miguel and Jose [20] have proposed a general framework for numerical simulation of blanking process using FEM, and analyzed the influence of clearance on stress distribution prior to material separation.

Clearance parameter impact on the blanking process is widely tested. Fang *et al.* [19] investigated the punch–die clearance values for a given sheet material and the thickness are optimized by using a finite element technique in which the shearing mechanism was studied by simulating the blanking operation. Goijaerts *et al.* [21] performed finite element simulations and experiments on both blanking and tensile testing to evaluate the validity of both approaches with corresponding criteria for five different metals. Maiti *et al.* [3] analyzed the blanking of thin sheet of mild steel using an elastic plastic finite element analysis based on the incremental theory of plasticity. The study has helped to evaluate the influence of tool clearance, friction, sheet thickness, punch/die size, and blanking layout on the sheet deformation. Hambli *et al.* [10] investigated the blanking process using tools with four different wear states and four different clearances and studied the effects of the interaction between the clearances, the wear state of the tool and the sheet metal thickness on the evolution of the blanking force and the geometry of the sheared profile. The results of the proposed experimental investigation show that there is no universal optimal clearance value. Whether clearance should be set at 5% or 10% ultimately depends on the priorities of the practitioners.

Simulation techniques applied for the blanking process are beneficial to the understanding of the process behavior. Shim *et al*. [14] investigated the blanking operation of very thin sheet metals like membranes. Klingenberg and Singh [12] investigate the behavior of the blank material during the process through finite element simulations, analytical modeling, and experimental work. They have found that the quality of blanking process output is the determinant factor in assessing the goodness of the tool and parameters design. The quality of sheet metal blanking processes part can be assessed by the burr height of the sheared edge after blanking [15]. Thomas *et al.* [22] presented results from a numerical model validated by experiment, which illustrate the effects of some process parameters on blanking forces and edge quality of aluminum sheets.

A review of the literature on the blanking process shows that while a large number of analytical techniques have been used to study the process, the amount of theoretical and practical work done is relatively insufficient and thus further investigation is still needed. One reason for this may be the difficulty of simulating the shearing process because of the narrowness of the shear band formed and the lack of an appropriate fracture criterion. The most recent studies in the field of manufacturing processes show that, despite the increasing progress in blanking process analysis, there is still a lack of models allowing for the optimal design of sheet metal shearing processes [10].

3. Methodology

Finite Element Method (FEM) and Design of Experiments (DOE) techniques are used to achieve the study objectives. The combination of both techniques is proposed to result in a reduction of the necessary experimental cost and effort in addition to receiving a higher level of verification. Design of Experiments provides the guidance in the selection of the proper combination of the process parameters at their specified levels, in such a way that costly dies will not be manufactured until the finite element simulations show the best set of process parameters. The methodology that is followed to attain the research objectives is divided into the following work phases:

- Classify the blanking parameters into controllable and uncountable. A summary of the blanking parameters with their classification is presented in Figure 1. The identified controllable parameters are clearance, blank holder force, sheet metal thickness, and material type. While, the uncountable parameters are material prosperities inconsistency and conditions (shape, defects and internal stresses), friction and wear state of the tool, stroke rate or blanking speed, and punch-die alignment.

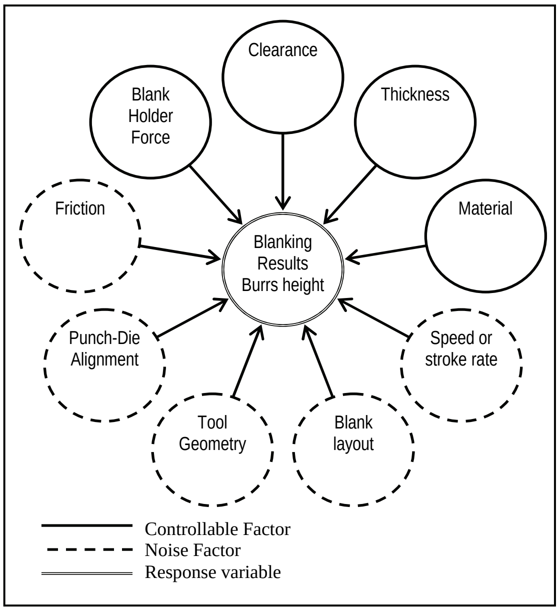

Figure 1. Summary of the blanking parameters situation in this research

- Choose the controllable factors that influence the blanking process as the interest domain.
- Select an appropriate working range for each potential factor. It is found that the working range of clearance fall within the range (0-25)% of the sheet metal thickness, the working range of the blank holder force fall within the range (0-30)% of the shearing force and

the working range of the thickness of their used material fall within the range (0.5-0.8) mm.

