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Analysis of Chip Thickness of the High Strength Steel D2 Cylindrical Object during CNC Turning Operation: An DOE based Study

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A B S T R A C T

The aim of this study was to evaluate the impact of cutting velocity on chip formation and surface roughness in high strength alloy steels (tool steel D2). The cutting velocity was varied from 150 to 400 meters per minute, while the feed rate and depth of cut were also varied. The selected alloy steels were characterized by high strength, high hardness, and low corrosiveness. The chip thickness was analyzed using the surface response technique. In addition, the shape of the chip formation and its effect on quality were analyzed. The research was conducted using the Taguchi method of design of experiment, and the results were analyzed using signal to noise ratio analysis.

Keywords: Tool Steel D2, Machining, Taguchi method, chip formation, surface roughness, signal to noise ratio, analysis of variance (ANOVA)

1.Introduction

The impact of chip velocity on chip thickness during CNC turning operations is a significant factor to consider in order to achieve optimal machining performance. Chip velocity, also known as cutting speed, refers to the speed at which the cutting tool moves through the material being machined. It is an important process parameter that can have a significant effect on the quality and efficiency of the machining process.When the chip velocity is increased, the chip thickness tends to decrease. This is because the increased cutting speed allows for a higher material removal rate, resulting in a thinner chip. However, it is important to note that the relationship between chip velocity and chip thickness is not linear. As the chip velocity increases, the chip thickness may initially decrease at a faster rate, but eventually reach a point where further increases in cutting speed result in only minimal changes in chip thickness.

There are several factors that can influence the relationship between chip velocity and chip thickness, including the properties of the material being machined, the geometry and design of the cutting tool, and the feed rate and depth of cut. In addition, the type of CNC turning operation being performed (e.g. roughing, finishing, etc.) can also impact the chip velocity-chip thickness relationship.Overall, the impact of chip velocity on chip thickness during CNC turning operations is a complex and multifaceted issue that requires careful consideration and optimization in order to achieve optimal machining performance. By carefully controlling and adjusting the chip velocity, it is possible to achieve the desired chip thickness and surface finish, while also improving the efficiency and productivity of the machining process.

To optimize the cutting velocity in CNC turning, it is important to carefully consider the various factors that can impact the machining process. This may involve adjusting the cutting velocity for different materials or using different cutting tools for different machining conditions. By carefully controlling the cutting velocity, it is possible to achieve the desired surface finish and improve the efficiency and quality of the machining process. In present study the D2 tool steel was selected as machining object and then different cutting velocities were selected to find the impact on the final product.

2.Literature Review

In a study by Balaji et al. (2022), the response surface approach was used to optimize machining parameters for turning super duplex stainless steel (SDSS) using uncoated carbide tools. The machining was conducted in a cooled gas atmosphere and the responses evaluated were surface roughness, tool wear, cutting force, and cutting temperature. The surface roughness was measured using a surface roughness tester and the cutting temperature was monitored with a thermocouple. Analysis of the readings was then performed and surface and contour plots were generated for the cutting temperature.

In a study by Rashid et al. (2013), the surface defect machining (SDM) method for high-throughput processing was examined. This method combines the benefits of porosity machining and pulsed laser pre-treatment to improve the controllability of the process and enhance the quality of the machined surface. The SDM technique was analyzed through the use of the finite element method (FEM) and molecular dynamics (MD) modeling.

Cotterell and Byrne analyzed the chip formation during the machining of titanium alloy. During orthogonal cutting, saw-tooth chips were formed through a two-stage process: first, material in front of the tool expands due to plastic deformation, and second, a shear band is created when the critical strain level is reached, resulting in concentrated high strain and catastrophic breakdown.

Halim et al. investigated the impact of tool wear on chip morphology during the milling of a nickel alloy with a coated carbide tool. They found that at an early stage of wear, a single element chip is produced, while in the steady wear stage, a twin element chip is formed due to the action of the worn tool geometry at the cutting edge. In some cases, the chips fused with the worn regions of the tool face as they passed over it. When localized flank wear occurred, the twin element chips transformed into segmental chips with a sawtooth-like shape. In a cryogenic environment, the segmented chip was produced in the steady wear stage, while in dry machining conditions, it was produced in the later stage of tool wear.

