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Experimental investigation of Machining Surface in Thermally Enhanced Machining using Taguchi's Approach.

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Abstract

Hot-machining operation is a machining method conducted on conventional machine tools in which work piece is preheated before cutting operation to become softer and thereby to reduce its shear strength and hardness. Due to reduction in hardness and shear strength, it becomes easy to cut materials as resulting low forces and gives improved surface fining of the product, extended tool life is another added advantage. As it known that the machining of hard materials such as EN 31 steel, which has high strength and toughness, has always been a great challenge. EN 31 steel consist of high chromium content which contributes to high hardness and wear resistance complicating the machining process. Machining of these alloys and materials requires cutting tool of high strength, which is sometimes not economical and sometimes even impracticable. Also during the machining maintaining of optimum temperature is also important as an excessive generated heat can cause tool wear and affects the quality of surface finish. Thus, the focus of the project work is to optimize the response that is "surface roughness" of hot machining (turning) process by controlling the process parameters like Temperature, Cutting Speed, Depth of cut.

1. Introduction

Turning is a material removal process at high speed, which is used to create rotational parts by removing unwanted material through cutting using special tools. The turning process requires a turning machine or lathe, work piece, fixture and cutting tools. In advancement in science and technology, there is a need of materials with has very high hardness and shear strength. Higher strength of material leads to increase in tool wear and frequent tool replacement and necessitating more frequent maintenance or down time that leads to higher production cost ultimately impacting the overall performance of the machine. So machining of such materials with conventional method of machining proved to be very costly as these materials greatly affect the tool life. Apart from tool wear and material properties manufacturer also has to consider impact of increased cutting forces, added cooling and lubrication need, longer machining times. So to increase tool life, to decrease the power consumption and for improving the machinability an innovative process Hot Machining came into existence. "Hot machining turning operation" is a machining method conducted on conventional machine tools in which work piece is preheated before cutting operation to become softer and thereby to reduce its shear strength." Hot Machining can be used to decrease tool wear, power consumed and increase surface finish. In Hot Machining as the temperature is increased, the strength of a metal decreases, while the ductility and plasticity of metal increases.

2. Literature Review

Nirav M Kamdar and Vipul K Patel [1] have studied the EN 36 steel specimen which is heated with gas flame and were machined on a lathe under different cutting conditions of Surface temperatures, Cutting speeds and Feed rates. Cutting force, feed force and surface roughness were studied under the influence of machining parameter at 200 °C, 300 °C, 400 °C, 500 °C and 600 °C at constant depth of cut 0.8 mm. The optimum result was achieved in the experimental study by employing Design of experiments with Taguchi. In present study, Analysis found that varying parameters are affected in different way for different response. The ANOVA analysis was used to obtain optimum cutting parameters.

The EN 36 Steel is a low carbon and high alloy content alloy steel. Characteristics of steel are toughness arising from the use of nickel and a more uniform hardness produced by the use of chromium. It is specifically designed for carburizing to give a very hard case with strong core. It is widely used for components with large cross section, requiring high toughness and Score strength such as gears, crane shafts and heavy-duty gear shafts in aircraft and truck construction and mechanical engineering. The chemical compositions of EN 36 Steel are given in Table 2.1.

EN-8	
Element	% Constitutes
Carbon (C)	0.420
Nickel (Ni)	0.079
Chromium (Cr)	0.170
Silicon (Si)	0.220
Manganese (Mn)	0.780
Sulphur (S)	0.050
Phosphorus (P)	0.035
Molybdenum (Mn)	0.025
Hardness: 55 HRC	

Table 2.1 Chemical Composition of EN 36 steel.

The result shows with increase in gas flame temperature the cutting force, feed force and power consumption reduces also surface roughness improves for constant cutting speed. Along with these result for same cutting speed the feed rate also reduces which ultimately affects the tool life.

K. A. Patel and S B Patel [2] have carried out evaluation and optimization of hot machining process parameters in the lathe machine using Taguchi orthogonal array is used for statistical method. For input values of speed, feed and depth of cut against output of surface quality for EN 8 steel material studied.