- Prepare to use of Design of Experiments (DOE) technique by selecting the experimental levels for each selected factor, i.e. the clearance to be in five levels (5, 10, 15, 20, 25) % of the sheet metal thickness, blank holder force to be in two levels (0, 3000N) and sheet metal thickness to be in four levels (0.5, 0.6, 0.7, 0.8) mm.
- Perform a factorial experimental design in order to take high-level interactions based on the findings of the previous steps.
- Develop a Finite Element Model (FEM) that represents the existing process in order to evaluate the quality of the inputs.
- Compare the two techniques (FEM and DOE) and analyze the results to get the proposed optimal set of parameters.

4. Finite Element Simulation

The problem studied in this work involves simulating of an axis-symmetric blanking operation of sheet metal. The simulation is designed to study a configuration that includes two types of materials (AISI-Steel 12 and AISI-Stainless Steel 480); five values of clearances (C= 5, 10, 15, 20, and 25 percent of sheet metal thickness); two values of the blank holder force (BHF = 0, and 3000 Newton); and four values of thickness of the sheet (t = 0.5, 0.6, 0.7, and 0.8 mm). Eighty simulations are performed for the above configuration according to the whole combinations of parameters. Simulations are conducted on the commercial finite element software package ABAQUS/Explicit.

The process is simplified by using a two-dimensional situation, under plane-strain conditions, since in a normal blanking operation the punch-die clearance is usually very small in relation to the blank diameter, otherwise, the deformation will be in a 3-D form. In all simulations, a circular disc with a diameter of 55 mm has been used as the blank. Only half of the blank was modeled because the blanking process is symmetric about a plane along the center of the blank. Figure 2 shows part of the finite element mesh used to model the plate in the shear zone.

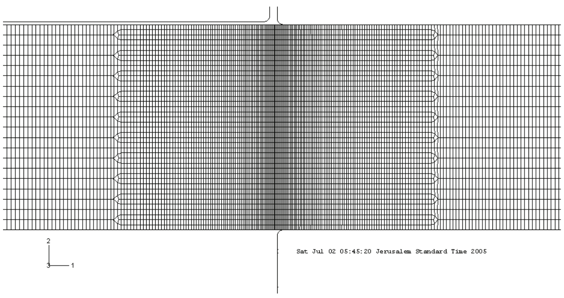

Figure 2. A part of the finite element mesh used to model the plate in the shear zone.

In the blanking operation, deformation is concentrated along very narrow shear band. The width of the shear band is a few microns, thus, the number of elements used is critical for every simulation since a large number of elements increases the accuracy of the result, but also substantially increases the calculation time. Therefore, a very dense mesh is defined in the shearing region and relatively large elements for the remainder. The blank is modeled using twenty layers of four-node axi-symmetric elements (ABAQUS type CAX4R). This number is doubled to be forty layer in the cutting region, one thousands axi-symmetric elements are used in the radial direction. The mesh is designed to be smaller as the cutting region is approached to get accurate results. A total of (23020) elements and (24041) nodes have been used in the model and the smallest element size is 3.324E-3 mm after testing different meshes. The tools are modeled with rigid surfaces and contacts are defined between the top of the blank and the punch, the top of the blank and the blank holder, and the bottom of the blank and the die. The friction coefficient between the blank and the other tools is assumed 0.1. The contact between components is established in a reasonably gentle manner to avoid large over-closures and rapid changes in contact pressure. This approach, although requires one more step, minimizes the convergence difficulties, and makes the solution more efficient.

For the materials aspects, most materials of engineering interest initially respond elastically. If the load exceeds some limit (the "yield load"), the deformation is no longer fully recoverable. However, a portion of the deformation will remain when the load is removed. Plasticity theories model the material's mechanical response as it undergoes such non-recoverable deformation in a ductile fashion. As a first approximation, the blanking process is simulated using two-dimensional plane-strain model. The specimen is modeled using isotropic material properties. The plastic material behavior is described by the Von Misses yield condition and isotropic hardening in which the strain-hardening behavior described using tabulated data (stress versus effective plastic strain). The classical metal plasticity model is used with isotropic hardening which is available in ABAQUS/Explicit. Stress-strain data representing the material hardening behavior are necessary to define the model and the mechanical characteristics of the material are obtained from tensile tests. A shear failure model offered in ABAQUS/Explicit is used to limit the subsequent load carrying capacity of an element (up to the point of removing the element) once a stress limit is reached.

Two separate tensile tests were performed to provide information on the properties of materials under uni-axial tensile stresses. The purpose of the first test is to get the stress-strain diagram while the purpose of the second test is to get the modulus of elasticity and Poisson's ratio. The results are presented in Table 1.

