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Araştırma Makalesi / Research Article

Finish Turning of AISI 5140 Tempered Steel to Improve Machinability for Engineering Applications: An Experimental Approach with Dry Cutting

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Abstract

This study explores the best finish turning conditions for AISI 5140 tempered steel which is commonly used in automotive, agriculture and construction sectors thanks to its high strength and toughness properties. The steel is proper for surface hardening which makes it a perfect option to employ in various engineering applications. However, there are a few studies about this material and no paper is seen on finish turning operation which is highly critical to prepare the parts for workspace. Therefore, this work focuses on the impacts of feed rate, cutting speed and depth of cut parameters on roughness of workpiece along with cutting force and cutting temperatures while dry cutting of AISI 5140 steel. The results of the experiments evaluated with statistical analysis and Taguchi's optimization approach. Accordingly, cutting speed is the dominant parameter on all response parameters namely surface roughness, cutting force and temperature with 92.6%, 61.6% and 91.6% contribution rate respectively. For maximum surface quality, highest cutting depth (0.3 mm) and cutting speed (200m/min) along with lowest feed rate (0.15 mm/rev) should be employed. Such an approach is expected to be a guide for the practical applications where tempered steels are used in different engineering disciplines.

Keywords: AISI 5140 tempered steel, finish turning, machinability, and surface roughness.

Introduction

Machinability is a general term that commonly used for the definition of feasibility for machining a metallic material on a machine tool. As a consequence, machinability should be identified by several factors which are generally maintained by the machining outputs (Binali, Demirpolat, Kuntoğlu, & Sağlam, 2023; Rüstem, Süleyman, & Süleyman, 2021). Therefore, machinability indicators can be classified for the ones belong to workpiece material, machine tool and cutting tool. However, measuring all these outputs related with these elements is a difficult task. On the other hand, determination of the required machinability indicators is significant to increase the quality of workpiece, to prolong the tool life of cutter and to minimize the expenses and waste (Pimenov et al., 2022). In the concept of this specific study, it was aimed to optimize surface roughness of the workpiece which is significant in finish turning. In addition, cutting temperature and cutting force during machining were measured on-line with advanced sensor systems to elaborate the study.

Machining is the process of removing pieces from the raw material called chips in various forms and lengths, continuously or intermittently, by giving a certain depth of cut (Arrazola, Özel, Umbrello, Davies, & Jawahir, 2013). Such processes generally constitute the last round of the manufacturing processes and create the final surface and dimensions of the machined material. In this respect, although it is sometimes applied to rough operations, it also allows operations to be carried out with very high precision (Mia, Singh, Gupta, & Sharma, 2018). One of the important ways to perform precision machining in machining processes is the recognition of material properties and their correct use in this sense. Soft materials have a structure that can be cut and shaped more easily (Santos, Machado, Sales, Barrozo, & Ezugwu, 2016). On the other hand, hard materials have a structure that does not undergo easy deformation and affects the environment or material which interacts with physically and chemically during manufacturing (Sarıkaya et al., 2021). AISI 5140 tempered steel belongs to the second group mostly due to the high chrome ratio and carbides with excessive hardness in the main structure (Kuntoğlu, Aslan, & Sağlam, 2021). Also, high strength and toughness of the steel makes it hard to machine owing to elevated cutting forces, temperatures and vibrations during machining. For such reasons, observations on this special material are valuable considering its broad utilization in the industry.