EN-36	
Element	% Constitutes
Carbon (C)	0.700
Nickel (Ni)	3.200
Chromium (Cr)	1.050
Silicon (Si)	0.250
Manganese (Mn)	0.420
Sulphur (S)	0.010
Phosphorus (P)	0.012
Molybdenum (Mn)	0.140
Hardness: 55 HRC	

Table 2.2 Chemical Composition of EN 8 steel.

The investigation carried out by varying three control factors Temperature, Cutting Speed and Feed rate on hot machining. For experimental work of hot turning 35 mm diameters EN 8 Steel bar used for constant depth of cut 0.8 mm. Control factors along with their levels are listed in Table 2.4. Hence Taguchi based design of experiment method was implemented. In Taguchi method L25 Orthogonal array provides a set of well-balanced experiments, and Taguchi's signal-to-noise. (S/N) ratios.

Factors	Parameters	Level 1	Level 2	Level 3	Level 4	Level 5
A	Speed(m/min)	60	90	135	202	303
B	Feed (mm/rev)	0.111	0.222	0.33	0.444	0.555
C	Temp (°C)	100	200	300	400	500

Table 2.3 Control Factors

Sr No	Speed (m/min)	Feed (mm/rev)	Temp (°C)	Surface Roughness
1	60	0.111	100	5.4234
2	90	0.222	100	5.3389
3	135	0.333	100	5.2194
4	202	0.444	100	5.0487
5	303	0.555	100	4.7988
6	60	0.111	200	4.7170
7	90	0.222	200	4.6325
8	135	0.333	200	4.5131
9	202	0.444	200	4.3424
10	303	0.555	200	4.1654

Table 2.4 Taguchi's L25 Standard orthogonal array

It has been concluded by the authors that, hot machining process gives good surface finish at high cutting speed and low feed rate. And it is also beneficial in terms of surface roughness, Optimum results are achieved when Cutting speed is 300 rev/min, Depth of Cut is 0.8 mm, Feed is 0.111 mm/rev and Temperature is 500°C during hot machining.

Ketul M Trivedi, Jayesh V Desai and Kiran Patel [3] have tested material having very high hardness above 45 Hrc, which is very difficult to machine with conventional machining process. The Work piece is preheated or heated during machining operation in hot machining method and it was reported that many advantages have been observed like longer tool life, better surface finish and cost-effective production. In this work, an experimental investigation had been carried out for hot machining of AISI 4340 steel using a tungsten carbide cutting tool. AISI 4340 steel is high-carbon chromium steel, with small quantities of silicon and manganese. AISI 4340 Steel is exceptionally hard and wear-resistant, and is It is widely used for aircraft landing gear, power transmission gear, shaft and other parts. An excellent choice for applications where high operating temperatures is needed. The heating of the work piece was carried out by burning a mixture of oxygen and acetylene gas. The influence of the cutting parameters namely cutting speed (Vs), feed rate (fs) and depth of cut (ap) at 200°C, 400°C and 600°C hot machining of AISI 4340 steel on surface roughness are studied. Individual and combined effects of cutting parameters i.e. temperature, cutting speed, feed on the surface roughness of the work piece are investigated. The relationship between the parameters and the performance measure is determined using multiple linear regression equation. The experiment was conducted on an auto feed lathe for hot machining operation of AISI 4340 Steel using a Tungsten Carbide cutting tool. The temperature was measured by infrared thermometer for different condition.

AISI 52100	
Element	% Constitutes
Carbon (C)	1.100
Nickel (Ni)	0.001
Chromium (Cr)	1.600
Silicon (Si)	0.300
Manganese (Mn)	0.450
Sulphur (S)	0.025
Phosphorus (P)	0.025
Molybdenum (Mn)	0.350
Hardness: 60-67 HRC	

Table 2.5 Chemical Composition of AISI 4340

The result shows that at 200°C for increasing the cutting speed from 13.84 m/min to 21.75 m/min the feed rate adjusted to 0.065 mm/rev to 0.102 mm/rev which gives surface roughness in the range of 1.520 to 1.485 μm respectively. Similarly, for 400°C for increasing the cutting speed from 13.84 m/min to 21.75 m/min the feed rate adjusted to 0.065 mm/rev to 0.102 mm/rev which gives surface roughness in the range of 1.356 to 1.289 μm respectively. The result shows the improvement in the surface roughness and tool life due to hot machining.