4.1. Model Verification

In order to assess the quality of the model, a comparison with experiments is made. A company that deals with dies and tools manufacturing and steel sheets forming, is selected for conducting the experiments. The blanking experiments were carried out using a blanking machine at a local industrial company.

Table 1. Material characteristics of Steel 12 and Stainless steel 480 obtained from the load-elongation diagrams.

Material	Yield stress [MPa]	Ultimate tensile stress [MPa]	Ductility as % elongation	strain-hardening exponent n	strength coefficient K [MPa]	Modulus of Elasticity [GPa}	Poisons ratio
Steel 12	201	296	37.6	0.2354573	524.448	201	0.31
Stainless steel	296.54	475	24.4	0.20651387	816.44	187	0.29

A die of a 20 mm in diameter and a punch of 19.9 mm in diameter, which gives a clearance of 10% for the 0.5 mm thick stainless steel specimen and 7% for the 0.7 mm thick steel specimens, were selected for conducting the experiments. The capability of controlling the blanking velocity is limited; as a result, one value is selected for the blanking velocity that is 0.1 m/s. The steps in executing the blanking process are shown in Figure 3.

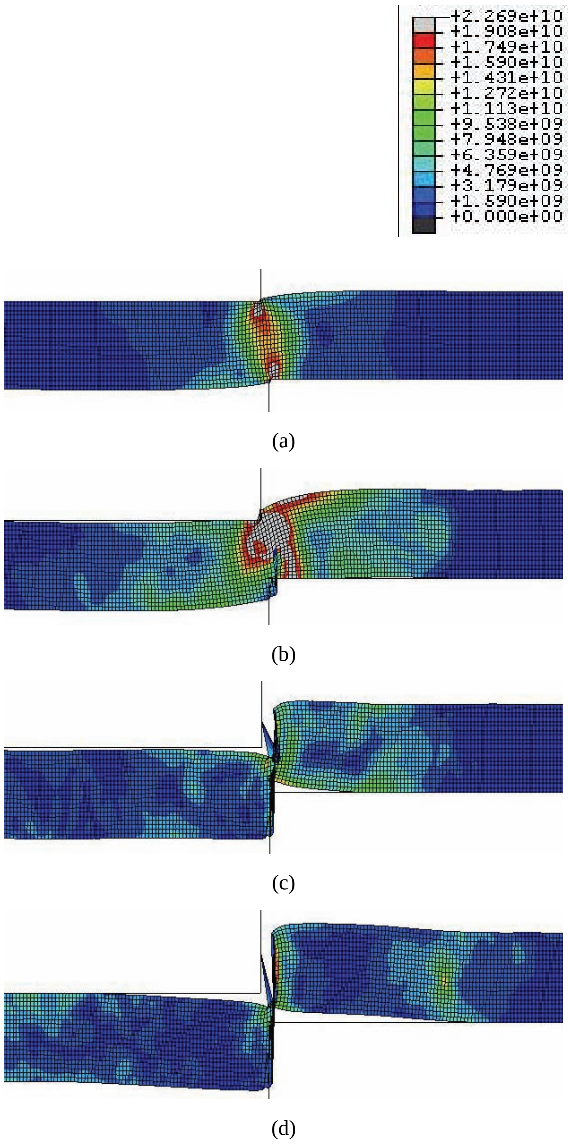

Figure 3. Crack propagation in the mesh for Steel 12

The FEA model was validated through the compression of the experimental and the simulated punch load-penetration curves and the experimental and the simulated burrs height that were developed off line. Figure 4 shows the experimental and the simulated punch load-penetration curves for stainless steel. The agreement between both curves is good with a percent error in blanking force of 7.6%. Figure 5 shows the burs height in the mesh for Steel 12 with 7 % clearance and 3000 N applied blank holder force. The burrs appear clearly and its height is 0.0811 mm. In the experiment, the average burrs height for five blanked specimens was 0.085 mm measured by a digital V-Caliper with ±0.005 accuracy, which seems to be in good agreement with the simulation results with an error of about 5%.

It was determined that the four inputs (factors) that are considered important to the blanking process are material type; clearance; sheet metal thickness and blank holder force. To ascertain the relative importance of each of these factors on burrs height, a set of experiments are conducted for different factors levels combinations. Table 2 represents these factors and their level values.

