Experimental Study of the Cutting Parameters Effect on Hole Making Processes in Hardened Steel

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Abstract
Hardened steels are commonly used in wide areas of technologies and industries. In respect of poor machinability of these steels and requirement of expensive cutting tools, study of machining economy is a matter of importance. Thus the present study deals with the economic considerations of various hole making processes. For this purpose, the hard steel samples were machined by conventional drilling and modern helical milling with and without predrilling. The experiments were performed on AISI D2 steel workpieces with a hardness of 52 HRC. The tool wear, surface roughness, cutting forces and machining time were measured. Results revealed that despite general knowledge, applying predrilling step is not a suitable strategy in hole making on hardened steels. Furthermore, helical milling enhances the efficiency of process by improvement of tool life and surface roughness and reducing the cutting forces. The aforementioned results make helical milling a more economical process than conventional drilling.

Keywords
Hardened Steel, Helical Milling, Drilling, Tool Life, Hole Quality, Machining Economic

1. Introduction

There is a direct relation between manufacturing and economical aspects. Therefore, it is imperative to establish processes with improved quality, low manufacturing cost and high production rate [1]. Machining processes have been considered as the core of manufacturing. Machining is the broad term used to describe a controlled-removal process of material from a base workpiece to achieve desirable dimensional tolerances and surface quality. Increasing production rate along with manufacturing cost reduction are the two main goals of modern machining technologies. In order to meet these demands, manufacturing process should be optimized. Selection of optimal machining conditions can establish a balance between quality and cost at various stages of operation. In this case, it can be expected to fabricate a high performance product with minimal manufacturing cost [1, 2].

Along with developments of machining tools and apparatuses, the machined parts are also changed to demonstrate better performance. One of the widespread changes is using hardened steel which introduces some challenges in their respective machining process. Accordingly, machining of such components has been very active research field over the last decades [3, 4]. Friction and chemical reaction of cutting tool and hardened workpiece, lead to an increase in chip formation, wear rate and cutting region temperature and subsequently accelerate tool failure [5, 6]. To avoid the

aforementioned phenomena, studying the machining parameters of hardened steels is of importance. Hardened steels are commonly used materials in aerospace, die, excavation and power plants industries. Generally, steel parts with hardness of higher than 45 HRC are classified as the hardened steels [7]. Compared to the conventional steels, the hardened steels show different machining behavior (such as cutting conditions at high feed rate, etc.) [7, 8].

To the best knowledge of the authors, limited investigations have been reported economics of machining of hardened steels. Narita [9] presented a detailed investigation on the calculation method of cutting conditions achieving minimum machining cost. In order to predict a total machining cost, following parameters were chosen as the decision variables: cutting tool life, electric consumption of a machine tool, coolant, lubricant oil and metal chip. Applying activity-based costing (ABC) concept, the calculation of cutting conditions were formulated and discussed. The results indicated that increasing of cutting speed up to specified value can effectively reduce the machining cost. Further increase of the cutting speed showed reverse result due to excessive wear of cutting tool.

Okada et al. [10] investigated cutting performance of various cutting tools in end-milling of hardened steel. Their results showed that controlling tool wear, surface roughness, cutting force and cutting temperature can effectively improve machining performance. Furthermore, in case of carbide tools, higher tool wear was observed compared to cubic boron nitride (CBN) tools. Excellent surface roughness was also obtained using CBN tools. Iyer et al. [11] studied drilling of hardened steel using conventional drilling processes and innovative helical milling. The results revealed that applying helical milling can enable dry machining conditions which provide significant environmental and cost benefits. Effects of applying different cutting tools geometry were evaluated by Olvera et al. [12]. They reported that increasing angle of helix in the cutting tools leads to an increase of the wear volume. Jianxin et al. [13] scrutinized wear mechanism of cemented carbide tools in dry cutting of hardened semi-austenitic stainless steel. The SEM micrographs represented transfer of material between the workpiece material and the tool. The EDX spectroscopy also showed presence of W and Co on the stainless steel workpiece, while Fe, Cr, Ni, Mn and Mo were identified on the tool. Based on the observed results, they attributed the instability of cutting force, surface roughness and tool wear to the mentioned material transfer.

In the light of above-mentioned explanations, in the present study conventional drilling and modern helical milling of AISI D2 steel workpiece at a hardness of 52 HRC have been experimentally compared. Tool wear, surface roughness, machining time and cutting forces are measured as the output variables.