AISI 4340	
Element	% Constitutes
Carbon (C)	0.430
Nickel (Ni)	2.000
Chromium (Cr)	0.900
Silicon (Si)	0.400
Manganese (Mn)	0.900
Sulphur (S)	0.040
Phosphorus (P)	0.035
Molybdenum (Mn)	0.300
Hardness: 45-50 HRC	

Table 2.6 Chemical Composition of AISI 52100.

Nikunj R Modh, G D Mistry and K B Rathod [4] studied parameters like cutting force, feed force and surface roughness under the influence of machining parameters namely cutting speed (Vs), feed rate (fs) and depth of cut (ap) at 200 °C, 400°C and 600 °C. The optimum result was achieved in the experimental study by employing Design of Experiment with full factorial design. The ANOVA analysis was used to obtain optimum cutting parameters and optimum parameters are cutting speed - 965rev/min, Depth of Cut - 0.8 mm, Feed - 0.265mm/rev and Temperature - 600 °C Also the relation between the parameters and the performance measure were determined using multi regression equation.

Hot machining process gives good surface finish at high cutting speed, high temperature and low feed rate and it is also beneficial in terms of low cutting force and feed force. Optimum results are achieved when Cutting speed is 965 rev/min, Depth of Cut is 0.8mm, and Feed is 0.265mm /rev and Temperatures 600°C. During hot machining, the change of the work piece surface colour was also observed at temperature of 600°C.

Shyamkumar Karna, and Dr. Rajeshwar Sahai[5] carried out Optimization of process parameters to get good control over quality, productivity and cost aspects of the process. Authors have presented brief review of The Taguchis' method and concluded that off-line quality control is considered to be an effective approach to improve product quality at a relatively low cost. Analysis of variance (ANOVA) is used to study the effect of process parameters on the machining process. The approach is based on Taguchi method, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) are employed to study the performance characteristics. Authors claim that The Taguchi's approach can facilitate manufacturer to identify the common parameters because it will not vary and can provide robust standard for widely and frequently changing situation.

3. Result and Discussion

Minitab software is widely used for statistical analysis, including design of experiments and data interpretation. It provides tools for graphical analysis, regression, and ANOVA, which can help in understanding the impact of different parameters on experimental results.[5][6] The following factors based on L_{27} full fraction shown in Table 3.1 are obtained using Taguchi's approach[7][8]

Factors Levels	**Temperature (^{0}C) A**	**Cutting speed (m/min) B**	**Depth of cut (mm) C**
1	200	18.18	0.3
2	400	25.82	0.2
3	600	35.81	0.1

Table 3.1 Levels of Taguchi Design

Upon finalizing the setup, the workpiece was securely clamped between the headstock and tailstock to ensure stability during the machining process. For the heating phase, a controlled mixture of LPG gas and oxygen gas was employed, enabling precise adjustments to the gas pressure. This variation directly influenced the thermal profile of the workpiece surface throughout the turning operation.[3][4]

Following the completion of the turning process on all bars, the surface roughness of the workpieces was quantitatively assessed using a calibrated surface roughness tester. The measured surface roughness values were systematically recorded and subsequently input into Minitab software for advanced statistical analysis. A range of analytical techniques was employed, with a particular focus on Taguchi analysis, to rigorously evaluate the experimental results. This approach facilitated the identification of optimal process parameters and the assessment of their effects on surface quality, thereby enhancing the overall understanding of the machining process [1]-[4]. Detail analysis of the experiments is shown below

Temp.	**cutting speed**	**depth of cut**	**surface roughness**	**Temp.**	**cutting speed**	**depth of cut**	**surface roughness**
200	18.18	0.3	4.28	400	25.82	0.1	3.15
200	18.18	0.2	3.96	400	35.81	0.3	3.05
200	18.18	0.1	4.12	400	35.81	0.2	2.79
200	25.82	0.3	3.75	400	35.81	0.1	2.56
200	25.82	0.2	3.48	600	18.18	0.3	2.96

200	25.82	0.1	3.28	600	18.18	0.2	2.78
200	35.81	0.3	3.33	600	18.18	0.1	2.45
200	35.81	0.2	3.08	600	25.82	0.3	2.72
200	35.81	0.1	2.98	600	25.82	0.2	2.66
400	18.18	0.3	4.05	600	25.82	0.1	2.38
400	18.18	0.2	3.38	600	35.81	0.3	1.96
400	18.18	0.1	3.25	600	35.81	0.2	1.59
400	25.82	0.3	3.35	600	35.81	0.1	1.13
400	25.82	0.2	3.70				

