The Influence of Change in Microstructure by Heat Treatment on Drill Quality of Hot Forged AISI 4140 Steel

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Abstract

Heat treatment is a link between the forging process and machining process, and heat treatment can regulate and control the mechanical properties and machinability of the workpiece through the change of microstructure. In industry, quality, efficiency and cost are the most important components in the manufacturing process. The accurate way to come up with these components depends on the selection of the accurate and suitable production conditions. In this context, AISI 4140 (42CrMo4) steel is one of the most widely used materials in the industry and is used in automotive, aircraft and space fields. Therefore, it is very important to process this steel material effectively and efficiently. AISI 4140 steel in experiments was chosen as reference material due to its extensive applications in many areas. In the present work, the effect of heat treatment on machinability of hot forged AISI 4140 steel in the drilling process was investigated at constant cutting parameters using different drill types (uncoated and TiAlN coated HSS twist drills). For this purpose; the surface roughness, dimensional accuracy, and circular and cylindrical deviations characterizing the hole quality were investigated experimentally. As a result, coated drill compared with uncoated drill gave positive results for each evaluation criterion. A better drill quality was obtained for the heat-treated samples than those of the unheat-treated samples at all conditions.

1. Introduction

Metal cutting is a widely used method in manufacturing technologies and it is mostly applied to all mechanic items. The most important point about the machining method is to produce with the desired quality and appropriate standards by obtaining the lowest costs [1-3]. In industry, quality, efficiency and cost are the most important components in the manufacturing process. The most accurate way to uncover these components depends on improving machinability. AISI 4140 steel is one of the most commercially used quenched and tempered steels. It's a most important feature is that it has a high rate of the martensitic structure as a result of heat treatment by having Cr and Mo elements and it allows some mechanical properties in the structure to coexist, such as strength, ductility, toughness etc. AISI 4140 steels are widely used in many fields such as axles, gears, shafts, turbine engines, automobile and airplane manufacturing, brake rings and arms of turbo generators, ship chains and anchors, railway wheels and shafts, machinery and building elements etc. These parts are regularly processed via machining operations like drilling or turning. Therefore, it is very important to machining this steel material effectively and efficiently [4-6]. Forging technology is commonly used in steel alloy forming process, heat treatment also usually is employed to regulate and control the microstructure and mechanical properties, and the forging part must be machined to increase dimensional accuracy and improve surface integrity. Hence the heat treatment can be an important link between the forging process and machining process. During the hot forging process, the grain structure of the metal is rearranged to make the manufactured part more durable but residual stresses occur. It is necessary to eliminate the residual stresses in order to obtain better and permanent performance of the parts with these superior properties. It is aimed to eliminate residual stresses in the structure by heat treatments in different combinations that we will apply to the parts and to improve the properties of the material such as mechanical strength, machinability, hardness. AISI 4140 steel produced by hot forging is able to impart various properties through different heat treatments and this greatly expands the field of use in the industry [7-12].

The drilling process is one of the most important material removal processes, covering approximately 33% of machining operations [13]. Since drilling application has an important place in machining processes, investigation of its process is very important for the manufacturing industry. There are many problems in drilling applications. The dimensional accuracy, circularity, cylindrical deviation, and the quality of the drilled surfaces are a significant design specification that is known to have considerable influence on mechanical properties such as wear-resistance and fatigue strength. As these indicators are important for obtaining high-quality holes, additional operations such as reaming are necessary [14]. Surface roughness in machining has been found to be influenced in varying amounts by a number of factors such as cutting parameters, cutting fluid, and workpiece hardness. Important properties such as hardness, strength and toughness are greatly influenced by heat treatment processes [15]. Most of the previous investigators examined the effect of heat treatment on the mechanical properties [5-15]. However, only a few

researchers have focused on the relationship between heat treatment and surface roughness. From the literature review, it was noticed that design of parameters in drilling of AISI 4140 was observed to be inadequate although a substantial work was performed in the drilling process with various materials. The objective of the study is to examine the surface quality in the drilling process on hot forged AISI 4140 steel, and the effect on the machinability of change in microstructure by various heat treatment was identified.

2. Experimental Procedure

2.1. Material and heat treatment details

The material studied was a hot forged AISI 4140 steel, and the chemical composition of the material is shown in Table 1.

Table 1. Chemical composition of the material (wt%)

C	Si	Mn	P	Cr	S	Cr	Ni	Mo
0.38	0.15	0.75	0.035	0.80	0.04	0.80	0.045	0.15
0.45	0.30	1.00	max	1.10	max	1.10	0.05	0.25

In this study, the differences in terms of machinability between unheated hot forged parts (HF) and heat-treated groups given in Table 2, were investigated experimentally.