Wear and fracture are two main factors affecting tool life. Wear is a gradual process which depends on several factors such as work piece material, cutting fluids, process parameters (cutting speed and depth-of-cut), characteristics of the machine tool and process [14]. Figure 1 shows the most effective tool wear parameters [15, 16]. Tool wear manifests itself in different ways. However, it is not impossible to restrict or minimize tool wear and optimized machining process. As a result of process optimization, economic conditions of machining can be provided.

2. Helical Milling

Helical milling is known as an innovative method for producing high quality holes [17, 18]. In this method, milling tool moves along a helical path and removes materials from a workpiece. The advantages of helical milling over conventional drilling are its flexibility to produce holes with any diameters and reducing manufacturing time. In addition, because of the helical movement of tool, significant reduction of tool wear is also obtained due to slighter contact of tool and workpiece surface [19]. The schematic of the helical milling process is illustrated in Figure 2.

3. Experimental Work

3.1 Materials and Equipment

A rectangular block of AISI-D2 steel with dimensions of 300x115x12 mm^3 was employed as the workpiece. The workpiece was hardened using a vacuum heat treating furnace. In order to eliminate any possible distortions, the workpiece was face milled after the heat treatment. Chemical composition of the workpiece was also analyzed by optical emission spectrometry (Table 1).

A 10.5 mm diameter carbide tool for drilling process and an 8 mm diameter indexable tool holder for helical milling process were applied. The inserts were held on tool holder of model K2-CLC, PROMET, Co. Ltd. The cutting experiments were conducted on a three-axis computer numerical controlled (CNC) machine with a Heidenhain controller (FS0, CME, Co. Ltd) and maximum spindle speed of 1800 rpm (Figure 3).

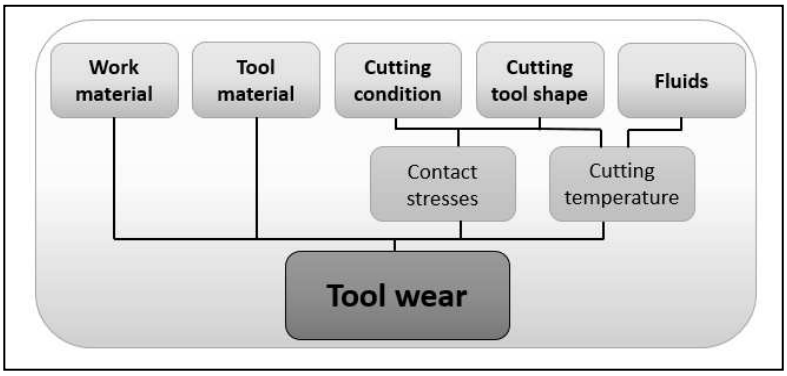

Figure1. Factors influencing tool wear

Table1. Chemical compositions of hardened AISI-D2 steel

Chemical elements	Weight percent %
Chrome	12.1
Carbon	1.6
Vanadium	0.8
Molybdenum	0.71
Silicon	0.5
Manganese	0.3
Nickel	0.2
Iron	Based

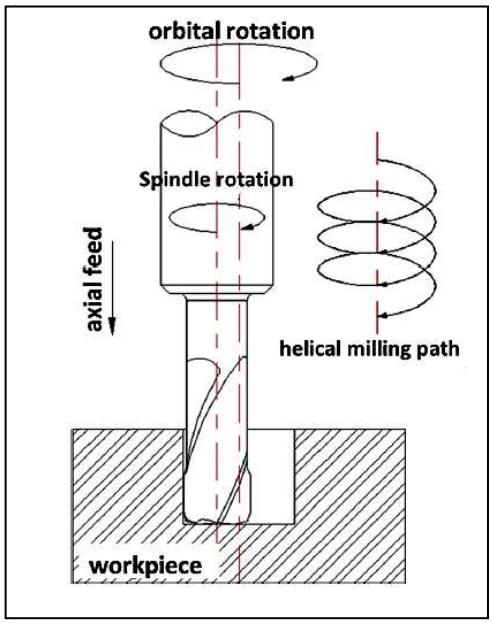

Figure2. Schematic of helical milling process [20]

Figure3. Applied machine tools in the milling tests

In order to measure the cutting forces, a dynamometer of model 9255B (Kistler, Co, Ltd) was used (Figure 4a). In addition, a tool maker's microscope was employed to evaluate the wear width of the cutting tools. The wear width was quantified by comparing the readings at the baseline of the cutting tools before and after machining. The tool maker's microscope is shown in Figure 4b. Surface roughness measurements were also carried out with a surface roughness tester (PS1, Mahr Co, Germany). The calculation was based on the mean roughness (roughness average Ra). Ra is an arithmetic average of the absolute value of the roughness profile ordinates. The average value of surface roughness for three different points was reported as the surface roughness of samples.