In a study by Nandhakumar et al., the chip formation and wear mechanisms of silicon nitride based ceramic and silicon carbide whiskers reinforced alumina round inserts were examined during the turning of solution-annealed Inconel 718 with a 10% concentration cutting fluid. The cutting speed was 250 meters per minute in the first set of tests and 300 meters per minute in the second set. The results showed that the SiAlON turning inserts produced the best results in terms of tool flank wear, total tool life, and workpiece surface polish at a cutting speed of 300 meters per minute. At cutting rates above 250 meters per minute, the Inconel 718 chip morphology indicated significant shear band localization in the major shear zone of the chip/tool interface, resulting in the segmentation of chips.

In a study by Al-Ajmi et al., experiments were conducted to investigate the effects of cutting speed and feed rate on the surface roughness and machinability of Inconel 718 when turning with coated carbide tools. The results showed that an increase in cutting speed led to a decrease in surface roughness, while an increase in feed rate led to an increase in surface roughness. The results also indicated that the machinability of Inconel 718 improved with an increase in cutting speed and a decrease in feed rate. These studies demonstrate the complex and multifaceted nature of chip formation and tool wear in various machining processes and the importance of carefully controlling and optimizing process parameters in order to achieve optimal performance.

3.Objective and Methodology

The aim of this study was to examine the effect of cutting velocity on high strength alloy steels. The cutting velocity was varied from 20 to 100 meters per minute, while the feed rate and depth of cut were also modified. Three different types of AISI D2 Tool Steel alloy steels were chosen for the test samples due to their high strength, hardness, and low corrosion properties. The focus of the study was on chip formation and surface roughness, which were analyzed using the surface response technique. The research process included defining the scope of the study, developing a research plan, conducting experiments on the work components, and analyzing the results. The data was recorded using the Mini-Tab program, and the conclusion of the study was drawn. The research flow diagram is shown in Figure 1.