Table 2. Heat treatment applied to the workpieces

Code of workpieces	Type of the heat treatment
HT1	normalization
HT2	normalization + quenching
HT3	normalization + quenching + tempering
HT4	normalization + quenching + cryogenic + tempering

First of all, normalization heat treatment was applied to all samples. Preheat process was performed before the normalization process. A pre-heat treatment process was done by standing at 450 °C for 40 minutes prior to normalization. The samples were placed in the oven and reached 880 °C after normalization was done in 29 minutes of processing time. The protective atmosphere containing 0.15 carbon was used to prevent oxide layer formation on the sample surfaces during heat treatment. After the normalization process, the samples were given HT2, HT3, and HT4 codes and then tempered with the same parameters and at the same time. In the tempering process, it waited 29 minutes after reached 860 °C process temperature and 0.67 carbon-containing protective atmosphere was used to prevent oxide layer formation on the sample surfaces during heat treatment. The hardening process was achieved by sudden cooling in the oil for 30 minutes at the processing temperature of 70 °C. Normalization and quenching with the same parameters were applied to HT3 coded samples and subsequently subjected to tempering. Tempering was done at 410 °C process temperature. The samples that placed in the heat treatment furnace reached a temperature of 410 °C after 30 minutes and the holding time at this temperature was kept for 120 minutes. During the process, propane gas was fed to the furnace and a protective atmosphere containing 0.67 carbon was used on the purpose of making a heat treatment in which the desired properties are obtained. Samples given HT4 code were applied for normalization, quenching and afterwards cryogenic heat treatment was performed for 2.5 hours at -100 °C.

2.2. Drilling

In this study, the properties characterizing the hole quality such as the surface roughness, dimensional accuracy, circular and cylindrical deviations were investigated experimentally as a function of change in microstructure by heat treatment. Drilling experiments were performed on a commercially available VCM 4824 model CNC milling machine repeating the same cutting parameters in cooling lubricant condition. The drill cut completely through the test piece on each hole. The workpiece was a rectangular block of length 150 mm, width 100 mm and depth 5 mm. The drilling parameters and drill specifications used in the drilling process are given in Table 3.

Table 3. Cutting tool specifications and cutting parameters

Type of tool	HSS high-speed steel, (uncoated and TiAlN coated)
Toll geometry	Ø 5 mm, point angle 118◦, helix angle 30◦
Cutting speed	40 m/min
Feeding rate	0.15mm/rev

Characterization of the surface finish of workpiece was carried out using a SJ-201P model Mitutoyo surface roughness measurement device. Coordinate measuring machines (CMMs) are widely used to obtain three-dimensional metrological shape information on a workpiece and to evaluate it. CMMs was used for measuring the hole diameters, circular and cylindrical deviations for the holes obtained from the drilling tests. The machinability properties of different heat-treated materials were compared with each other. The studies made are discussed in comparison with the literature.

3. Results and Discussion

Microstructure and hardness of the material to be machined plays an important part in understanding the characteristics of machined surfaces. The hardness and microstructure properties of the parts to be machined are given in Table 4.

Table 4. Hardness and microstructures of unheated and heat treated parts.

Code of workpieces	Hardness, HRC	Phases in microstructure
HF	34.45	Ferrite, perlite
HT1	24.73	Ferrite, fine perlite
HT2	67.85	Perlite, bainite, martensite
HT3	54.76	Perlite, bainite, martensite
HT4	54.56	Bainite, martensite

Achieving the desired hole quality in drilling processes is one of the most important issues in the manufacturing industry. It is very difficult to ensure the dimensional

accuracy and geometric circularity of the hole diameter within the desired tolerances for holes directly drilled by the drilling machine. It is extremely important that this difference should be within acceptable limits. The application type, workpiece properties, cutting parameters and tool properties affect the dimensional accuracy of the hole in drilling operations [14,16]. The accuracy of hole diameter dimension, circular deviation, cylindrical deviation and machined surface quality (average surface roughness) to determine the hole quality were evaluated. The effect of material structure changing by heat treatment and drill types (uncoated and coated) on the surface roughness, results of deviation from diameter, results of circular deviation, results of cylindrical deviation expressing the dimensional accuracy of the hole in drilling operations is given in Figs. 1-4.