When looking at the literature papers on AISI 5140 steel, limited number of machining studies can be seen. Plus, none of them addressed finish turning operation using multiple sensors. For example, Kuntoğlu et al. (Kuntoğlu, Aslan, Pimenov, et al., 2020) modeled tool geometry and cutting parameters for vibration and surface roughness optimization. With a good correlation rate about 90%, the researchers obtained a good model which minimizes vibrations and roughness deviations. In another study (Kuntoğlu, Aslan, Sağlam, et al., 2020), the authors carried out a comprehensive optimization for single and multiple targets using fundamental turning parameters. Accordingly, optimal values for wear, roughness and data acquired with high accuracy (82.5%). Aslan (Aslan, 2020) analyzed cutting forces, vibration and wear patterns using statistical and graphical methods. The study focuses on the multiple optimization techniques such as response surface method for optimal design of turning parameters. Kuntoğlu and Sağlam (Kuntoğlu & Sağlam, 2021) used sensor fusion technique in predicting wear. Acoustic emission and temperature signals provided outstanding results to protect cutting tool from catastrophic effects. On another work (Kuntoğlu, Acar, et al., 2021), the researchers used naturally inspired algorithms to optimize material removal rate and cutting forces. The Bees algorithm and response surface methods compared in giving the maximum success rate in multiple optimizations. Grzesik (Grzesik, 2008) observed wear patterns during hard turning operation and the study provided comprehensive information about abrasive and adhesive wear behavior. Usca et al. (Usca et al., 2022) made an experimental work based on milling operation using different cooling and lubricating mediums. Seemingly, cryogenic machining created powerful effect on the machinability characteristics over dry and minimum quantity lubrication method. Ebrahimi and Moshksar (Ebrahimi & Moshksar, 2009) researched the impact of machining parameters on machinability index and especially for the flank wear of 5140 material. On other studies, generally flank wear or wear mechanisms were studied by the academicians (Bican, Bayca, Ocak-Araz, Yamanel, & Tanis, 2020; Huang, Ren, Li, Zhou, & Zhang, 2018; Kahraman, 2017; Li et al., 2015; Zhang, Cheng, Hu, & Yin, 2017). Therefore, there is a large gap in finish machining of the AISI 5140 steel and this work focused on this area in this specific work.

Industrial materials have great attention nowadays due to the materials processing technologies are very costly. Since the minimization of the total cost maximizes the productivity, manufacturing and industrial engineers generally focuses on the optimum approaches. In line with this scope, data will be kept up to date. This study has a novel approach for AISI 5140 material as per presenting a finish turning operation under dry conditions. In this way, different levels of turning parameters added in the test plan. The evaluation of the machinability of the workpiece was done with surface roughness, temperature and cutting force data. Results will be investigated by optimization and analysis methods to reach the optimal ranges of cutting parameters.

Materials and Methods

Materials, machine tool and experiments

Industrial materials can find extensive usage area in many sectors. AISI 5140 is a special type of tempered steel group which have outstanding toughness and strength properties allowed this material to be used in many prominent areas. Since this material commonly utilized in the sector, it was selected as the machining material. The chemical content of the material is given in Table 1. Coated carbide tools were used to machine the materials and for each experiment a fresh cutting insert was taken. Each experiment was operated under different cutting conditions and these compromised the experimental plan. This plan illustrated in Table 2 where v is the cutting speed, f is the feed rate and d is the cutting depth. The physical tests were performed on a conventional lathe machine (De Lorenzo). No cutting fluid or coolant was used in the experiments. The figure of the machine tool and general perspective of the study is given in Figure 1.

Table 1. Chemical content of 5140 (wt%) (Karakan, Alsaran, & Çelik, 2002)

C	Mn	Si	Cr	Ni	Mo	V	S	Cu	P
0.426	0.77	0.287	0.845	0.134	0.054	0.0287	0.064	0.0154	0.019

Table 2. Turning parameters used in the experiments

Cutting parameters	v	f	d
1. level	100	0.15	0.1
2. level	200	0.3	0.2
3. level	-	-	0.3
Units	m/min	mm/rev	mm

