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Improvements in Machinability, Microhardness, and Impact Toughness of AISI O1 and AISI D2 Alloy Steels by Controlling the Grain Size During Heat Treatment

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Abstract

This research aims to study the effects of grain size of heat-treated alloy steels, AISI D2 and AISI O1, on their machinability, impact toughness, and hardness. The hardening temperatures for AISI D2 steel ranged from 950 to 1070 °C, with increments of 40 °C. Meanwhile, the hardening temperatures for AISI O1 steel ranged from 780 to 870 °C, with increments of 30 °C. For AISI D2 and O1 specimens, the tempering temperatures were set at 550 °C and 250 °C, respectively. The impact toughness, average surface roughness (Ra) after turning process, and hardness test were conducted. The main findings are; very smooth surface roughness, for AISI O1 specimens, Ra = 0.115 µm, at a grain size of 46 µm, depth of cut of 0.15 mm, cutting speed of 120 m/min, and feeding of 0.05 mm/rev. For AISI D2, the Ra value is 0.134 µm, at grain size =14.6 µm, depth of cut of 0.2 mm, feed rate 0.05 mm/rev, and cutting speed of 120 m/min for AISI O1 steel, moreover, a pronounced enhancement in hardness and impact energy for both alloy steels were achieved.

Keywords: Machinability; AISI D2; AISI O1; Heat treatment; Grain size.

1. Introduction

The real-life applications of any material strongly depend on its properties such as strength, hardness, ductility, etc. Also, some manufacturing processes considerably affect the surface texture and metallurgical structure of component material, thus, they affect its mechanical properties [1]. These properties of steels can be highly controlled by properly designed heat treatment [2]. The material's grain size is a crucial factor that affects most of the mechanical properties, as defined by the Hall-Petch principle [3]. For instance, by decreasing the grain size of the steels, the tensile and fatigue strengths will increase, as well as, the hardness and the impact toughness. Therefore, heat treatments are widely utilized as grain refinement methods [2, 4, 5]. Compared with other grain refinement methods, structural and phase changes can be achieved by the heat treatment method [4, 6]. For instance, a study by Sun, Jiang [5] investigated the grain size effect on the mechanical characteristics of 0.61wt%C steel. The findings of the study indicate that the grain refining process induces a transformation in the martensite substructure, shifting it from a twin-dominated state to a dislocation-dominated state. This transition enhances significantly the tensile strength. In that study, a proposed model explained the results based on the relation between dislocation slip and twin stresses and the average grain size. The critical grain size is determined by the point at which the magnitudes of twinning and dislocation stresses are equivalent. However, When the grain size is smaller than the critical size, it was shown that the stress required for twin formation is larger compared to dislocation gliding. These efforts of the heat treatment methods gained continuous attention from the researchers to enhance such properties. For the purpose of enhancing the mechanical properties of steel alloys, massive efforts have been made using several of heat treatments processes. For instance, Biswas, Kundu [7] studied the effects of annealing, normalizing, and quenching on the microstructure and hardness of EN 8 steel. The experimental findings indicated that the process of tempering following the normalisation of EN 8 steel resulted in elevated hardness measurements, accompanied by a refined grain structure. In another study, Kreitcberg, Brailovski [8] investigated the impact of heat treatment and pressing under hot isostatic on the microstructure and mechanical behaviours of IN625 alloy fabricated using laser powder bed fusion (L-PBF) technique. The study revealed that the tensile strength and failure strain of the IN625 alloy treated with L-PBF were comparable to, or somewhat higher than, those of the annealed wrought alloy. There have been documented instances of comparable outcomes