3.2 Experimental procedure

In view of different nature of drilling and helical milling processes, different cutting parameters should be applied to attain optimized condition. To this end, the optimized cutting parameters of drilling and helical milling were extracted by initial experiments. Accordingly, the cutting speed, feed rate and depth of cut were 30 mm/min, 0.1 mm/tooth and 3 mm for drilling, and 50 mm/min, 0.1 mm/tooth and 0.1 mm for helical milling, respectively. Each process was carried out with and without predrilling step. The predrilling and final diameters of holes were 5.2 mm and 10.5 mm, respectively. All the holes were created through the workpiece thickness. To ensure the accuracy and repeatability, the average values of the measured values for four different holes were reported. Totally, sixteen sets of experiments were accomplished. For the sake of the environmental and economic considerations, no cutting fluids were used in the machining processes.

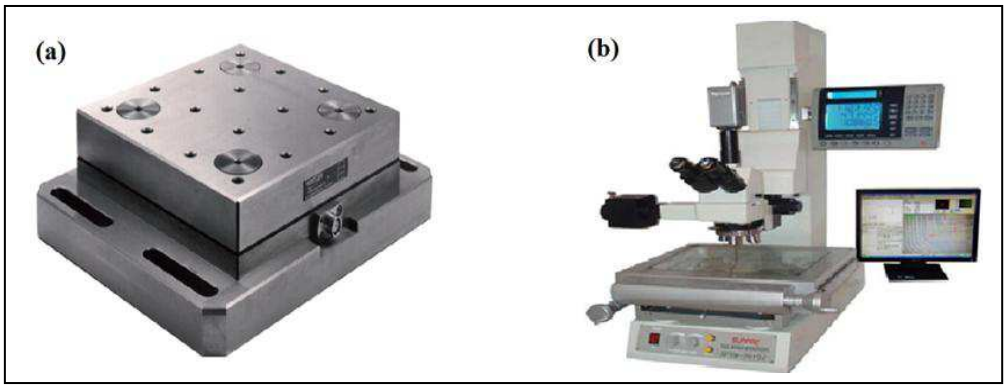

Figure4. The used a) dynamometer and b) tool maker's microscope [4]

4. Results and Discussions

Table 2 contains the hole making processes and their respective tool wear, surface roughness, cutting forces and machining time. All of the obtained results were analyzed by using Minitab 16 software. In the following, output variables are discussed separately.

4.1 Tool Wear

The tool wear results are illustrated in Figure 5. As it can be seen in this Figure, the tool wear in helical milling decreases 263% and 647% compared to the drilling process and with and without predrilling, respectively. This reduction in tool wear can be attributed to the different nature of helical milling and conventional drilling processes. In helical milling, due to slighter physical contact between tool and workpiece and lesser material removal rate, the cutting tool encounters minimum wear rate. Furthermore, significant decrease of tool wear is observed in holes without predrilled step.

Table2. The machining parameters and their respective characterization results

Number	Test conditions	process	Cutting speed (mm/min)	Feed (mm/tooth)	Depth of cut (mm)	Tool wear (mm)	Surface roughness (Mm)	Cutting force (N)	Time (s)
1	Without pre drilling	Helical milling	50	0.1	0.1	0.08175	0.501	34.33	151
2		Drilling	30	0.1	3	0.21437	1.02	984.67	15
3	With pre drilling	Helical milling	50	0.1	0.1	0.14043	0.62	64.49	193
4		Drilling	30	0.1	3	0.90892	1.72	1324	52

The reduction may be ascribed to the decrease of cutting forces and temperatures in machining region. Higher cutting forces and temperatures lead to easier plastic deformation and subsequently easier material removal.