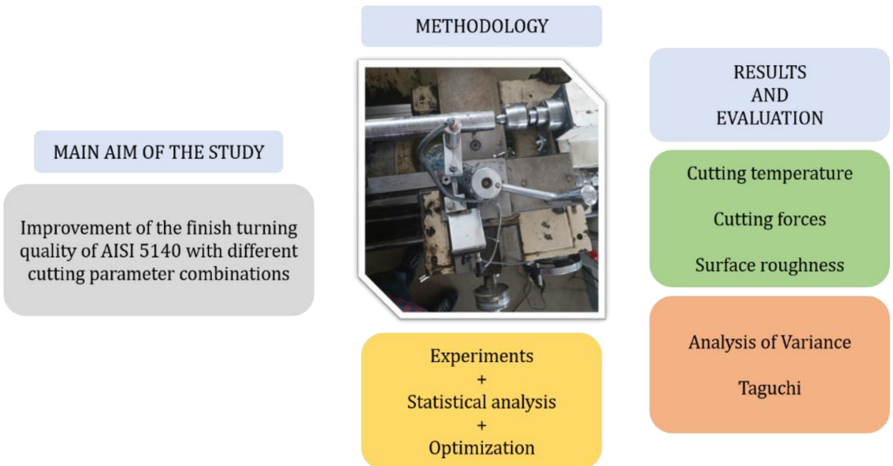

Figure 1. Machine tool and general perspective of the study.

Machining outputs

Common parameter used for surface roughness measurement is the parameter that gives the average surface roughness and is denoted by Ra. It is calculated by taking the arithmetic mean of the areas around a certain center line (which can be positive or negative because these areas can be above or below the line). Surface roughness devices are used to measure surface roughness. While the measuring probe of the device moves over the surface at certain distances, it scans the surface structure with a sensitive micrometer-sized needle at its tip. In this way, the peaks and valleys can be easily detected. In this study a perthometer (Mahr M1 type) was used to determine the surface roughness. Cutting force is a natural outcome of machining operations which is needed to produce chips. In this work, cutting force was detected with a dynamometer (TeLC) which is mounted on the carriage and used also as the cutting tool holder. Similarly, the cutting temperature sensor (TeLC) was set to the dynamometer which uses the radiation measurement method. The red beam focused on the tool tip measures the chip/tool tip temperatures. The figures of the sensors are given in the Figure 2.

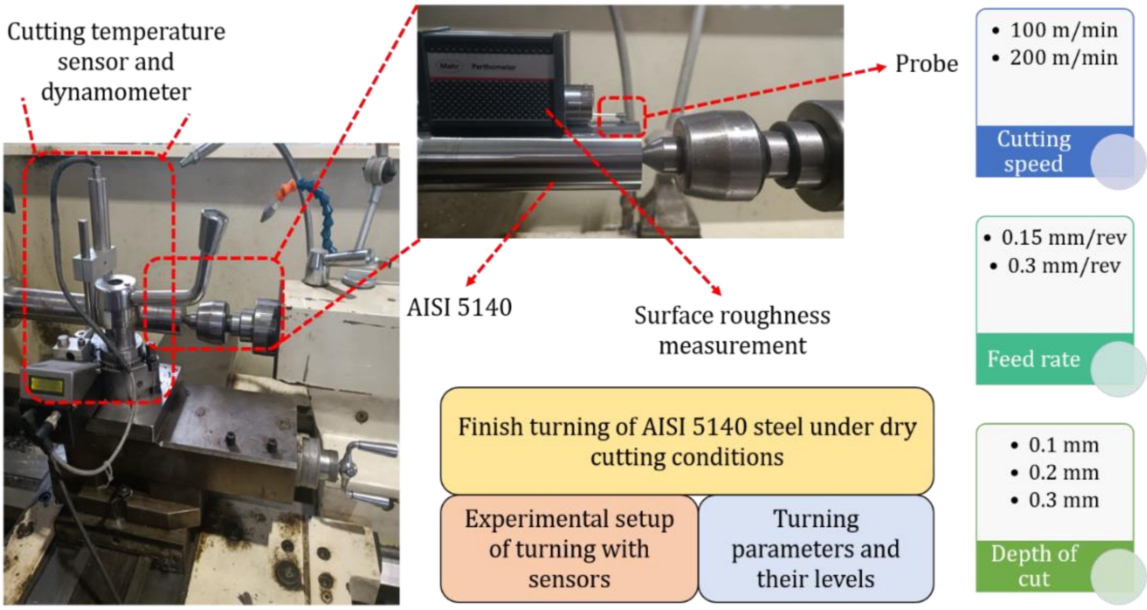

Figure 2. The experimental setup and sensors.