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observed in relation to AISI 5160 steel [9], low-alloy steel-boron [10] and hot work die steel of nitrogen-alloyed high-Mn austenitic [11]. Effects of heat treatment methods were explored on other properties such as tribological properties, and high positive impact were reported. For example, Bourithis, Papadimitriou [12] provided a comparison study of wear behaviour of commercial cold work tool steels; AISI O1 and AISI D2 that have the same level of hardness. It was observed that the microstructure's of steel showed a significant effect in influencing the wear behaviours; at low sliding speeds, O1 steel demonstrated a wear resistance that was twelve times better, as compared with D2 steel. After heat treatment process, subsequent of machining processes such as cutting, milling, turning...etc. is required in order to achieve the proper design of the mechanical components. Therefore, machinability plays a significant role in the manufacturing processes. Economically, in USA, the machining cost of steel is estimated by $125 billion annually [13]. The machinability of a material is primarily influenced by its chemical composition, mechanical properties like hardness, stiffness, and yield strength, and metallurgical features such as microstructure, grain size, and the presence of inclusions. Machinability not only depends on the work material properties, but also depends on other parameters such as cutting conditions and coolant properties [14]. Parameter optimization techniques are critical to improve the efficiency and effectiveness of machining processes. In recent years, several studies have been conducted to examine and improve these techniques, [15-20]. Several researches have been undertaken in the literature to examine the effect of different heat treatment approaches on the machinability of steels. For instance, Demir, Gündüz [2] studied the effects of quenching and tempering heat treatments on both the machinability and microstructure of AISI H13 tool steel. It was found that the heat treatment strongly affects the surface roughness and thus its machinability. For instance, compared to the untreated samples, the water-quenched samples recorded the lowest values of surface roughness under all cutting conditions. However, quenched and single-tempered samples showed lower values compared to untreated samples. These findings were explained based on the different effects of both the quenching and tempering process on the mechanical properties. In contrast with the quenching process, tempering process is usually accompanied by a low hardness which motivates the easy disposal of the chips during the machinability process. Literature investigations showed a considerable influence of heat treatment processes on the mechanical behaviours as well as the microstructure of steels, and on other properties such as wear behaviour. However, it was observed that there is a need to investigate the effect of various heat treatment processes on the machinability of steels.

The main aim of this study is to determine how grain size affects the machinability of AISI O1 and D2 steels. The work was motivated by the need to maximize the ideal machining conditions because the austenitic phase happened throughout a range of temperatures. Heat treatment regimens for hardening and tempering allow for grain size manipulation. The study also investigates how the steels' hardness and impact toughness are affected by the size of their grains. The study intends to shed light on how grain size affects the machinability and mechanical qualities of AISI D2 and AISI O1 steels by examining these variables.

2. Materials and Methods

In this study, the steels AISI D_2 and AISI O_1 were received as hot forged bars with an outside diameter equal to 25.4 mm. Table 1 presents a summary of the chemical compositions of D_2 and O_1 alloy steels.

2.1. Preparation of specimens

The samples were prepared by sawing process as following: Diameter = 25.4 mm and length =120 mm. A single point carbide cutting tool was used to turning the specimens by using MDT 225-65-CNC lathe machine in accordance with the standard cutting conditions presented in TABLE 2. Hard turning experiments were performed at a constant-cutting speed of 120 m/min, four different feed rates (i.e., 0.05, 0.1, 0.15 and 0.20 mm/rev), and four different cutting depths (i.e., 0.1, 0.15, 0.2 and 0.0.25 mm) for AISI D2 alloy steel. For AISI O1 alloy steel, hard turning experiments were performed at a constant-cutting speed of 170 m/min, four various feed rates (i.e., 0.05, 0.1, 0.15, and 0.20 mm/rev) and four different cutting depths (i.e., 0.1, 0.15, 0.2 and 0.25 mm).

2.2. . Heat treatments of AISI D_2 and AISI O_1 alloy steels

For AISI D_2, the hardening process was as follows: by pre-heating it to 700 °C then raising the temperature to 950 °C and changing it to 1070 °C by a step of 40 °C for 40 min, it quenched in oil at 50 °C as shown in Figure 1(a). While the heat treatment process for AISI O1 started by pre-heating it to 650 °C, then raise the temperature to 780 °C and change it to 870 by a step of 30 °C, finally it quenched in oil at 50 °C as shown in Figure1(b).

TABLE 1. Chemical compositions of AISI D_2 and AISI O_1 alloy steels

Element wt.%	C	V	Si	Mn	Cr	Mo	W	Fe
AISI D_2	1.55	0.8	0.3	0.4	11.8	0.8	-	Bal.
AISI O_1	0.95	0.1	-	1.1	0.6	-	0.6	Bal.

TABLE 2. Standard cutting conditions for the AISI D_2 and AISI O_1 alloy steels [21]

Type of steel	Cutting Conditions			
	Vc (m/min)	f (mm/rev)	Depth of cut (mm)	Type of tool
AISI D_2	120	0.15	0.15	K15c.c.
AISI O_1	170	0.15	0.15	P10c.c.