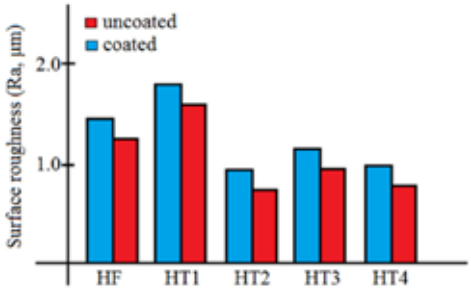

Figure 1. Effect of the heat treatment on the surface roughness

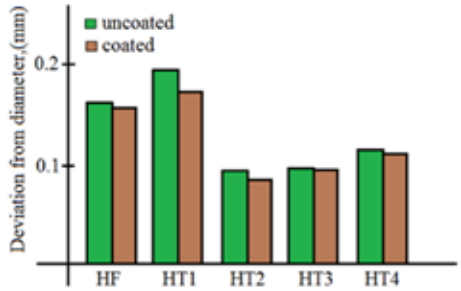

Figure 2. Effect of the heat treatment on the results of deviation from diameter

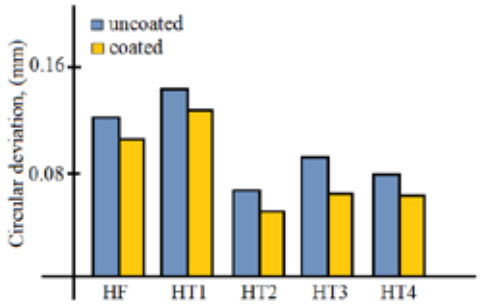

Figure 3. Effect of the heat treatment on the results of circular deviation

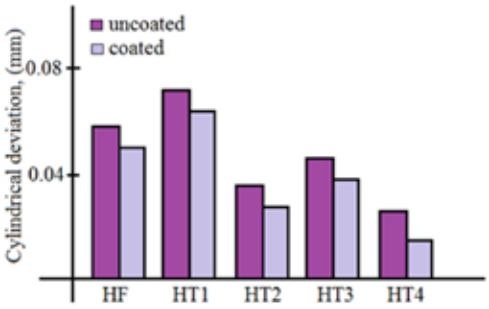

Figure 4. Effect of the heat treatment on the results of cylindrical deviation

When the graphs in Figs. 1-4 compared with each other in terms of coated and uncoated drills, it was observed that applying the coating on the drills affected positively the surface quality. This situation can be referred to the abrasion resistance of the drill and easier chip disability due to low friction coefficient when the coated drill is used. An improvement in drill quality was observed because the increasing temperature by heat energy during the cutting processes made the plastic deformation and chip flow easier [14]. Chip disposal in the drilling process is one of the most serious problems depending on the drilling depth as it causes the chip adhesion to cut tool surface, resulting in poor surface quality, and the cutting tool breakage [16]. Meral et al. [14] stated that the drillability of the workpiece can be easier during the drilling process when the recommended values for the workpiece and the drill materials were not exceeded.

The graphs in Figure 1, the surface roughness of AISI 4140 steel decreases with heat treatment. But, it increased with the normalization process expressed with HT1 due to the decrease in the hardness value. The improvement of the surface roughness for HT2, HT3 and HT4 groups drilled with the coated drill was calculated as 42%, 47% and 28%, respectively. The graph in Figure 2 showed that the deviation from hole diameter was slightly lower than holes drilled by uncoated drill when the coated drill was used. The graph in Figure 3 showed that the heat treatment and drill type were effective parameters on the circular deviation for drilled holes. It is recommended to use the coated drill to obtain the hole dimension within tolerance limits. According to Figure 4, the cylindrical deviation values obtained from coated drill compared to results by uncoated drill was relatively more than impact on surface roughness, and deviation from the diameter and circular deviation. When the graphs in Fig. 1-4 were evaluated, it was seen that the heat treatment was an effective parameter on dimensional accuracy. The heat treatment operations applied have created important differences in the hole quality. Particularly, the holes drilled by coated tools have become more evident. The HT2, HT3 and HT4 heat treatment groups showed a finer-grained and homogeneous martensite morphology, especially HT4 group produced by the

cryogenic process. The cryogenic process has improved microstructure strength-ductility properties. The entire structure is converted to martensite with the cryogenic process at low temperatures. In this way, it is possible to increase the toughness without hardness [17-18]. Quenching and normalizing heat treatments were increased the hardness level of the workpieces. Better surface roughness was obtained for the heat-treated samples than those of the unheat-treated samples at all cutting conditions. Most of the previous researchers examined the effect of heat treatment on the mechanical properties. However, only a few researchers have focused on the relationship between heat treatment and surface quality. Dwivedi et al. [19] and Brunzel and Fomin [20] found that heat treatment reduced the surface roughness. Choi et al. [21] indicated that heat treatments improved the quality in terms of microstructures and surface roughness. The results obtained from this study are in good agreement with the previous researcher's works. A significant correlation between the machinability and the hardness determined by the microstructure changing with heat treatment could be determined.

4. Conclusion

In this paper; the influence of microstructure on and machinability was studied through heat-treatment process. The following results are obtained:

- A better drill quality was obtained for the heat-treated samples than those of the unheat-treated samples at all conditions.
- The properties of the heat-treated workpiece microstructure and its high hardness caused the workpiece surface roughness to be reduced.
- For the HT2 group, higher values were obtained in improving the hole quality with both drills.
- Coated tools compared with uncoated tools gave positive results for dimensional accuracy.

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