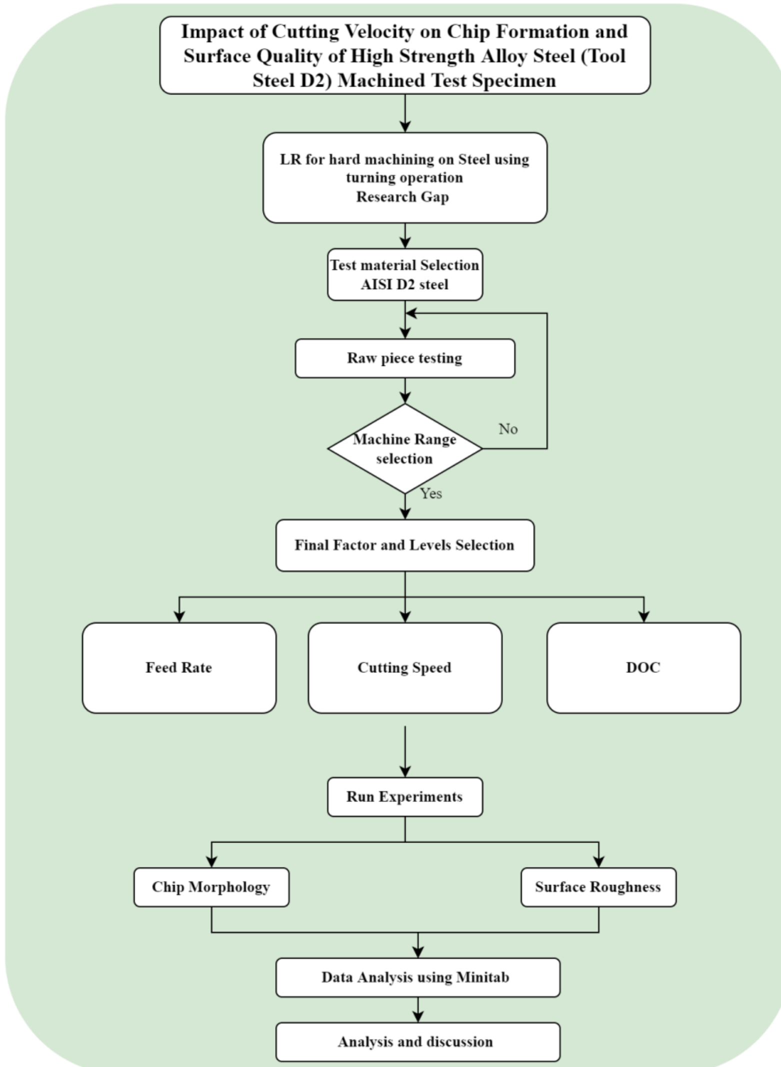

Fig.1.Research Flow Diagram for Present Study

4.Material and Methods

AISI D2 tool steel was used as the test material to assess its machinability. The test specimens were cylindrical rods with a diameter of 50 millimeters and a length of 70 millimeters, made from bar stock. Smaller diameter rods are preferred due to their high tensile strength and elongation, as well as their lower cost and ease of storage and handling. Tables 1 and 2 provide the characteristics of the D2 steel used in the experiment.

Table 1

Chemical composition of Tool Steel "D2" [36]

Steel	C	Mn	Si	Cr	Mo	V	Fe
D2	1.52	0.34	0.31	12.05	0.76	0.92	Bal

Table 2

Mechanical Properties of Tool Steel "D2" [36]

Steel	Modulus of Elasticity	Yield Strength	UTS	Displacement at Fracture
	GPa	MPa	MPa	mm
D2	203	350	758	0.61

The experiments were conducted in a wet environment using a TM-1 model tool room lathe and a HAAS vertical lathe center, as shown in Figure 2. The HAAS vertical computer numerical control machining center has x, y, and z motions of 30 inches, 12 inches, and 16 inches, respectively, and can accommodate larger workpieces with dimensions of 762 mm x 305 mm x 406 mm. The capabilities of the HAAS vertical machining center used in the experiments are listed below. This machining center is equipped with a range of features that make it well-suited for use in a variety of applications. It has a high-speed spindle with a maximum speed of 10,000 rpm, as well as a large work envelope and a fully programmable control system. It is also equipped with a range of safety features, including an automatic door lock and a built-in safety interlock system, to ensure the safety of the operator and the equipment. The combination of the TM-1 model tool room lathe and the HAAS vertical machining center allowed for the precise and efficient machining of the test specimens in a wet environment, enabling the researchers to accurately assess the machinability of the AISI D2 tool steel.

Fig.2.Lathe Turning Machine

5.Pilot Experiments for Present Study

Pilot experiments are important in machining research because they allow researchers to test and optimize their experimental setup and methodology before conducting the main study. They can be used to test different machining parameters, such as cutting speed, feed rate, and depth of cut, to determine their impact on the machining process and the final machined component. They can also be used to test different tool materials and geometries to identify the most suitable option for the main study. Pilot experiments can be used to test and validate measurement techniques, such as surface roughness measurement or tool wear assessment, to ensure their reliability and accuracy. They can also be used to assess the repeatability and reproducibility of the machining process. Overall, pilot experiments help to optimize the experimental setup, identify the most suitable machining parameters and tools, and validate measurement techniques, leading to more reliable and accurate results in the main study.

The final range selection for the present investigation using pilot study was present in table 3.

Table 3

Pilot Experiments for present research work

Sr No	Factor	Range after Pilot Ex
1	Feed Rate (mm/rev)	0.2 to 1
2	Speed (RPM)	1000 to 2000
3	Depth of Cut (mm)	0.3 to 1

This range is verified by using pilot experiment on the machine. These trial results are validated when full final completed product was made by the machining process. The final product should looks like shown in figure 3.