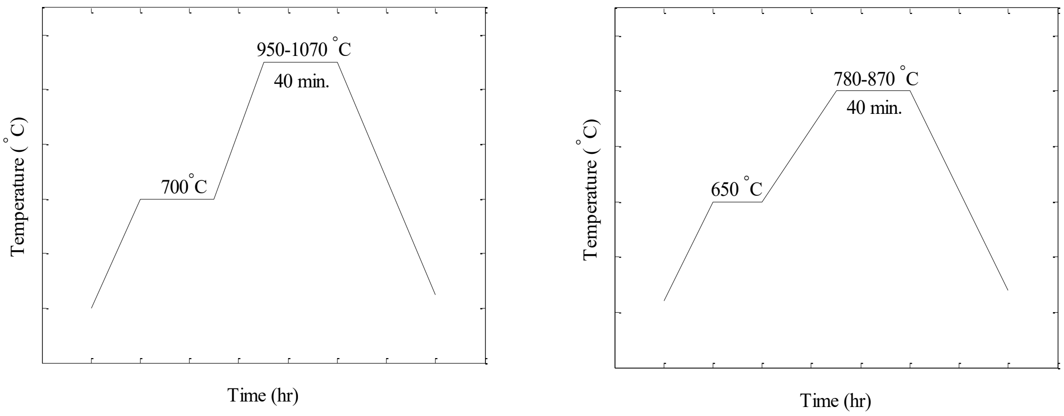


Figure 1. Hardening cycles for; a) AISI D_2 and b) AISI O_1

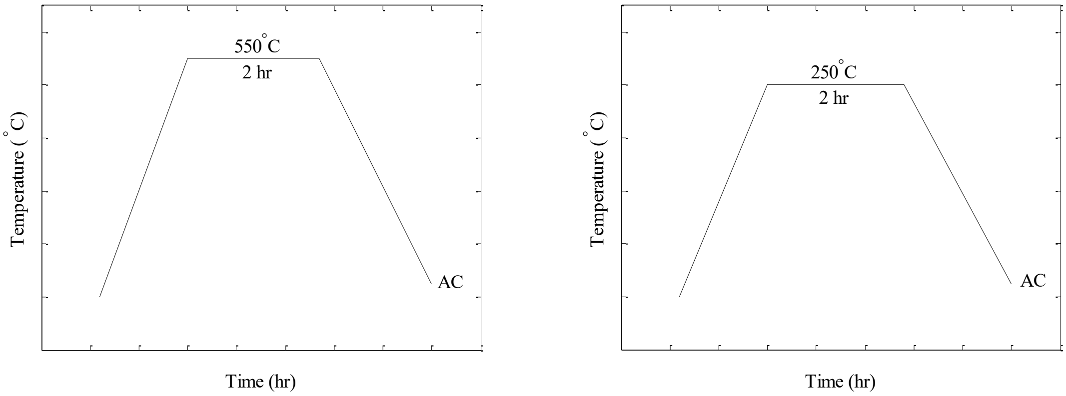


Figure 2. Tempering cycles for; a) AISI D_2 and b) AISI O_1 alloy steel

The tempering process for AISI D2 was conducted by raising the temperature to 550 °C for 2 hr, then cooling under ambient temperature as demonstrated in Figure 2(a). The tempering process for AISI O1 was conducted by raising the temperature to 250 °C for 2 hr, then cooling under ambient temperature as shown in Figure 2(b).

2.3. Microstructure examination

The examination of the samples' microstructures was conducted using an optical Microscope (NIKON108) at a magnification of X200. First of all, the samples were cut on a form of cylindrical shape. The flat surfaces of samples were initially grinded using different grits of sandpaper ranging from 80 up to 1200. Secondly, Furthermore, the surfaces underwent polishing utilizing a rotary polishing machine while utilizing 7 µm diamond paste till a reflective surface like a mirror was attained. Subsequently, the polished surfaces underwent etching using NITAL (97%CH_3CH_2OH, 3%HNO_3), an etching solution, for a duration ranging from 15 to 60 seconds. For determining the size of the grains, the average grain size was obtained using the linear intercept method.

2.4. Roughness test

Nowadays, the word surface roughness is increasingly being replaced by the Ra parameter when studying the processing of novel materials or when managing intricate machine parts, [22]. The measurement of average surface roughness (Ra) was conducted following each machining operation. The SURF-CORDER roughness tester was utilised, employing a cut-off distance of 0.8 mm and adhering to the ISO 13565 (Rk) standard. The appendix includes Figure A, which displays a representative example of surface texture used for Ra measurement. Measurements were conducted at three distinct places, followed by the calculation of the average value (Ra).