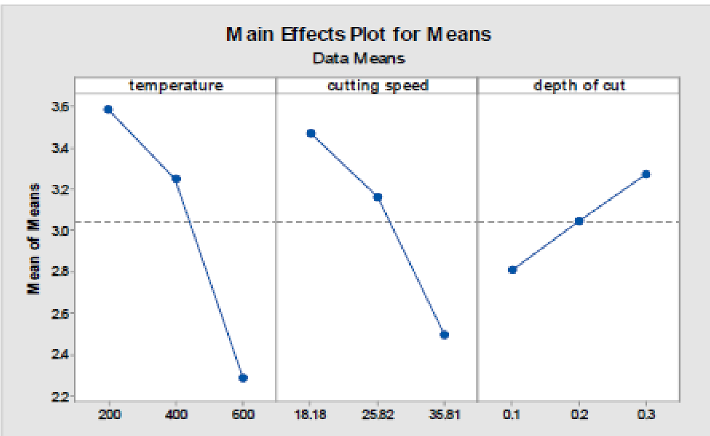
Table.3.2 Result table of hot working

The experimental results were analysed using Minitab software, focusing on the Taguchi analysis for surface roughness versus temperature, cutting speed, and depth of cut.

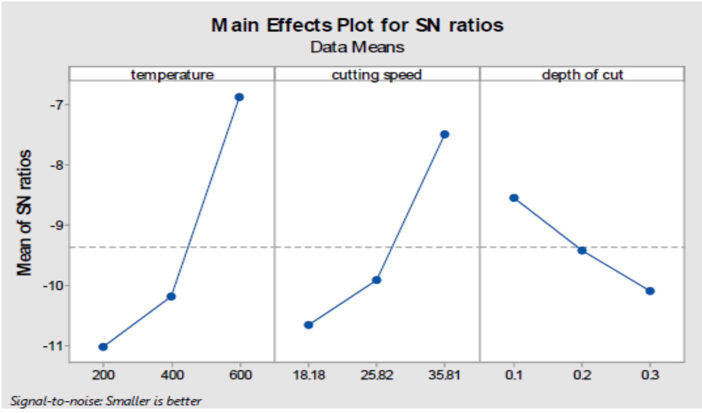
Cutting speed (m/min)	**Depth of Cut (mm)**	**Surface Roughness Ra(mm)**
18.18	0.3	8.62
25.82	0.3	7.16
35.81	0.3	6.47
18.18	0.2	8.41
25.82	0.2	7.15
35.81	0.2	7.10
18.18	0.1	7.62
25.82	0.1	6.58
35.81	0.1	5.95

Table 3.3 Result table of cold working

3.3.1 Main Effects Plot for Means and SN ratios: -



(a) MAIN EFFECT PLOT FOR MEANS



(b)