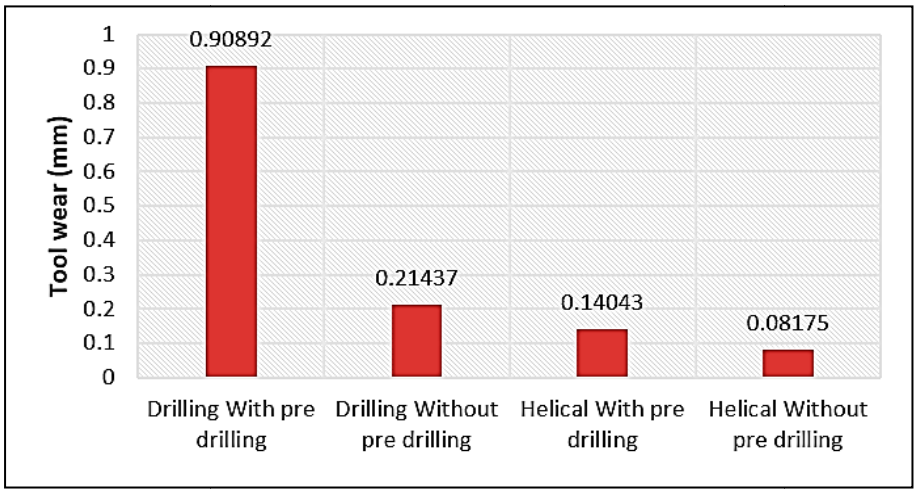

Figure5. Tool wear of different machining conditions

4.2 Surface Roughness

Surface roughness is one of the fundamental parameters which influence surface quality and product life. Surface roughness raises stress concentration and possibility of crack growth in dynamic loadings. These phenomena reduce product life. In the current study, the surface roughness of each hole was measured at three different positions. The average value of the obtained data was reported as the surface roughness of the holes [21, 22].

As it is obvious in Figure 6, the surface roughness of holes which created by helical milling decreases more than 2.5 times than that of drilling process, due to reduction of built-up edges. Unlike the drilling process, in helical milling, the removal material is in the form of tiny chips which itself improves surface finish. Furthermore, on the basis of the kinematic mechanisms and type of material removal, lower cutting forces are generated in helical milling process in which it reduces vibration and instability of process. On the other hand, the predrilling step increases surface roughness by producing discontinues chips.

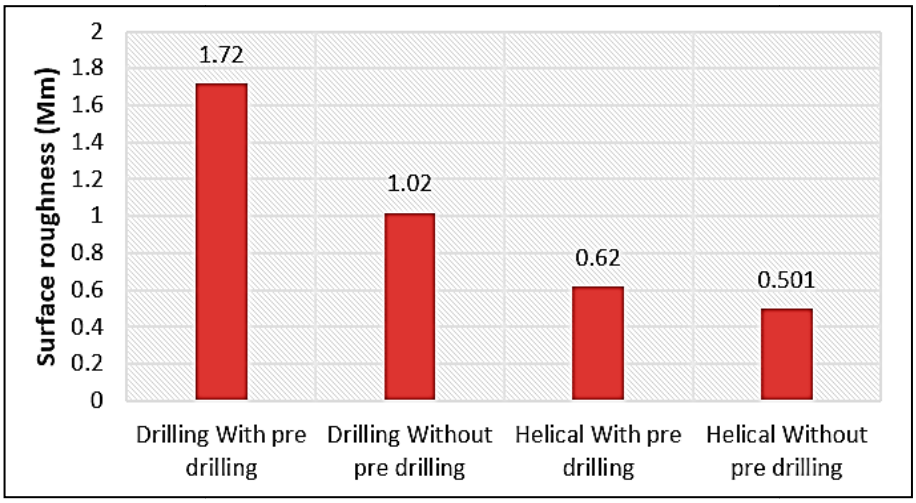

Figure6. The varaitions of surface roughness

4.3 Cutting Forces

Because of the negligible values of forces in X and Y directions, the cutting force was only calculated along Z direction. The cutting force in drilling process is much higher than helical milling (Figure 7). As it is mentioned above, the observed reduction of cutting force is related to the kinematic of material removal in helical milling. Note that the material removalin helical milling produces discontinuous chips which leads to sinusoid dally variation of cutting area. Thus, tool-chip contact length is lower compared to what in conventional drilling. Increasing of the cutting force in the processes with predrilling step is attributed to the nature of cutting process. In general, predrilling of the holes leads to an interrupted-cutting condition which causes the cutting tool to impact repeatedly and subsequently increases the cutting force.