2.5. Hardness test

For AISI D2 and AISI O1 alloy steel workpieces, the hardness was measured using a microhardness tester type: Falcon 400 micro-Vickers tester at 1000 gf, according to ASTM E140, measurements were conducted at five different locations, subsequently resulting in the calculation of the mean hardness. Brostow al. et. reported that vickers hardness is classified as a mechanical property, but it is also a surface property, [23].

2.6. Impact test

Charpy impact tester of 300 J capacity is used to investigate the impact toughness of both alloy steels, ASTM 23 standard is used (55*10*10 mm), and three samples for each condition as shown in Figure 3 are tested from which the average was determined.

Figure 3. Charpy impact specimen (ASTM 23)

3. Results and Discussion

3.1. Influence of hardening temperature on the general microstructure

This section presents the findings of a study that investigated the impact of varying hardening temperatures on grain size. Figure 4 depicts the microstructural characteristics observed in quenched and tempered steels, considering the temperature range encompassing the minimum and maximum values of the steel samples as indicated in Figure 1 and Figure 2. The literature has documented comparable microstructures in both tool steels as reported, for instance, by Roberts, Kennedy, and Krauss [24]. The observed trend indicates that the grain sizes of both AISI D2 and AISI O1 steels exhibited a reduction as the hardening temperature was elevated. As an example, the grain size of AISI D2 steel underwent a progressive reduction from 22.7 µm to 15.8 µm with a stepwise rise in the hardening temperature by 50 °C. Conversely, after increasing the temperature by 30 °C from 780 to 870 °C, the AISI O1 steel's grain size decreased from 56.3 µm to 32.6 µm. Also, it can be noticed from Figure 4 (c, d) that LPC (large primary carbides) and LSC (large secondary carbides) nearly unchanged compared to SSC (small secondary carbides) that refined greatly. The calculated average grain sizes for AISI D2 and AISI O1 steels in the examined temperature ranges are depicted in Figure 5. The histograms show a distinctive relationship between the hardening temperature and grain size, with a drop in particle size occurring with an increase in hardening temperature. The relationship under consideration pertains to the critical temperature of steels, sometimes referred to as the austenitizing temperature.

3.2. Influence of heat treatment temperature on the grain size

The size of a metal grain affects its mechanical qualities; metals with finer grains often have better mechanical properties than those with bigger grains. This is mainly because closer-spaced atoms have a larger "slip interface" in the lattice structure, which improves deformation resistance against outside forces. Larger grain metals, on the other hand, are typically easier to work with and can harden more readily when heated. Figure 5a. shows the effect of quenching temperature on the grain size of AISI D2, it is obvious that as the quenching increases the average grain size increases, and the maximum increase in grain size is 30.4 % which is achieved at 1000 °C, where Figure 5b, shows the influence of quenching temperature on the grain size of AISI O1, it obvious that as the quenching increases the average grain size increases, and the maximum increase in grain size is 42.1 % which is achieved at 870 °C.