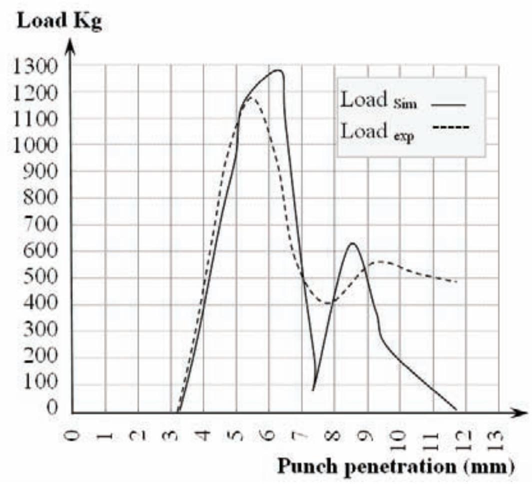

Figure 4. The experimental punch load-penetration curve and the ABAQUS result of the simulated punch load-penetration curve for stainless steel where Load $_{Simulation}$ = 12.75 kN, and Load $_{exp}$ = 1200 Kg * 9.81 N/m^2 = 11.772 kN.

The analysis is based on a full factorial experimental design. Running the full complement of all possible factor combinations means estimating all main and interaction effects. The specific statistical objectives of the experiment are to determine the important factors that affect burrs height of the blanked edge, the settings that minimize burrs height of the blanked edge, and a prediction equation that functionally relates burrs height to various factors. The FEM simulations were run with 80 different settings and their results are shown in Table 3. The response data is plotted in several ways to see if any trends or anomalies appear that would not be accounted for by the standard linear response models.

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Table 2. Blanking process factors and their corresponding level values.

Factor	Number of levels	Level Values				
		Level 1	Level 2	Level 3	Level 4	Level 5
Material type	2	Steel 12	Stainless steel			
Clearance	5	5	10	15	20	25
Thickness	4	0.5	0.6	0.7	0.8	
Blank holder force	2	0	3000			

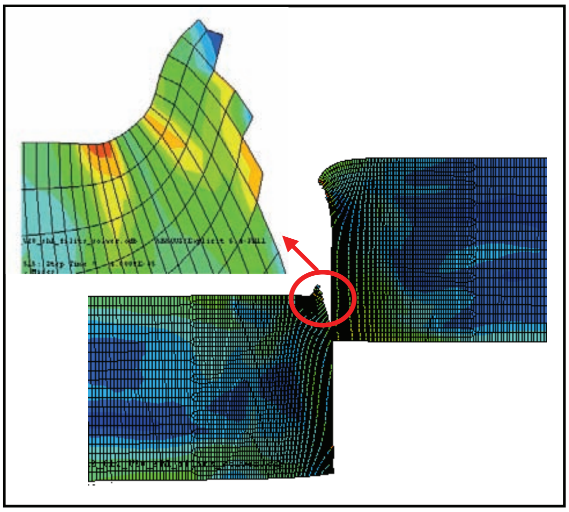


Figure 5. FEM result for Steel 12 with 7 % clearance and 3000 N blank holder force.

5. Blanking Process Modeling

The basic steps of the model building process are model selection, fitting, and validation. In the model selection step, plots of the data, process knowledge, and assumptions about the process are used to determine the form of the model to be fit to the data. Then, using the selected model and possible information about the data, an appropriate model-fitting method is used to estimate the unknown parameters. When the parameters are estimated, the model is then carefully assessed to see if the underlying assumptions of the analysis appear plausible. If the assumptions seem valid, the model can be used to estimate, predict, and optimize the burrs height value of the blanked product. If the model validation reveals problems with the current model, then the modeling process is repeated using information from the model validation step to select and/or fit an improved model.

With a full factorial experiment, a model containing a mean term, four main effect terms, six 2-factor interaction terms, 3-factor interaction term and a 4-factor interaction term (15 parameters) can be fitted. However, to eliminate the least impact factors, it is assumed that the three factor interaction terms and more are non-existent since it is very rare for such high-order interactions to be significant, and they are very difficult to interpret from an engineering viewpoint. Because of eliminating the high order interactions, a theoretical model with eleven unknown constants is obtained, and the analysis of the experimental data will clarify which of these are the significant main effects and interactions needed for a final model. The analysis of variance (ANOVA) is used to test the following hypotheses:

H_{o1}: There is no main effect for material type, clearance, thickness, and blank holder force

H_1: There is a main effect for material type, clearance, thickness, and blank holder force.

H_{o2}: There is no interaction effect among any of the material type, clearance, thickness, and blank holder force parameters.

H_2: There is an interaction effect among any of the material type, clearance, thickness, and blank holder force parameters.

The MINITAB-14© results for fitting the eleven-parameter model are displayed in Table 4. The table shows that both of the null hypotheses are rejected since many factor-mean effects and interactions are significant. This fit has a high R^2 and adjusted R^2, but the large number of high p-values (>0.05) makes it clear that the model has many unnecessary terms. Starting with these eleven terms, a stepwise regression option is used to eliminate unnecessary terms. By a combination of a backward elimination stepwise regression and the removal of remaining terms with a *p*-value higher than 0.05, a formula is achieved with an intercept and five significant effect terms where the thickness and all its interactions are removed from the model in addition to the material-blank holder force interaction. Equations (1) and (2) are the final equations resulting from Design Expert© for Steel 12 and Stainless Steel 480, respectively.