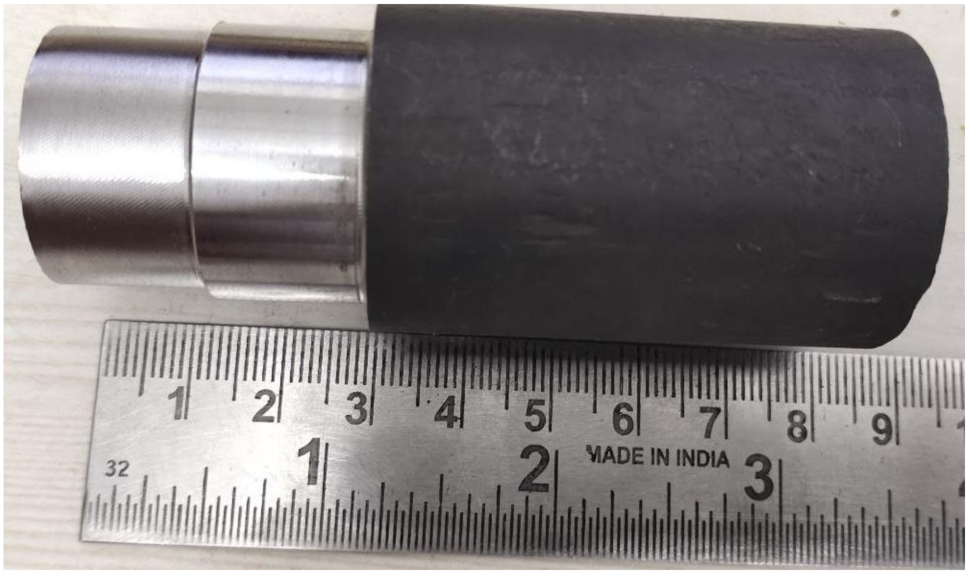

Fig. 3 Product made for pilot experiment (Stepped Turning)

The CAD model of the product with dimension was shown in figure 4, all dimensions are in mm.

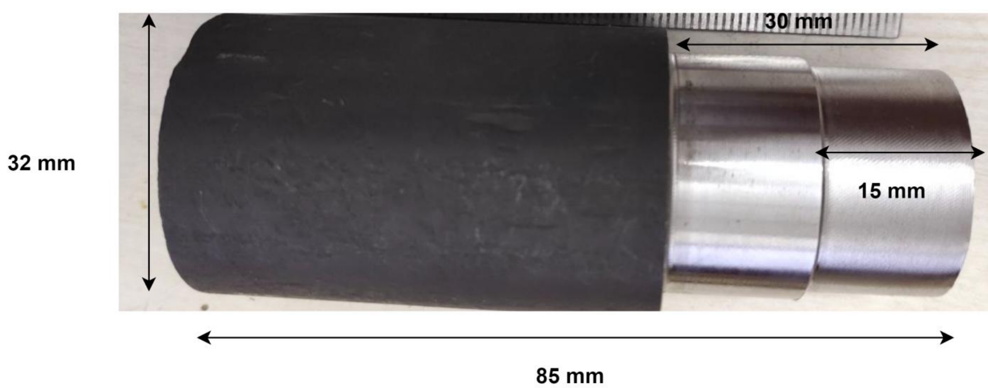

Fig.4Dimensions of the final Product

6.Taguchi Method

The Taguchi method is a statistical approach to design of experiments (DOE) that is used to optimize processes and product designs. It was developed by Dr. Genichi Taguchi in the 1950s and is based on the idea that the quality of a product or process can be improved by minimizing the variability of its design parameters. The Taguchi method involves the use of an orthogonal array, which is a table of values that represents the different combinations of design parameters that will be tested in the experiment.

The main advantage of the Taguchi method is that it allows researchers to study the effect of multiple design parameters simultaneously, using a relatively small number of experimental runs. This is achieved through the use of an orthogonal array, which is designed to provide a balanced distribution of the design parameters across all experimental runs. This allows researchers to efficiently study the interactions between different design parameters, and to identify the optimal combination of these parameters that will result in the desired product or process performance.