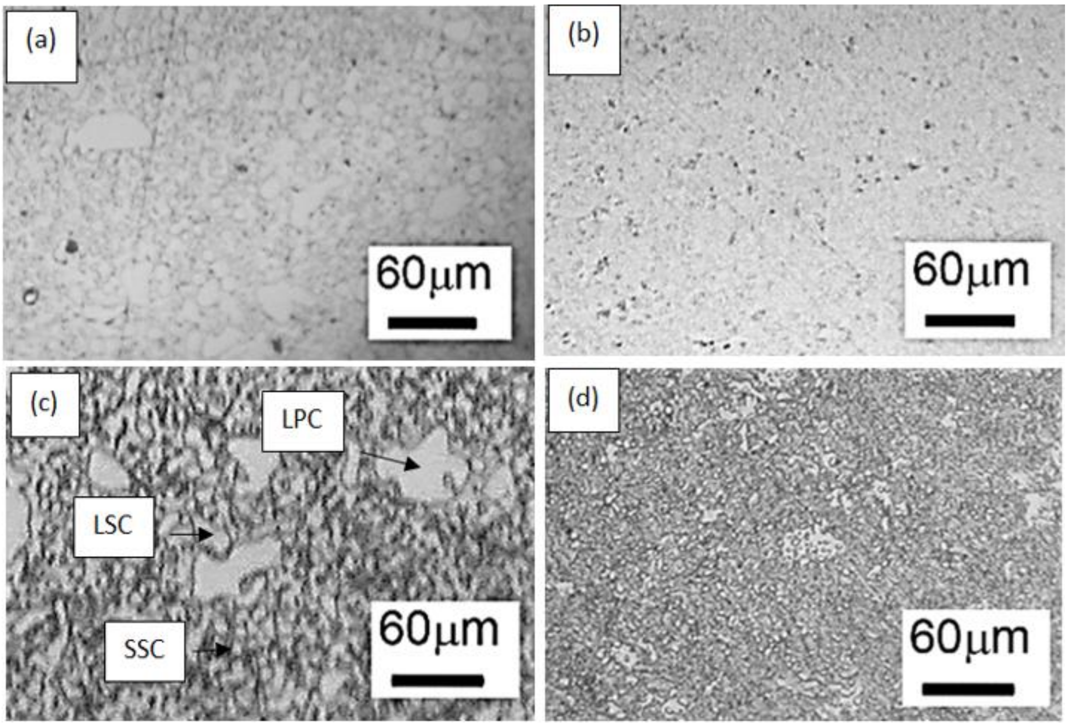


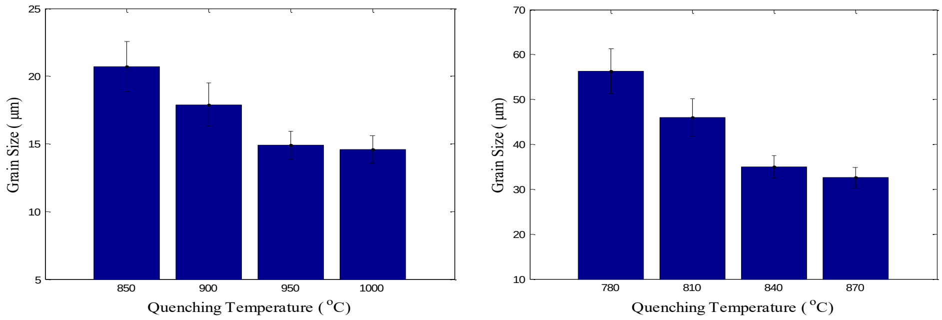
Figure 4. Optical micrographs in case of both heat-treated and tempered steels. (a) AISI D2 steel treated at 850 ºC, (b) AISI D2 steel treated at 1000 °C, (c) AISI O1 steel treated at 780 ºC and (d) AISI O1 steel treated at 870 °C. Where SSC: small secondary carbides, LPC: large primary carbides, LSC: large secondary carbides. [25]

3.3. Influence of average grain size on the microhardness

The microhardness of AISI D2 and AISI O1 steels is examined in Figure 6(a) in relation to variations in grain size. The main relationship between hardness and grain size is a direct relation. This means that the highest hardness can be achieved from small grain size. Also, the increase in quenching temperature will increase hardness. Additionally, the rise in hardness might be attributed to the creation of the martensite structure, which is known for its high level of hardness. The entire martensitic transition is well-documented in the finer structure. Both AISI D2 and AISI O1 tool steels consist of additional alloying elements, including chromium (Cr), manganese (Mn), and vanadium (V), as indicated in Table 1. These components are recognised as precipitate-forming elements [26]. Hence, it is possible for a secondary hardening phenomenon to arise because of the segregation of precipitates formed by alloying elements. The observed phenomena exhibits a positive correlation between the microhardness value and the hardening temperature, while displaying an inverse correlation with the grain size [27]. To clarify, the microhardness value that exhibited the greatest magnitude was observed in the context of small grain structure, which was achieved with the application of the maximum hardening temperature. This finding results in high wear resistance and enhancement of its fatigue life. Varaprasad al. et. in turning process examined the effects of the cutting speed, feed rate, and depth of cut on the surface roughness. A mixed ceramic tool was used to process AISI D3 steel that had been hardened to 62 HRC, [28].

3.4. Influence of average grain size on the impact energy

It is obvious from Figure 7(a) that the impact energy of AISI D_2 steel is decreased as the grain size increases, where the maximum is 20 J that attained at 20.7 µm. Regarding AISI O_1 steel we have the same trend of toughness but with higher impact energy nearly duplicated, and this is consistent with Algarni [29]. This finding makes AISI O_1 steel used for applications that need both high hardness and high toughness. The AISI D_2 steel has favourable characteristics for applications requiring high wear resistance. Additionally, the utilisation of steel slag in the formation of concrete holds potential as a promising development within the construction sector [30].



(a) (b)

Figure 5. Effect of quenching temperature on the average grain size of (a) AISI D2 and (b) AISI O1.