(c) MAIN EFFECTS PLOT FOR SN RATIOS

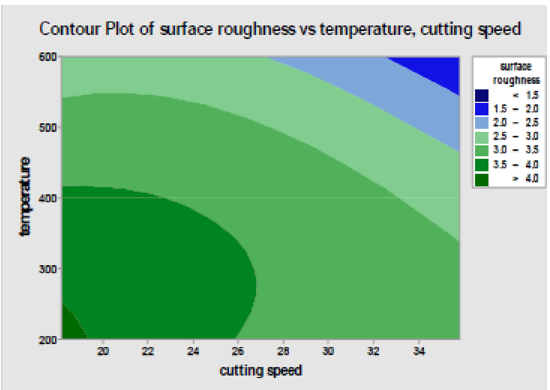
Fig.1 Main Effects Plot

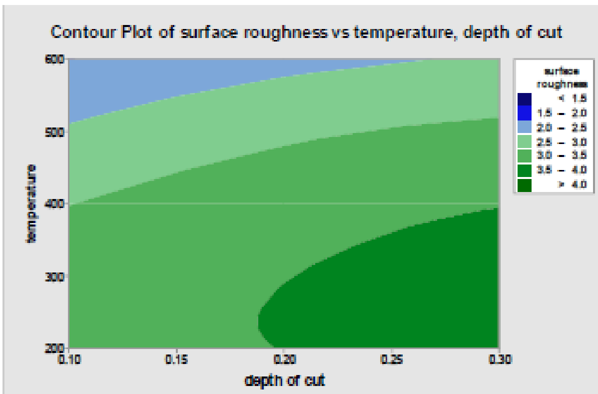
The analysis of the data in Fig.1 reveals that surface roughness (Ra) is inversely related to both cutting temperature and cutting speed. As cutting temperature increases, surface roughness decreases due to thermal softening of the material, which facilitates smoother machining and reduces built-up edge formation [3][4][9]. Similarly, higher cutting speeds lead to lower surface roughness by enhancing shearing action and reducing tool–workpiece contact time, minimizing friction and material adhesion [10]. In contrast, increasing the depth of cut results in higher surface roughness. This is due to greater material removal volume, which intensifies cutting forces and vibrations, leading to increased surface irregularities. Similar trends were observed by Trivedi et al. [3] and Modh et al. [4] in their studies on AISI steels. The thicker chips generated at higher depths also contribute to elevated heat and tool wear, further degrading surface finish. Optimizing cutting parameters—specifically increasing cutting speed and managing temperature while minimizing depth of cut—is essential for achieving superior surface quality in machining processes.

The graph illustrates in Fig.2 the main effects of various parameters—temperature, cutting speed, and feed rate—on surface roughness during the hot machining of EN 31 steel.

Key observations include that the optimal surface roughness is achieved at a temperature of 600 °C. At this temperature, the thermal softening of the material enhances machinability, leading to smoother surface finishes. A cutting speed of 35.81 m/min is identified as optimal for minimizing surface roughness. This speed promotes effective shearing and reduces tool–workpiece contact time, thereby decreasing friction and improving surface quality. A depth of cut of 0.1 mm is associated with the lowest surface roughness. This shallow cut minimizes the impact of cutting forces and vibrations, contributing to a finer surface finish. Overall, the combination of these parameters—600 °C temperature, 35.81 m/min cutting speed, and 0.1 mm depth of cut—results in the best surface quality for EN 31 steel in hot machining conditions.

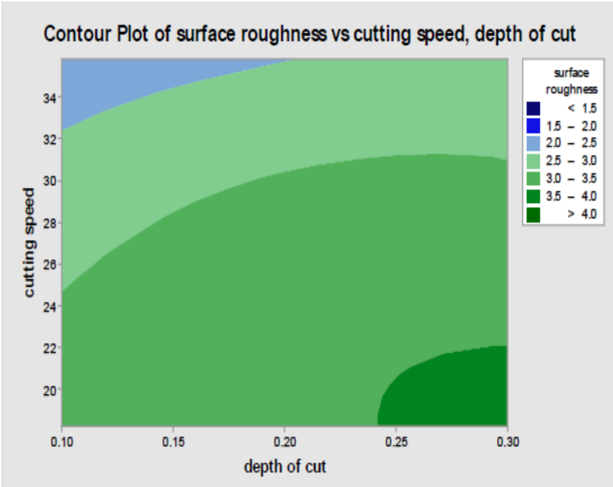
3.3.2 Contour Plot





(a) Contour Plot of Surface Roughness Vs Temperature, Cutting Speed

(b) Contour Plot of Surface Roughness Vs. Temperature, Depth of Cut



(c) Contour Plot Of Surface Roughness Vs. Cutting Speed, Depth Of Cut

Fig.2 Contour Plot

The analysis of the contour plots provides valuable insights into the effects of various machining parameters on surface roughness:

Contour Plot (a): It is observed that an increase in both cutting speed and temperature correlates with a decrease in surface roughness values. Higher cutting speeds enhance the shearing action during machining, reducing friction and material adhesion, which leads to smoother surfaces. Elevated temperatures facilitate thermal softening of the material, improving machinability and contributing to a finer surface finish. Together, these factors significantly reduce surface roughness, emphasizing the importance of optimizing cutting speed and temperature for improved surface quality.