One of the key features of the Taguchi method is the use of signal-to-noise (S/N) ratio analysis to evaluate the results of the experiments. This involves comparing the variation in the response variable (e.g. surface roughness, tool wear, etc.) to the variability in the design parameters. The S/N ratio is used to determine the relative importance of each design parameter, and to identify the optimal combination of these parameters that will result in the highest

S/N ratio.

The Taguchi method has been widely used in a variety of fields, including engineering, manufacturing, and product design, to optimize processes and improve product quality. It has been shown to be particularly effective in the optimization of complex systems, where multiple design parameters may interact in complex ways. The use of the Taguchi method, along with an orthogonal array, can allow researchers to efficiently identify the optimal combination of design parameters, leading to improved process and product performance.

TABLE 4

Factors and levels for hard turning

Factors/Levels	Speed	Feed Rate	DOC
	m/min	mm/min	mm
I	140	0.5	0.2
II	190	0.6	0.3
III	240	0.7	0.4
IV	290	0.8	0.5

These factors and levels are required to select the experiment table for present investigation. The selection of experiment runs are done by using Taguchi method and the final orthogonal array was present in table 5.

TABLE 5

Orthogonal array developed for present experiment work

Run	Speed	Feed Rate	DOC
1	140	0.5	0.2
2	140	0.6	0.3
3	140	0.7	0.4
4	140	0.8	0.5
5	190	0.5	0.3
6	190	0.6	0.2
7	190	0.7	0.5
8	190	0.8	0.4
9	240	0.5	0.4
10	240	0.6	0.5
11	240	0.7	0.2
12	240	0.8	0.3
13	290	0.5	0.5
14	290	0.6	0.4
15	290	0.7	0.3
16	290	0.8	0.2

6.Result and Discussion

The final table in which both response parameters are presented was list out in table 5. As saw in table 6, the first response parameter was chip thickness of the object which was measured after performing the turning operation as per experiment table.

TABLE 6

Experiment results for l16 orthogonal array

Run	Speed	Feed Rate	DOC	Chip Thickness
1	140	0.5	0.2	716
2	140	0.6	0.3	723
3	140	0.7	0.4	732
4	140	0.8	0.5	741
5	190	0.5	0.3	687
6	190	0.6	0.2	707
7	190	0.7	0.5	719
8	190	0.8	0.4	721
9	240	0.5	0.4	662
10	240	0.6	0.5	687
11	240	0.7	0.2	706
12	240	0.8	0.3	714
13	290	0.5	0.5	642
14	290	0.6	0.4	665
15	290	0.7	0.3	696
16	290	0.8	0.2	717

The formula required for the signal to noise ratio analysis was present in table 7.

TABLE 7

SIGNAL TO NOISE RATIO FORMULATION FOR RESPONSES

Response Parameter	S/N ratio Option	Formula
Tensile Strength	Larger is better	$S/N = -10\log\frac{1}{n}\left(\sum y^2\right)$
Drilling Time	Smaller is better	$S/N = -10\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right)$

7.S/N Ratio-Surface Roughness

The signal-to-noise (S/N) ratio is a key measure used in the Taguchi method to evaluate the performance of a product or process. It is defined as the strength of the desired output or response (the signal) relative to the undesired variation or error (the noise). The S/N ratio is calculated by dividing the mean of the signal by the standard deviation of the noise. A higher S/N ratio indicates better performance, as the signal is stronger and the noise is weaker. Conversely, a lower S/N ratio indicates poorer performance, as the signal is weaker and the noise is stronger.

In the Taguchi method, the S/N ratio is used to identify the optimal levels of factors that impact the performance of a product or process. By changing these factor levels and measuring the resulting S/N ratio, researchers can identify the combination that leads to the highest S/N ratio and the best performance. The S/N ratio is a commonly used metric in quality control and engineering to assess and improve the performance of products and processes. It is an important concept in the Taguchi method and is widely applied in various fields.