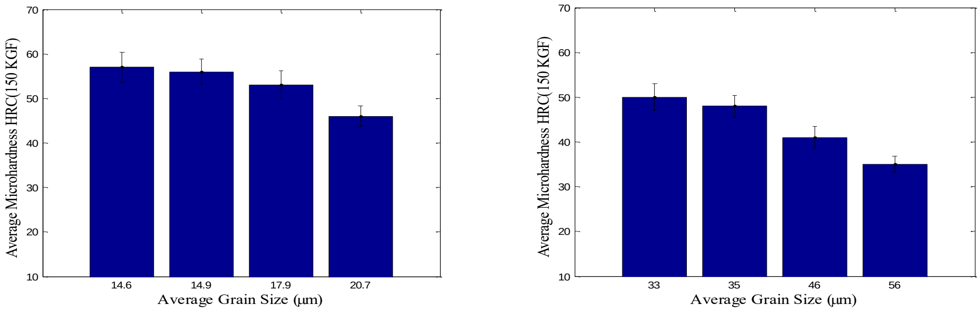


Figure 6. Effect of grain size on the microhardness numbers of (a) AISI D2 steel and (b) AISI O_1 steel.

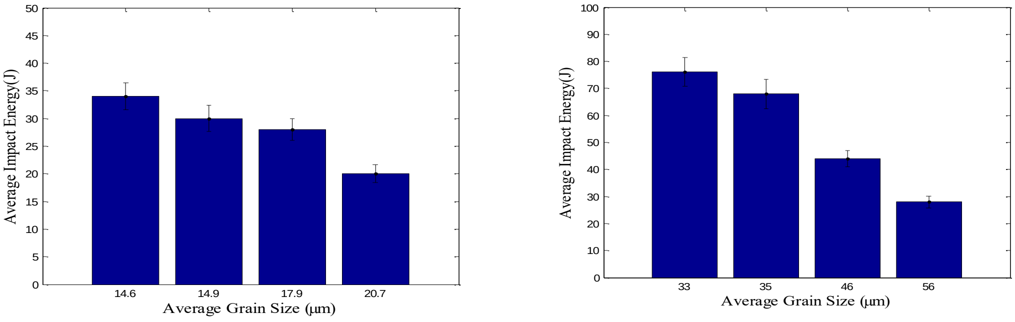


Figure 7. Impact of grain size on the impact energy of (a) AISI D_2 steel and (b) AISI O_1 steel

3.5. Influence of the average grain size on the surface quality at a different depth of cut

An important consideration for determining a metal's machinability is surface polish. Because it would cost more to achieve a fine surface finish after machining, a poor surface finish is indicative of inferior machinability. It has been noted that regulating grain size might result in a more affordable surface finish. It is well known that machinability can be evaluated by several methods such as the materials removal rate MRR and the wear rate of the cutting tool. The surface morphology produced at given cutting speeds feeds, and depths of cut are other measures of machinability.

Surface roughness (Ra) is used in this investigation. The impact of cut depth on (Ra) at feed rate of (0.05 mm/rev) and cutting speed of (170 m/min) for AISI O1 is shown in Figure 8. The surface quality (Ra) of the AISI O1 machined surface is directly affected by increasing the depth of cut. The best values of Ra (0.115 µm) were achieved at depth of cut equal to 0.14 mm, and this finding is consistent with the previous studies [31, 32]. Furthermore, the best finding was achieved at 810 °C and 46 µm grain size. This finding is so important in the manufacturing of molds and mechanical parts in which there is no need for the finishing process, however, it will result in a reduction of production cost. Figure 9 describes the impact of cut depth on surface roughness (Ra) for AISI D_2 at feed rates of 0.05 mm/rev and cutting speeds of 120 m/min. The surface quality (Ra) of the D_2 machined surface is directly affected by increasing the depth of cut. The best value of Ra (0.134 µm) was achieved at a cut-depth equal to 0.2 mm, this finding is so important because based on previous studies, it has been reported that the machinability of AISI D_2 is less than AISI O_1 [30, 31]. It is worth noting that no direct relation between the grain size and the Ra values as shown in Figure 8 the best surface roughness occurred at 46 µm grain size.