Optimization and statistical analysis

Optimization is highly necessary approach in each scientific area especially for the experimental studies. There are many optimization approaches. Taguchi is one of them and effectively used to obtain optimal ranges. In this paper, Taguchi method was employed to measure the impacts of the machining parameters. On the other hand, statistical analysis was done based on analysis of variance method. To realize these approaches, Minitab software was used. In depth analysis and explanation on used data will be given in the next sections.

Results

Surface roughness

The performances of the material during actual working conditions are directly affected by surface quality of a material. The production of machine parts is very important since these materials are generally being contacted with other parts in real life. Tribological effects on the contacting surfaces of co-working elements determine the lifespan of the material, and this is critical in terms of the overall cost and maintenance costs of the machine. Therefore, determining the surface quality of a material is of great importance by means of measuring the effect and quality of the manufacturing process and understanding the adequacy of the material. One of the universally valid parameters that show the surface quality of a machine part or a metallic material is surface roughness. The obtained results in this study belongs to the surface roughness is given Figure 3.

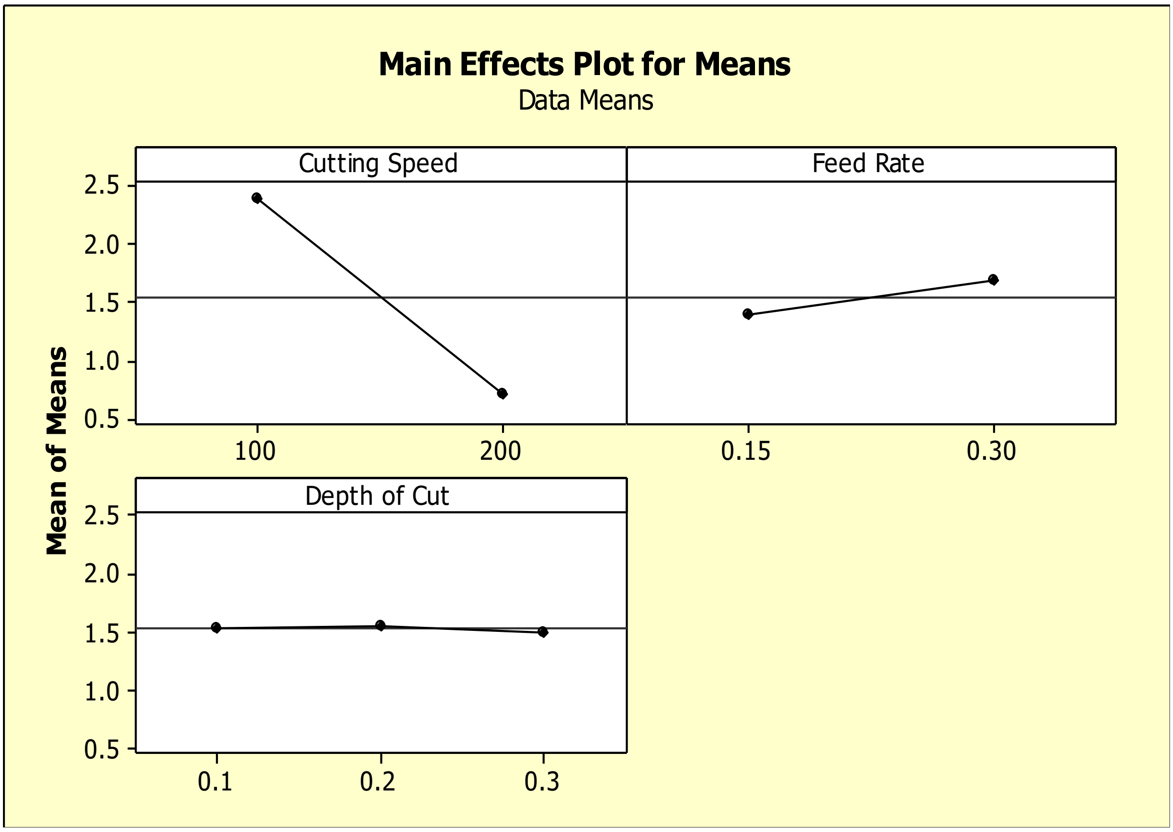

Figure 3. Determination of the effective parameters on surface roughness.

Cutting force

Basically, after the beginning of chip formation, contact areas between tool and chip are exposed to great pressure. Since there is a little contact length between these elements, cutting forces can be detected proportional to these contact areas and pressure. Cutting force is an essential variable to cut the material however it may ruin the surface quality of the material during forming the chips. Therefore, keeping the cutting force in some level is quite important. Figure 4 analyzes the cutting force changes depending on the different levels of cutting parameters. It was mentioned before those main effects plot provides the beneficial and detrimental parameters. As seen, the way to produce lowest cutting force depends on the selection of lower turning parameters namely 100 m/min, 0.15 mm/rev and 0.1 mm.