Steel 12: Burrs Height =

$$\begin{aligned}&0.05174\\&+2.8766X^{-3}*C\\&-3.3695X^{-6}*BHF\\&+1.0111X^{-6}*C*BHF\end{aligned} \qquad (1)$$

Stainless Steel 480: Burrs Height =

$$\begin{aligned}&0.05533\\&+1.7944X^{-3}*C\\&-3.3695X^{-6}*BHF\\&+1.011X^{-6}*C*BHF\end{aligned} \qquad (2)$$

Where: C: Clearance as a percent of sheet metal thickness, and BHF: Blank holder force measured in Newton.

The Design Expert© software is used for fitting the new model where only sixteen combinations are used. The obtained ANOVA results are shown in Table 4. At this stage, the model appears to account for most of the variability in the response, achieving an adjusted R^2 of 0.9914. All the remaining main effects with two 2-factor interactions are significant. Values of less than 0.05 indicate model terms are significant. In this case Material type, Clearance, Blank holder force, and the multiplication of the Material type by Clearance and the multiplication of the Clearance by Blank holder force are significant model terms.

Table 3. Design of experiment matrix with the corresponding burrs height

Material									
ST12					Stainless				
Exp #	Clearance (mm)	Thickness (mm)	BHF (N)	Height (mm)	Exp #	Clearance (mm)	Thickness (mm)	BHF (N)	Height (mm)
1	5	0.5	0	0.06795	41.	5	0.5	0	0.0633
2	5	0.5	3000	0.07075	42.	5	0.5	3000	0.07065
3	5	0.6	0	0.06794	43.	5	0.6	0	0.06332
4	5	0.6	3000	0.07076	44.	5	0.6	3000	0.07064
5	5	0.7	0	0.06746	45.	5	0.7	0	0.06319
6	5	0.7	3000	0.07026	46.	5	0.7	3000	0.07054
7	5	0.8	0	0.06656	47.	5	0.8	0	0.06304
8	5	0.8	3000	0.06936	48.	5	0.8	3000	0.07032
9	10	0.5	0	0.0843	49.	10	0.5	0	0.0733
10	10	0.5	3000	0.0913	50.	10	0.5	3000	0.09155
11	10	0.6	0	0.08426	51.	10	0.6	0	0.07328
12	10	0.6	3000	0.09128	52.	10	0.6	3000	0.09158
13	10	0.7	0	0.08328	53.	10	0.7	0	0.07299
14	10	0.7	3000	0.09028	54.	10	0.7	3000	0.09133
15	10	0.8	0	0.08168	55.	10	0.8	0	0.07256
16	10	0.8	3000	0.08864	56.	10	0.8	3000	0.09088
17	15	0.5	0	0.0996	57.	15	0.5	0	0.08485
18	15	0.5	3000	0.1116	58.	15	0.5	3000	0.11605
19	15	0.6	0	0.09962	59.	15	0.6	0	0.08486
20	15	0.6	3000	0.11156	60.	15	0.6	3000	0.11606
21	15	0.7	0	0.09833	61.	15	0.7	0	0.08447
22	15	0.7	3000	0.1103	62.	15	0.7	3000	0.11569
23	15	0.8	0	0.09616	63.	15	0.8	0	0.08384
24	15	0.8	3000	0.1202	64.	15	0.8	3000	0.11504
25	20	0.5	0	0.1128	65.	20	0.5	0	0.09515
26	20	0.5	3000	0.1651	66.	20	0.5	3000	0.14075
27	20	0.6	0	0.11282	67.	20	0.6	0	0.09512
28	20	0.6	3000	0.16508	68.	20	0.6	3000	0.14072
29	20	0.7	0	0.11135	69.	20	0.7	0	0.09462
30	20	0.7	3000	0.16364	70.	20	0.7	3000	0.14026
31	20	0.8	0	0.10888	71.	20	0.8	0	0.09384
32	20	0.8	3000	0.1612	72.	20	0.8	3000	0.13952
33	25	0.5	0	0.1235	73.	25	0.5	0	0.10315
34	25	0.5	3000	0.1937	74.	25	0.5	3000	0.1644
35	25	0.6	0	0.1235	75.	25	0.6	0	0.10316
36	25	0.6	3000	0.1937	76.	25	0.6	3000	0.16442
37	25	0.7	0	0.12192	77.	25	0.7	0	0.1026
38	25	0.7	3000	0.19213	78.	25	0.7	3000	0.16385
39	25	0.8	0	0.11936	79.	25	0.8	0	0.10168
40	25	0.8	3000	0.18952	80.	25	0.8	3000	0.16296

Table 4. The analysis of variance (ANOVA) for the modified linear model, height versus material type, clearance, and blank holder force.