3.6. Influence of average grain size on the surface quality at different feed rates

For AISI O_1 heat-treated alloy steel, various feed rates (0.05-0.2 mm/rev) were applied. It is obvious from Figure 10 that the surface quality of the AISI O_1 machined surface is directly affected by increasing the feed rate. The best value of Ra is 0.17 µm which is obtained at 0.01 mm/rev feed rate and 46 µm average grain size. By this finding, a high reduction in Ra, it is established that during the production of the mechanical part there is no need for finishing operations i.e. grinding process, which will result in the reduction of production cost. Figure 11 demonstrates the impact of feed rates on Ra at 0.1 mm depth of cut for and 120 m/min cutting speed for AISI D_2. The surface quality of the AISI D_2 machined surface is directly affected by increasing the feed rate. The best value of Ra is 0.169 µm that is obtained at 0.08 mm/rev feed rate and 17.9 µm average grain size. This finding is consistent with the previous study of Jeyapandiarajan and Anthony [32] which revealed that the feed rate is the primary input parameter that significantly impacts the finish turning process of hardened steel.

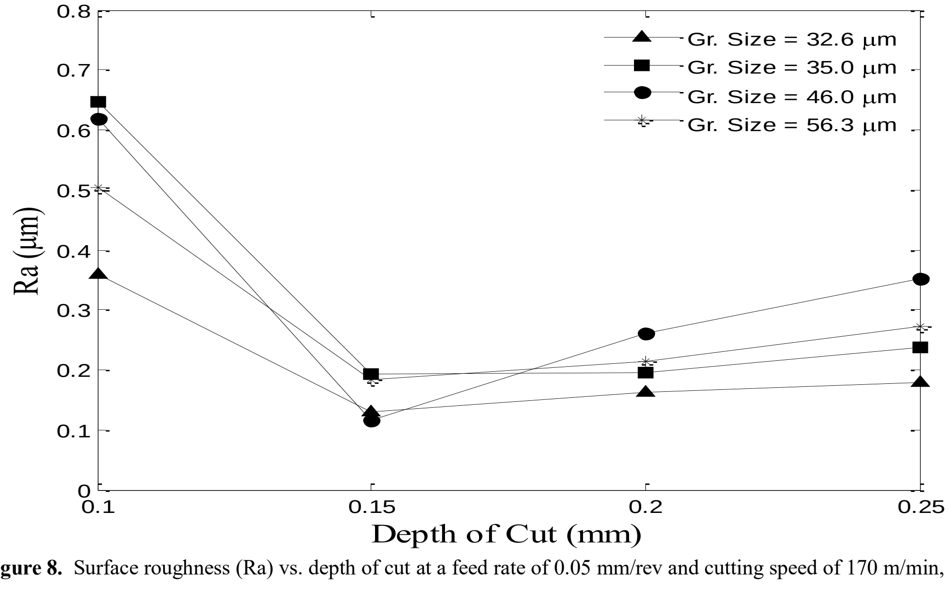


Figure 8. Surface roughness (Ra) vs. depth of cut at a feed rate of 0.05 mm/rev and cutting speed of 170 m/min, for AISI O_1

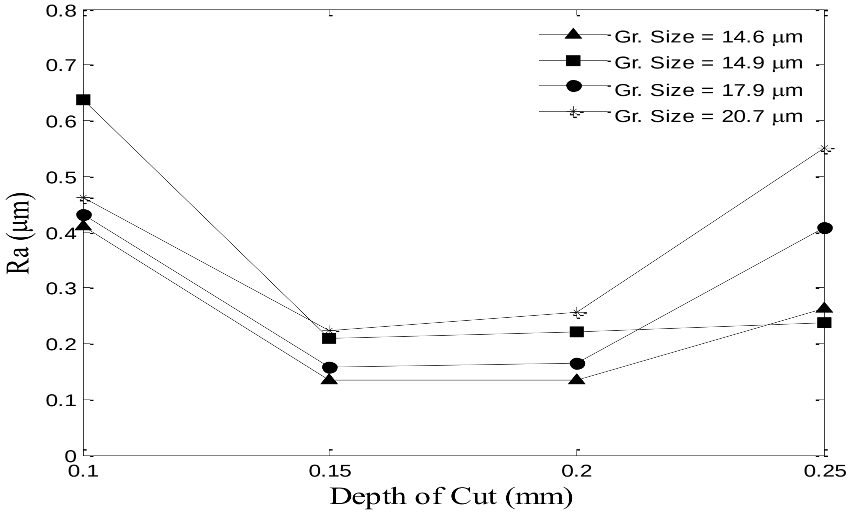


Figure 9. Surface roughness (Ra) vs. depth of cut at a feed rate of 0.05 mm/rev and cutting speed of 120 m/min, for AISI D_2