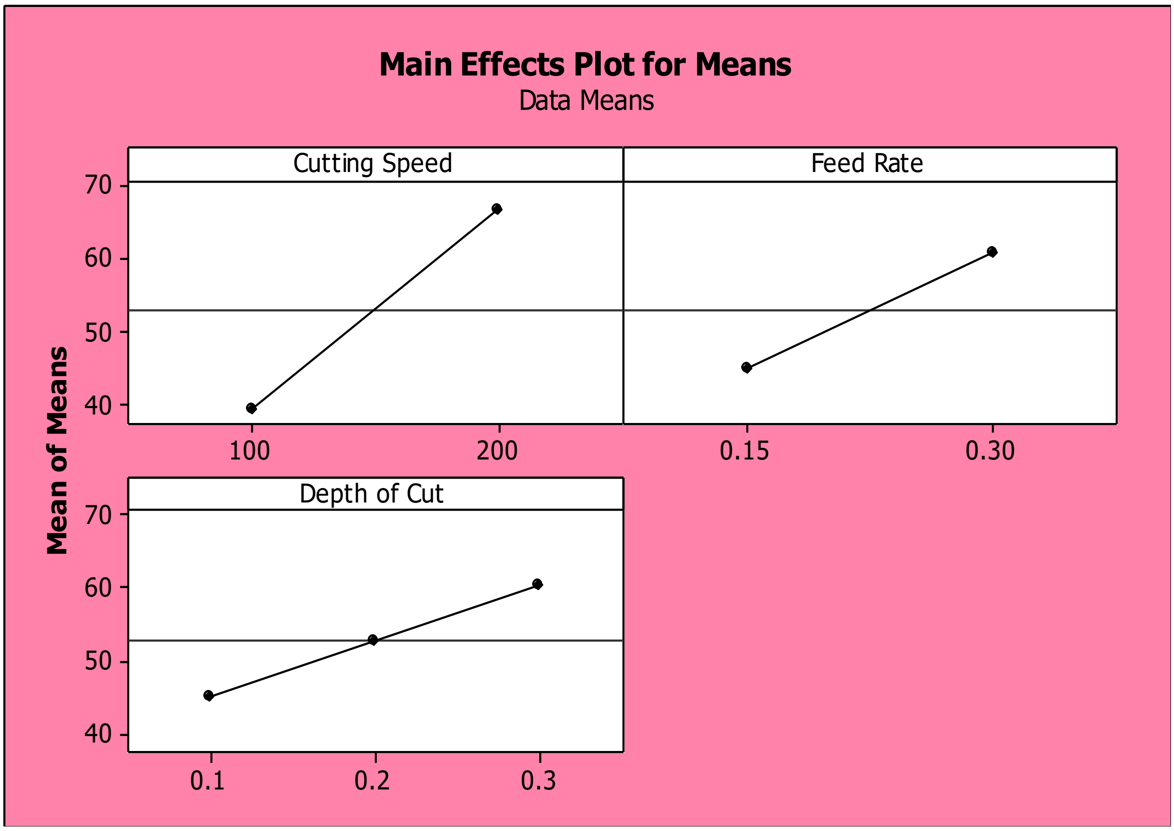

Figure 4. Determination of the effective parameters on cutting force.

Cutting temperatures

Although the general use of cutting inserts may seem quite simple, these tools, which are exposed to severe temperature and pressure, lose their properties over a certain period of time. The excessive temperatures occurring in the square millimeter area around a few edges where the cutting tool workpiece are being contacted, shared between the materials, chip and the cutting environment as a result of heat transfer. However, some heat is transferred to the workpiece and the cutting tool. As a result of high amounts of friction, severe tribological effects and temperature, various wear occurs at cutting tool and changes the microstructure of the material. Therefore, minimization of the cutting temperatures is of great importance. Figure 5 gives the impacts of the input parameters on the cutting temperatures. Means plot of main effects give the lines for each parameter which should be understood as the lower parameter gives better results. Seemingly, lower cutting speed need to be selected for the best surface quality. Similarly, low feed rate and depth of cut should be chosen for lowering the surface roughness. Means for the temperature scale shows that lower the parameter provides lower temperatures. This can be explained with the reduction of the cutting parameters automatically produce lower frictional forces, which reduces the temperatures and heat, transfer ratio.