Equation as present in table was utilized in order to determine particular S/N ratio for the present response chip thickness for each experiments. The individual S/N ratios were used to construct the average S/N ratio table, which was then used to calculate the delta variable by applying equation in order to determine the relationship between the factors and response parameters. Table 5.6 contains information on the average S/N ratio as well as delta for the chip thickness response parameter. The curve depicting the average chip thickness was displayed in figure 5.1 for the orthogonal array L16.

$$\text{Delta} = \text{Avg.}\{(S/N)_{max} - (S/N)_{min}\}$$

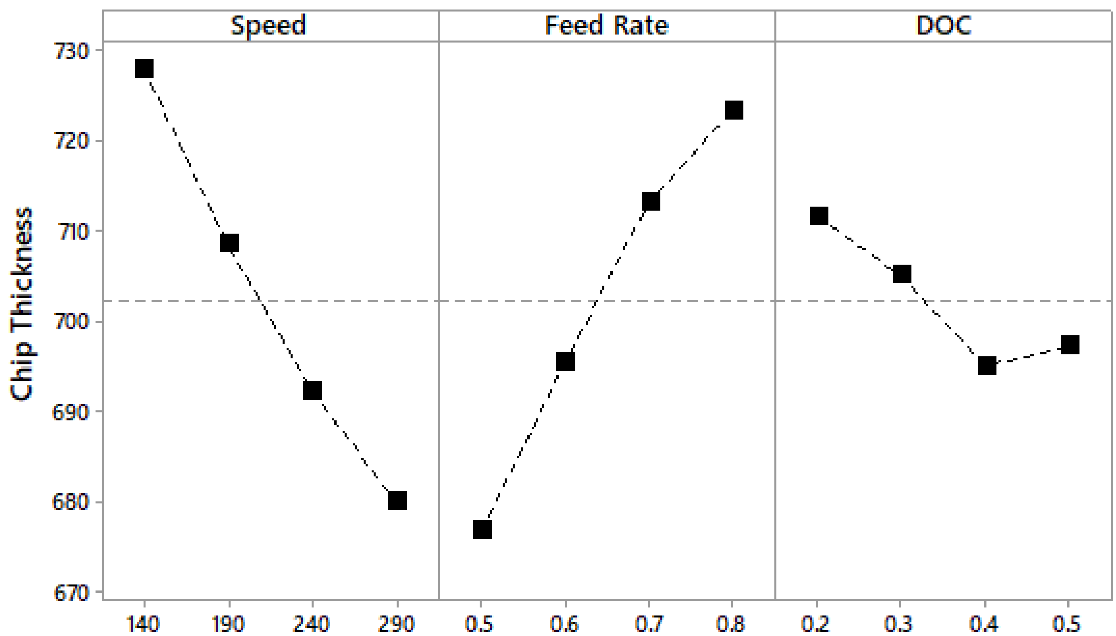

Fig. 5 Mean Chip Thickness plots for input parameters

As can be observed in figure 5, the average chip thickness of the orthogonal array tests L16 was the same regardless of the factor being considered. Cutting parameters such as speed, feed rate, and depth of cut When looking at the plot for the speed, one can observe that the chip thickness slow down as the levels of the speed increase. The machine's feed rate was also proven to have an increment of the same value. The chip thickness of the final object can be controlled by the impact of two additional factors as well as by the heating of the object itself. However, in DOC, the first three levels show an decrements in chip thickness, while the last level shows a increment in chip thickness. The average value of the signal to noise ratio was calculated in table 8 and delta was also present in the same table 8.