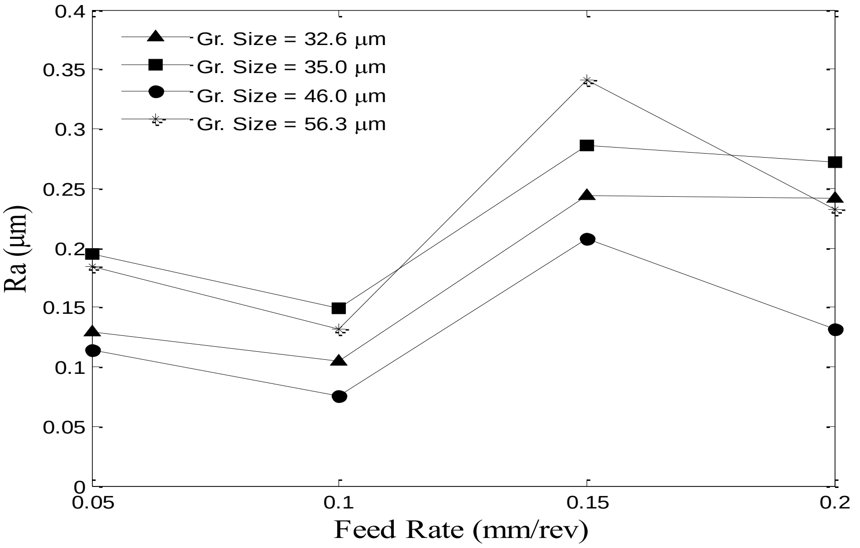


Figure 10. Effect of feed rates on surface roughness (Ra) at (0.15mm) depth of cut and (170 m/min) Cutting Speed for AISI O_1

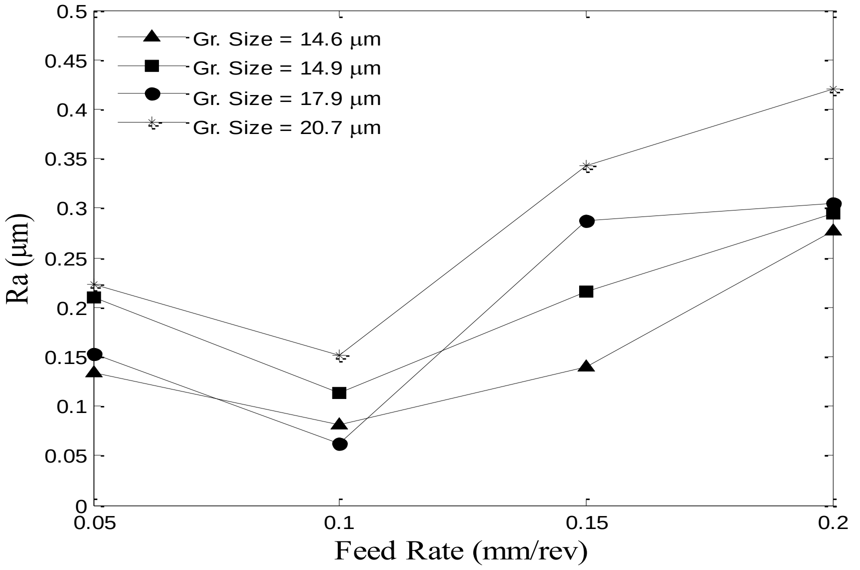


Figure 11. Effect of feed rates on surface roughness (Ra) at (0.1mm) depth of cut for and (120 m/min) cutting speed for AISI D_2

Conclusions

The following conclusions can be drawn:

- Since the heat treatment process's temperature has a significant impact on grain size, different range sizes of the same material may be obtained depending on temperature variation.
- The AISI O1 and AISI D2 alloy steels exhibit a decrease in grain size with an increase in heat treatment temperature.
- Refining the grain size has a major impact on hardness; the hardest materials have the finest grains.
- For AISI D2, the maximum reduction in average grain size is 30.4% attained during the 1000 °C heat treatment procedure; conversely, for AISI O1, the maximum reduction is 42.1% that attained at 780 °C.
- The heat-treated alloy steel used in the experiment produced extremely good surface quality for all designations. The optimal surface roughness (Ra) of 0.115 μm for AISI O1 was obtained by combining 46 μm grain size, 0.1 mm cut depth, 170 m/min cutting speed, and 0.05 mm/rev feed rate. Comparably, for AISI D2, the best Ra of 0.134 μm was attained with 17.9 μm of grain size, 0.1 mm of cut depth, 120 m/min of cutting speed, and 0.05 mm/rev of feed rate. These results emphasize the significance of particular factors in obtaining the best possible surface quality in heat-treated alloy steel.

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