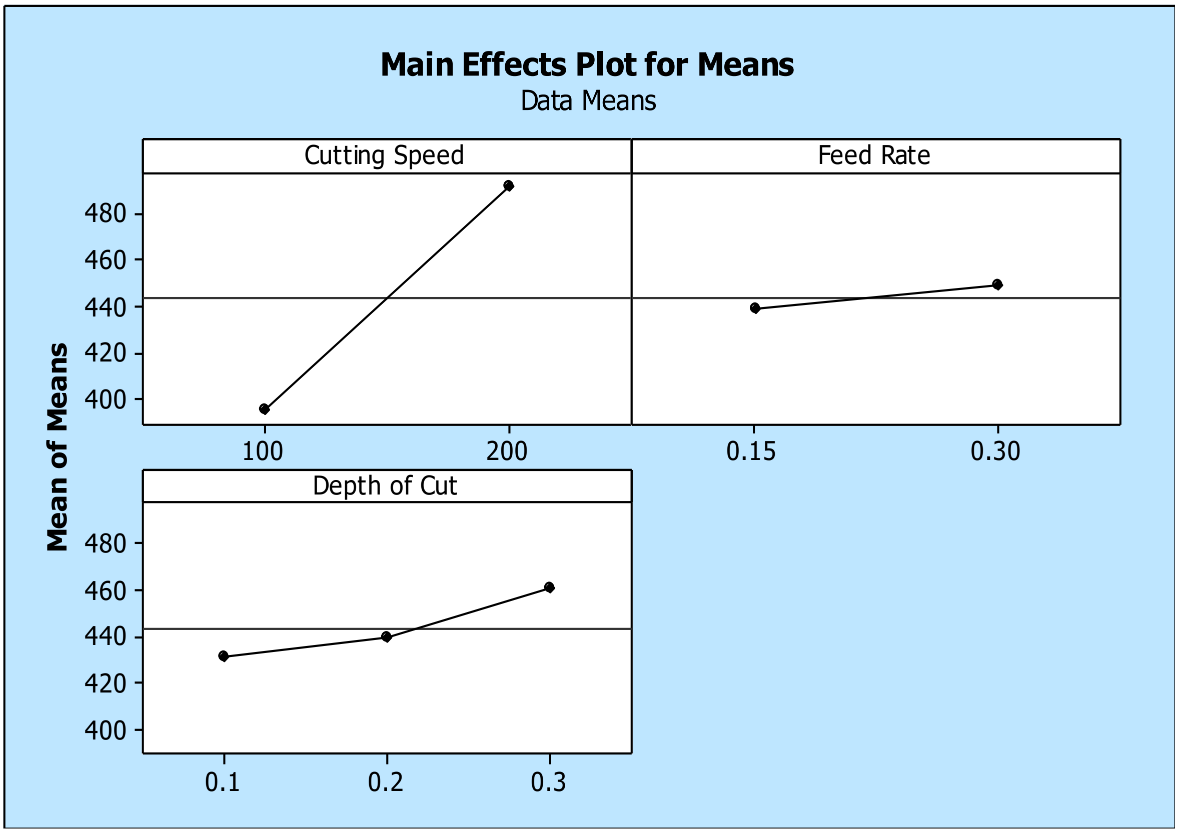

Figure 5. Determination of the effective parameters on cutting temperatures.

Statistical analysis and discussion

Statistical analysis gives the important levels for each parameter and these sorted values provide to design total machining group. This approach is widely utilized due to its simplicity and effective usage. Therefore, to improve the finish cutting quality, this study is built on this understanding. Statistical results are given in Figure 6 as per the findings of the experiments. Accordingly, surface roughness is affected by the cutting speed mostly (92.6%). This is understandable that changing cutting speed alters the cutting force and temperatures where tool wear index shifts. On the other hand, cutting force is influenced by the cutting speed effectively (61.6%) which is pursued by the feed rate and depth of cut. Cutting speed makes easier the cutting process if its higher rates are applied. Besides, this situation increases the wear rate of the cutting tool, which requires arranging the cutting speeds sensitively. Lastly, cutting temperature is affected by the cutting speed effectively (91.6%). Increasing movement of the workpiece during revolving enhances the coefficient of friction and increases the cutting temperatures.

Analysis of Variance for Means (Surface roughness)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	1	8.33833	8.33833	8.33833	154.39	0.000
Feed Rate	1	0.27877	0.27877	0.27877	5.16	0.057
Depth of Cut	2	0.00435	0.00435	0.00217	0.04	0.961
Residual Error	7	0.37806	0.37806	0.05401		
Total	11	8.99951				