Response: Heihgt ANOVA for Selected Factorial Model Analysis of variance table [Partial sum of squares]					
Source	**DF**	**Sum seq.**	**Mean Sq.**	**F**	**Prob > F**
Model	**5**	0.03400000	6.708E-003	939.85	< 0.0001 sign.
Material	**1**	6.401E-004	6.401E-004	89.68	< 0.0001
Clearance	**4**	0.02400000	0.02400000	3326.41	< 0.0001
Blank holder force	**1**	5.010E-003	5.010E-003	701.90	< 0.0001
Material * Clearance	**4**	4.685E-004	4.685E-004	65.64	< 0.0001
Clearance * Blank holder force	**4**	3.680E-003	3.680E-003	515.62	< 0.0001
Residual	**10**	7.137E-005	7.137E-006		
Cor Total	**15**	0.03400000			
Std. Dev.	2.672E-003		R-Squared	0.9979	
Mean	0.11		Adj R-Squared	0.9968	
C.V.	2.51		Pred R-Squared	0.9946	
PRESS	1.827E-004		Adeq Precision	6.4550	

Figures 6 and 7 show the mean and the interaction effects for burr heights. The slope of the line is an indication of the variable effect degree on the burr height - the higher the slope the higher the interaction effect. It is clear that the material type has an effect on burrs height and, in general, the Steel 12 gives a higher burr height than Stainless Steel 480 in general. The clearance effect on the burr height is large - the higher the clearance the higher the burrs height for both materials. It is also clear that as the clearance increases more than 15%; its effect starts to be higher for Steel 12 than for Stainless Steel. The thickness effect is insignificant since a horizontal line appears. However, the blank holder force has a clear effect, the lower the blank holder force the lower the burr height.