TABLE 8

Rank identification for chip thickness of d2 tool steel

Level	Speed	Feed Rate	DOC
1	57.24	56.6	57.04
2	57.01	56.84	56.96
3	56.8	57.06	56.83
4	56.64	57.18	56.86
Delta	0.6	0.58	0.21
Rank	**1**	**2**	**3**

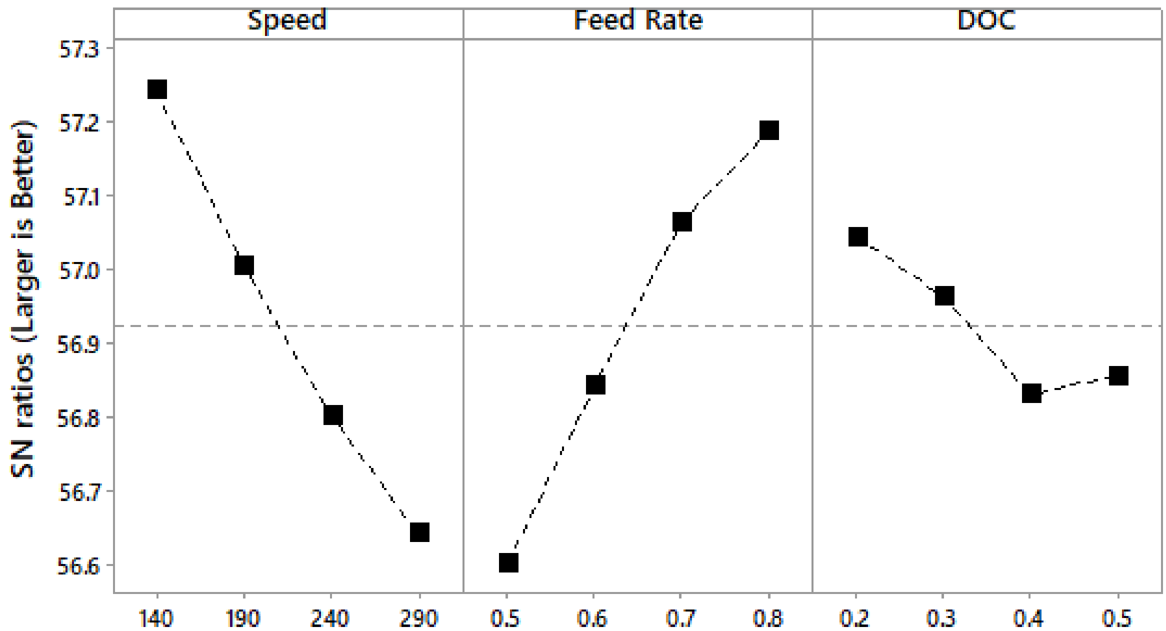

Fig. 6 S/N Ratio of Surface Roughness plots for input parameters

Table 8 and Figure 6 both show the results of rank identification as well as the S/N ratio, indicating that a higher ratio is better. As can be seen in Table 8, the most important element that can determine the chip thickness of an object is the speed. Feed rate is the second most important factor, and DOC is the least important factor for controlling the chip thickness. In present study the chip thickness was measured by using digital Vernier caliber devices.

Regression modeling is developing the statistical relation among independent and dependent factors and the validated with using Analysis of variance (ANOVA) test. In present section the linear regression modeling equations was developed for chip thickness. After developed equation was tested by ANOVA test in which percentage contribution of each factors was presented. The Pareto chart and AVOVA table was shown in figure 7 and table 9 respectively.