Analysis of Variance for Means (Cutting force)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	1	2241.3	2241.3	2241.33	97.35	0.000
Feed Rate	1	768.0	768.0	768.00	33.36	0.001
Depth of Cut	2	465.2	465.2	232.58	10.10	0.009
Residual Error	7	161.2	161.2	23.02		
Total	11	3635.7				

Analysis of Variance for Means (Cutting temperatures)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	1	27744.1	27744.1	27744.1	544.13	0.000
Feed Rate	1	330.7	330.7	330.7	6.49	0.038
Depth of Cut	2	1853.2	1853.2	926.6	18.17	0.002
Residual Error	7	356.9	356.9	51.0		
Total	11	30284.9				

Figure 6. Statistical analysis of the results.

Conclusions

This paper is about the finish turning performance of different cutting parameter combinations of AISI 5140 steel. The outputs namely cutting temperature, cutting force and surface roughness of the experimental study was evaluated with statistical analysis and graphical illustrations. Some of the findings are given below:

- Cutting speed was found as the dominant parameter on all response parameters namely surface roughness, cutting force and temperature with 92.6%, 61.6% and 91.6% contribution rate respectively.
- For minimize surface roughness, highest cutting depth (0.3 mm) and cutting speed (200m/min) along with lowest feed rate (0.15 mm/rev) should be selected.
- For minimize cutting force, highest cutting depth (0.3 mm) and cutting speed (200m/min) along with highest feed rate (0.30 mm/rev) should be selected.
- To minimize cutting temperatures, the same parameters that minimize cutting force should be used.

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