Contour Plot (b): An increase in temperature leads to a decrease in surface roughness values, attributed to the thermal softening of the material. This enhancement in machinability allows for smoother cutting action and improved surface finishes. Conversely, an increase in depth of cut results in an increase in surface roughness values due to the greater volume of material being removed per pass, which intensifies cutting forces and vibrations. These factors contribute to increased surface irregularities, degrading the surface finish. In summary, higher temperatures improve surface quality, while greater depths of cut negatively impact surface roughness.

Contour Plot (c): It is evident that an increase in cutting speed, coupled with a decrease in depth of cut, results in a reduction in surface roughness values. Higher cutting speeds enhance the shearing action during machining, minimizing friction and improving material removal efficiency, which leads to smoother surfaces. Simultaneously, reducing the depth of cut decreases the volume of material being removed per pass, lessening the cutting forces and vibrations experienced by the tool and workpiece. This combination effectively contributes to achieving finer surface finishes, thereby decreasing surface roughness.

The analysis of these contour plots highlights the critical role of cutting speed, temperature, and depth of cut in influencing surface roughness during machining processes. Optimizing these parameters is essential for achieving superior surface quality.

3.3.3 Interaction Plot for surface roughness

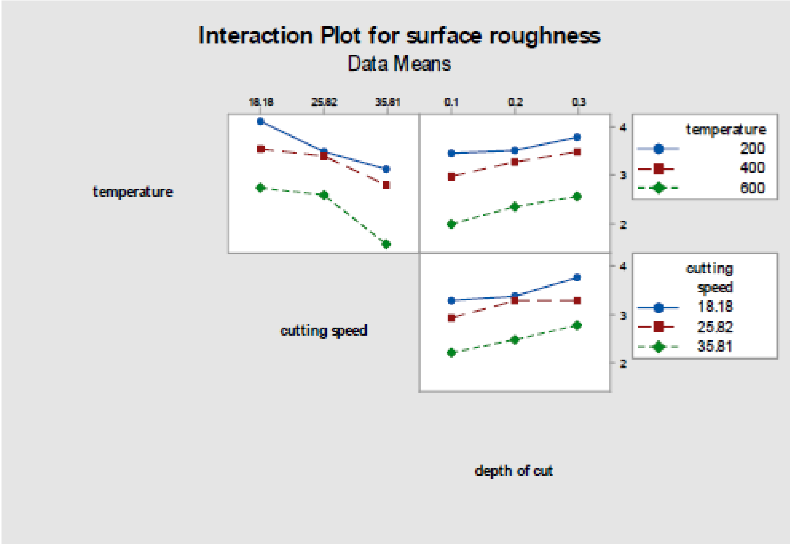


Fig.3 Interaction Plot for Surface Roughness

From the analysis of the graph, it is evident that the minimum surface roughness value is achieved at the following optimal parameters:

Temperature: 600 °C

Cutting Speed: 35.81 m/min

Depth of Cut: 0.1 mm

These specific conditions facilitate the best machining performance, resulting in a finer surface finish. The elevated temperature enhances the material's machinability, while the selected cutting speed and shallow depth of cut minimize cutting forces and vibrations, contributing to reduced surface roughness. This combination underscores the importance of carefully selecting machining parameters to optimize surface quality in manufacturing processes.

Conclusion

The experimental investigation demonstrates that hot machining significantly enhances the surface finish of hard materials compared to conventional machining under similar conditions. Optimal results were achieved at an elevated workpiece temperature of 600 °C, a cutting speed of 35.81 m/min, and a reduced depth of cut of 0.1 mm. Under these parameters, the minimum surface roughness (Ra) was recorded at 1.13 µm, indicating a notable improvement in surface integrity. The elevated temperature during hot machining reduces material hardness and cutting resistance, facilitating smoother chip formation and improved tool-workpiece interaction. Consequently, hot machining proves to be an effective approach for improving surface quality in the machining of hard-to-cut materials.

Future Scope:

In future work, an advanced attachment will be developed and integrated into the lathe machine to enable automated feeding and positioning of the heating torch. This modification aims to ensure consistent and controlled preheating of the workpiece during hot machining operations, enhancing process repeatability, operator safety, and surface finish consistency.

The automation of the heating system will also allow for precise temperature regulation, enabling real-time thermal control and better integration with CNC or semi-automated machining processes. This advancement could significantly improve the industrial applicability of hot machining techniques, especially for hard-to-machine alloys and high-performance materials.

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