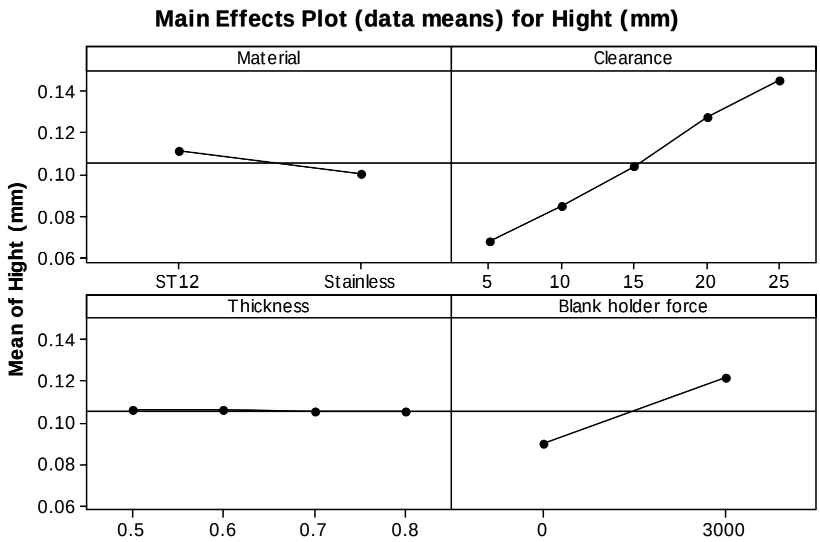


Figure 6. Mean effect plot for bur height

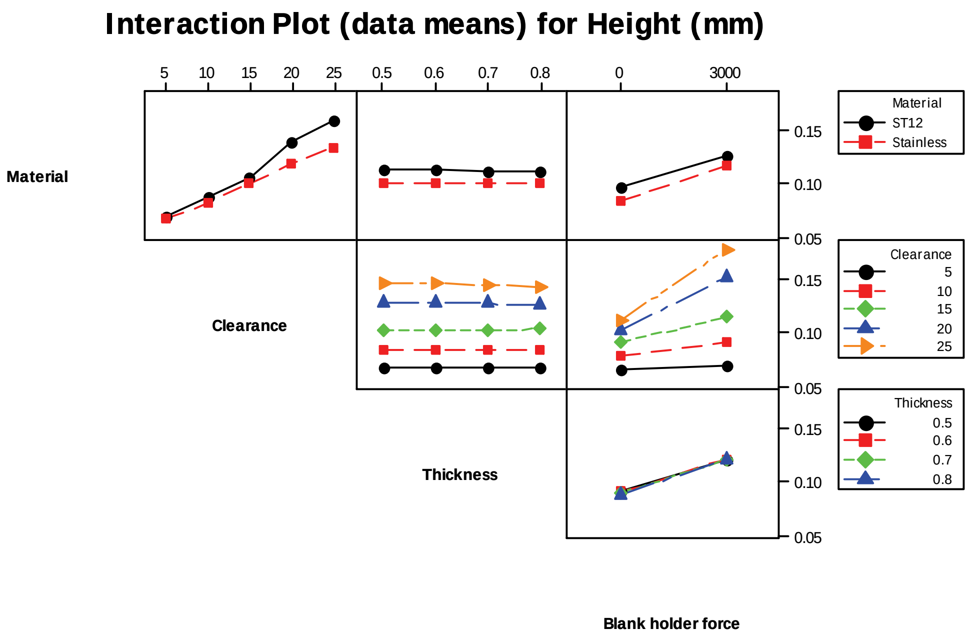
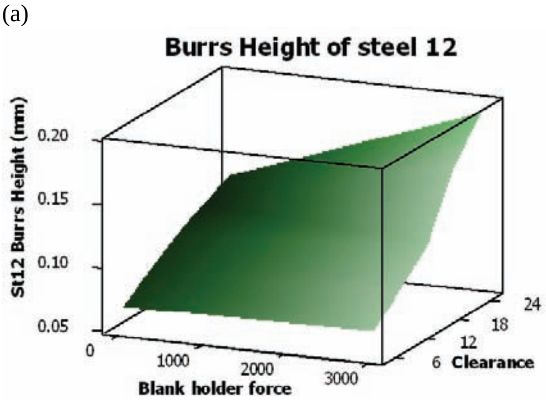


Figure 7. Interaction plot for bur height

The developed burrs height model is used for the prediction and optimization purposes. While prediction is used to determine the value of a new observation of the burrs height for a particular combination of the values of the blanking process significant parameters, optimization, on the other hand, is performed to determine the values of the blanking process inputs that should be used to obtain the desired burrs height output. Optimization is used to minimize the burrs height of the process and to increase the opportunity of using the same blanking setup for both materials (Steel 12 and Stainless Steel 480). Figure 8 shows the graphical representation of equations (1) and (2) which relate the burrs height to clearance and blank holder force, respectively. It is clear from Figure 8 (a and b) that the height increases with the increase in clearance and the blank holder force. The effect of clearance is higher than the effect of blank holder force; this is clear from the surfaces slope. As clearance increases, the effect of blank holder force on increasing the burrs height also increases.

In order to minimize burrs height, it is obvious that the clearance must be small. Since the blank holder force effect is not very significant at small clearance values, the small blank holder force is preferable. Figure 9 shows the burrs height as a function of clearance for both materials when no blank holder force is applied. It is clear that the optimum clearance that gives minimum burrs height for both materials simultaneously, in this case, is about 3 % that is the intended intersection point of the two lines. These readings can be seen in an easier and more obvious way through the contour plot shown in Figure 10. This plot is used to determine the settings that minimize the burrs height value for both materials. It shows that the contour curves are linear and start to have some curvature at the combination of high clearance and high blank holder force, which in turn imply that the interaction term is more significant at this condition. To get small burrs height, it is better to have a small clearance. For approximately the same burrs height, a small blank holder force makes the system more robust to the changes in clearance, where a clearance range up to about 12% exists, whereas, a limited range up to about 7 % exists at high blank holder force.

(a)



(b)

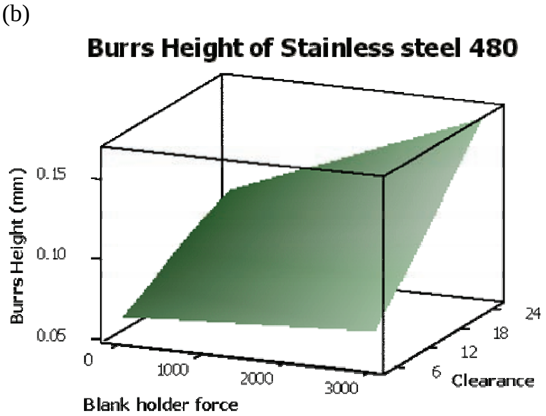


Figure 8. Surface plot burr height versus clearance and blank holder force a) Steel 12 and b) Stainless Steel 480

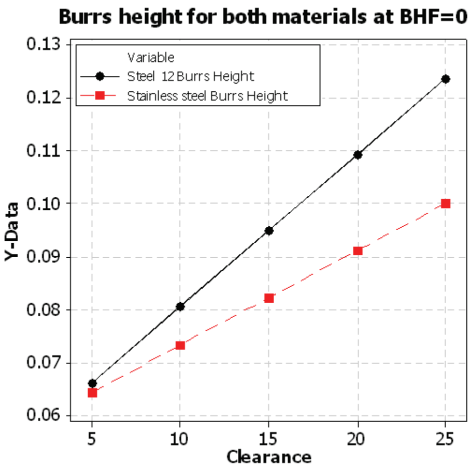


Figure 9. A plot for the burrs height of Steel 12 and Stainless steel 480 at no blank holder force and different clearances.