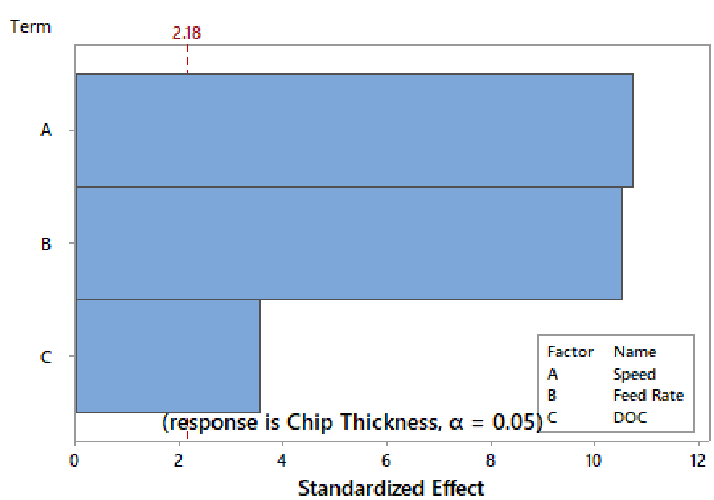

Fig. 7 Pareto Plot for Response Surface Roughness for Linear Regression

TABLE 9

ANOVA testing for regression of surface roughness

Source	DF	SS	Contribution	MS	F-Value	P-Value
Model	3	10638	95.22%	3546.01	79.63	0
Linear	3	10638	95.22%	3546.01	79.63	0
Speed	1	5136	45.97%	5136.01	115.33	0
Feed Rate	1	4945.5	44.27%	4945.51	111.05	0
DOC	1	556.5	4.98%	556.51	12.5	0.004
Error	12	534.4	4.78%	44.53		
Total	15	11172.4	100.00%			
R2			82.23%			

As seen in table 9 ,the highest contribution of among all factors was for Feed rate which was equal to 46% whereas the least percentage contribution was for DOC and the present factor was not significant for the liner regression model equation of the chip thickness. The normal probability plot for the residuals of the chip thickness was shown in figure 8.

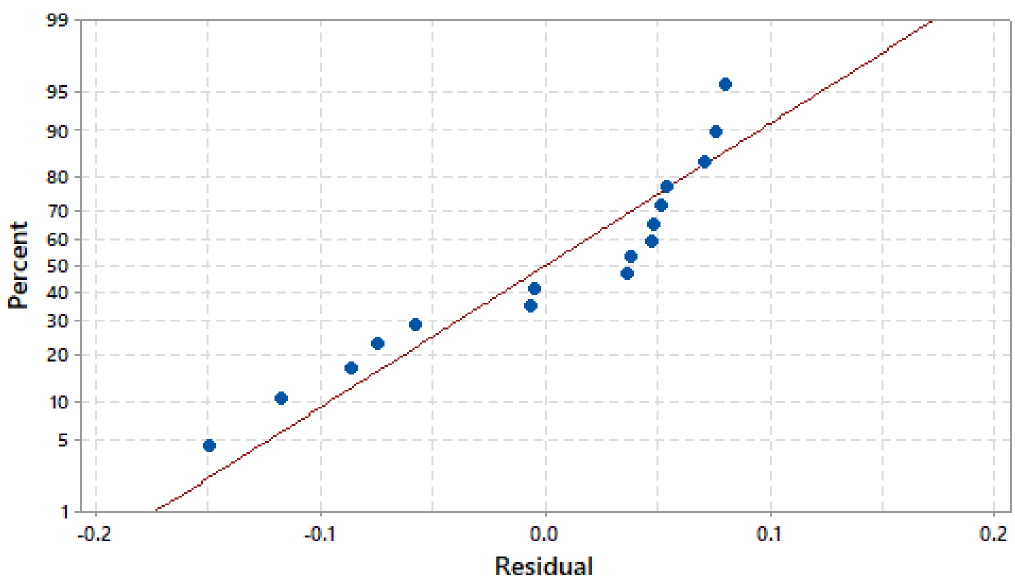

Fig. 8 Normal Probability plot for Regression of Surface Roughness

The final linear regression model equation developed for chip thickness was shown in equation

$$\text{Chip Thickness} = -(0.3205 * \text{Speed}) + (157.3 * \text{Feed Rate}) - (52.7 * \text{DOC}) + 687.3$$

8.Conclusion

Analysis of the signal-to-noise ratio, in which a higher value indicates less noise, was performed on the chip thickness response parameter. This led to many significant conclusions, which are as follows: The parameter with the highest ranking was speed, followed by the parameter with the second highest ranking, which was feed rate. The parameter with the lowest ranking was DOC. The Optimal solution for the surface roughness was at (Speed140 FeedRate0.8 DOC0.2) found. It was also discovered that raising the speed resulted in a reduction in the chip thickness of the object being processed. When the feed rate was raised, the chip thickness of the item was likewise increased. However, when the feed rate was increased for DOC, the chip thickness was initially dropped and subsequently increased.

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