4.4 Machining Time

The machining time for helical milling is much higher than drilling because of the longer moving path of tool in helical milling. However, different holes diameters can be milled without tool change by using helical milling. As a result, no setup time is wasted in switching between manufacturing operations which increases dimensional accuracy. The time results are shown in Figure 8.

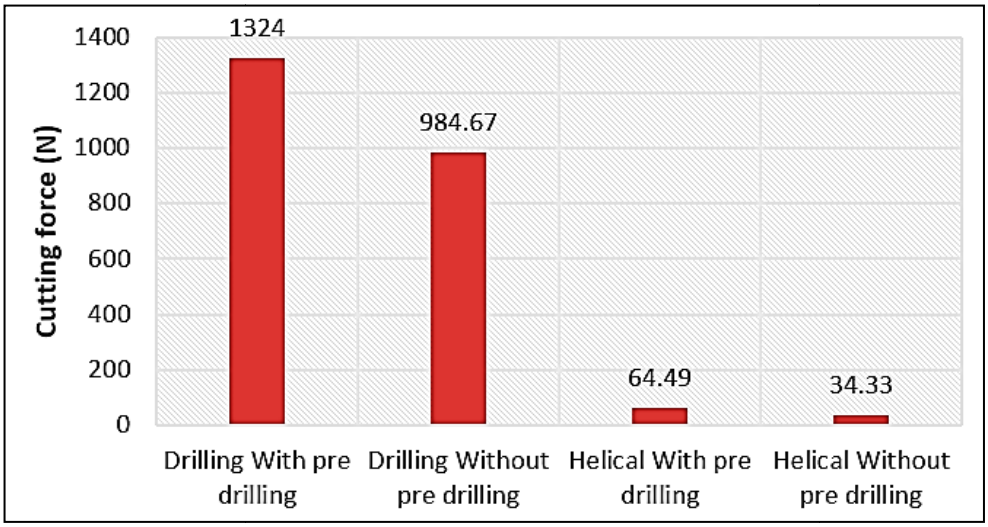

Figure7. The variation of cutting force in various processes

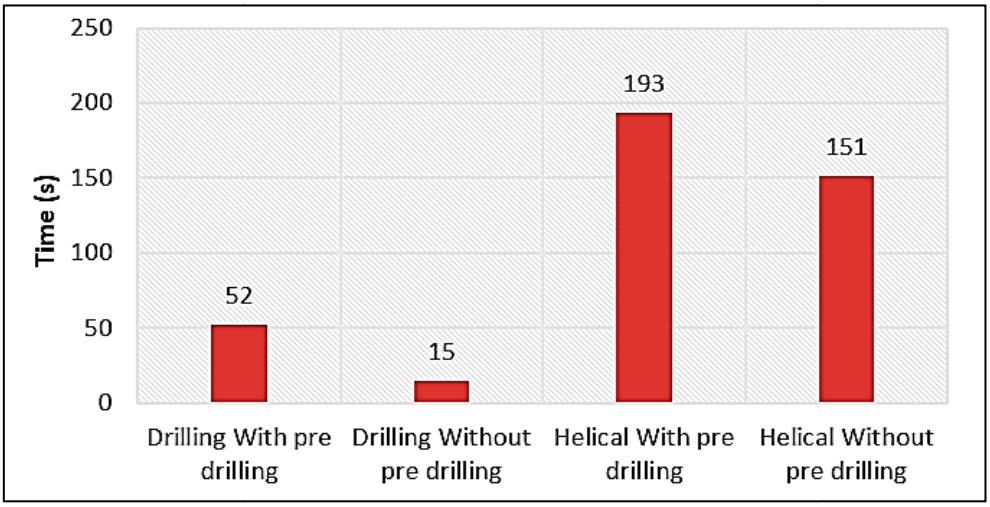

Figure8. The variation of machining time

5. Conclusion

In the present study conventional drilling and helical milling processes had been compared on AISI D2 steel workpiece with hardness of 52 HRC and with and without predrilling step. The results are summarized as follow:

1- High quality holes with low cost can be produced by using modern helical milling.
2- Remarkable reduction of tool wear was observed in helical milling compared to conventional drilling.
3- Unlike regular steels, predrilling of hardened steels deteriorates the machining quality of workpieces.
4- Acceptable surface roughness of created holes in helical milling eliminates the need of further finishing processes.

5- In helical milling, due to low material removal rate, the manufacturing time is higher than drilling process. However, helical milling is capable of greatly improving productivity and reducing costs, approaching the benefit of mass production.

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