5.1. Model Validation

In order to validate the results of the model, a comparison was made with experiments carried out in actual work environment in the selected company. Since the thickness parameter is found to be insignificant, the experiments are conducted for only one thickness value using the 20-mm diameter die with 19.90 mm diameter punch for Steel 12 specimen, which has the thickness of 0.7 mm. Two cases are studied with and without blank holder force of 3000 N. The burrs height is measured for five samples then averaged. The same procedure is repeated for the Stainless Steel 480, with a thickness of 0.5 mm, and a clearance of 10% is achieved on the previous setup. Table 5 compares the burr height results from the simulation, experiments, and the model for Steel 12 and Stainless Steel 480 at zero and 3000 N blank holder force, respectively.

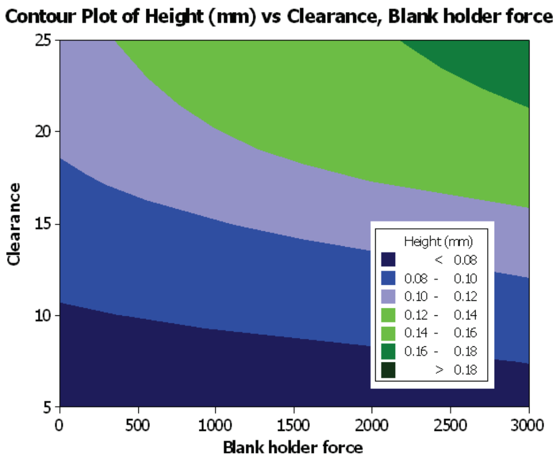


Figure 10. Contour plot of height versus clearance and blank holder force for both materials.

Table 5 shows the ability of the fitted model to predict the real burrs height with an error less than 10%. On the other hand, the experimental data validate the result of the FEM analysis, which stated that burrs height increases with increasing the blank holder force. If the objective is to find a model that is valid even when the sheet thickness is changed, then it is preferable to do not interact between thickness and the other factors. The main effect of the thickness is not important by itself, what is important is to identify the optimal clearance setting and the tool wear states that are not too detrimental to the process, regardless of the sheet thickness [15]. It is found that the thickness is not a significant factor in the developed model, which makes the experimental results robust for different sheet metal thickness.

6. Conclusions and Future Work

The developed experimental investigation of the sheet metal blanking process makes it possible to study the effects of process parameters such as the material type, the punch-die clearance, the thickness of the sheet and the blank holder force and their interactions on the geometry of the sheared edge especially the burrs height. The finite element and design of experiments methods are used in order to obtain a better understanding of the blanking manufacturing response. The process signatures indicate that the material types as well as the geometric characteristics of the tools and their configuration influence the burrs height of the sheared edge.

Table 5. Simulation, experimental and model burrs height for Steel 12 and stainless steel 480 at zero and 3000 N blank holder force.

Material Type	Simulation burrs height (mm)		Experimental burrs height (mm)		Model burrs height (mm)	
	BHF= 0	BHF= 3000 N	BHF= 0	BHF= 3000 N	BHF= 0	BHF= 3000 N
Steel 12	0.0721	0.0811	0.079	0.085	0.07188	0.0830
Stainless steel 480	0.0733	0.09155	0.076	0.095	0.07327	0.0935

This investigation shows that, in order to minimize the burrs height, the clearance should be set at about 5 % with almost no blank holder force. When blank holder force is set to zero, the process is slightly more robust to clearance changes than when a high blank holder force is used. It is not recommended to use a zero blank holder force; rather a small value in the order of about 2% of the blanking force can prevent the remaining skeleton from moving out of plane. The presented investigation of the blanking process makes it possible to predict optimum process parameters. It is possible to reduce the lead-time by using the Finite Element Analysis in conjunction with Design of Experiment technique in the design process, where computer simulations can replace many time consuming experiments. This will make the design process faster and more reliable. From another point of view, it is possible to build quality into products from the early design phases by predicting the shape of the cut edge and the burs height of a blanked product. This will improve the final products quality and reduce burrs removal rework in addition to increasing the manufacturing process flexibility and reducing its cost through building one blanking setup for different materials. In conclusion, it can be stated that the Finite Element Method coupled with Design of Experiments techniques can be used in order to contribute towards the optimization of sheet metal blanking processes. Further investigation is needed to explore more parameters and operating conditions to develop a general model for more material types. It is recommended to experimentally perform the blanking process that combines the optimal set of parameters and monitor its output quality.

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