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Optimization of process parameters for CNC turning on nickel alloy using PVD coated cemented tungsten carbide tool

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ABSTRACT

The growing demand for products that resist in environments considered severe has stimulated in the last years series of researches. They have the objective to improve the properties of materials and their processing and applications. Among the metals commonly used in extreme temperature and corrosion, there are the nickel superalloys. However, the same thermal, mechanical and metallurgical properties, which make it a material of great applicability, also characterized as one of the metals of low machinability. Given that the market trend is increasingly using special materials such as superalloys, a detailed study about the machining of these materials is strategic and it is necessary that companies constantly seek to improve their processes. Besides that, the attention to environmentally safe processes from society and governmental regulation is growing. Therefore, this paper evaluates the economic machinability of superalloy Inconel 625 round bar on CNC turning Lathe machine as Inconel 625 material has many industrial applications. In this work Taguchi's DOE L_9 orthogonal array was employed with the aim of simultaneously optimizing surface hardness, cutting force with tooling cost and cutting time incorporated. Cutting speed, feed rate and depth of cut were chosen as process control factors.

Keywords- *Inconel 625, Taguchi's DOE L_9*

1. INTRODUCTION

Machining process which consists of removing of material and modification of part surface is a part of main manufacturing processes including casting, metal forming, powder metallurgy and joining processes. Parts manufactured by latter processes often need machining operations before using them. In other words, machining processes are often considered as secondary or finishing operations [1]. Turning process using single-point cutting tool is the most common used metal cutting operation. A workpiece being machined by turning process is influenced by various force and temperature stresses, which, in turn, affect the final surface properties of the product. Achieving high accuracy and acceptable surface integrity including surface roughness, hardness, residual stresses, etc during turning process is of primary importance. Surface integrity has significant effects on performance characteristics of the final product such as fatigue strength and creep.

Nickel-based aerospace alloys are gaining substantial attention because of their admirable mechanical properties, excellent weldability, high corrosion and oxidation resistance etc. Inconel 625 is one of these superalloys, widely used in manufacturing sectors, particularly for aerospace components, gas turbine blades, springs, bellows for submarines, steam power plants and oceanographic instrument components. However, machinability of Inconel 625 is considered to be poor because of its poor heat conductivity, formation of built-up edge and high-sticking or welding tendency to insert/tool cutting edges. This places Inconel 625 in the category of hard to machine material.

Increasing the productivity and the quality of the machined parts are the main challenges faced by the manufacturing industry. General information on operating parameters employed when turning nickel based alloys are available in both academic and industrial literature. There are some technical challenges for nickel-based alloy materials machining such as precipitation strengthening, machining, hardness affinity, carbonized precipitation and thermal conductivity. The relative forces in a turning operation are important in the design of machine tools. The machine tool and its components must be able to withstand these forces without causing significant deflections, vibrations, or chatter during the operation. The purpose of this study is to analyze the significant factors of cutting time, tooling costs, cutting force and surface hardness. This helps in economic machinability in manufacturing and in practice, one of the most decisive factors in selecting the preferred cutting parameters is achieved.

The effects of cutting parameters on surface integrity and cutting force generated in turning have been investigated by several researches. Shao-Hsien et al [2] investigated a nickel alloy turning parameter model, built by using new uniform design and regression analysis to predict the I/O relationship among various combinations of variables. The errors between actual values and prediction values are validated for the cutting tool wear, surface roughness, machining time and cutting force; the errors of various dependent variables are approximately less than 10%, so a high precision estimation model is obtained through a few experiments. Fan et al [3] state a review on cutting tool technology in machining of Ni-based superalloys to better understand the current status of cutting tool technologies. It state that big data with advanced analytics can only be used to improve the current machining methods, rather than replacing them. Gong et al [4] used MQL strategy based on graphene nanofluids for sustainable turning of Inconel 718. Results showed that the nanofluid with the lowest size of graphene nanoplatelets promoted the best surface roughness quality compared to flood condition that represents the current machining standard. Dhananchezian et al [5] studied the effectiveness of cryogenic cooling using liquid nitrogen as coolant in turning of Inconel 625 with PVD-TiAl-N-coated carbide inserts. The result reveals that surface roughness was significantly improved and the SEM investigation state the used cutting insert's tool wear was reduced under cryogenic cooling compared to dry turning. Chen et al [6] focuses on the machining performance on the novel wrought nickel-based superalloy, AD 730™ under high speed turning conditions with advanced PCBN tools. With this result showed that high cutting speeds and a low feed rate are preferable in order to implement more cost-effective machining without largely reducing the surface quality and with optimum cutting force.

Cutting tools are subjected to force and temperature stresses which lead to tool wear. Various parameters affect tool wear rate and wear mechanisms such as cutting fluid, cutting speed and feed rate [7], as well as cutting material and geometry [8]. Furthermore, tool wear increases cutting forces and as a result, worsens surface quality [9]. Talwinder et al [10] experimented CNC turning of Inconel 625 using PVD coated carbide (Al,Ti)N under nanofluid minimum quantity lubrication (NMQL) coolant and compared it over dry and flood/wet machining. The results revealed superiority of NMQL in terms of better tool life and improved surface finish, thus provides the way forward for sustainable and environment friendly machining. Rodrigo et al [11] evaluated the performance of different conditions, dry and wet, on external longitudinal turning of Inconel 718 with ceramic tools. The result showed that in both conditions, the main tool wear is notch and flank wear and it is extremely high. In relation to tool life experiments, the best result was obtained by SiAlON, with cutting fluid application. It also put step towards environment friendly, economic and healthy machining.

Various methods have been used to optimize cutting parameters for improving tool life and achieving better surface quality such as Taguchi method. Kaitao et al [12] studied the machinability of Hastelloy C-276 using a newly developed hot-pressed sintered Ti(C7N3)-based cermet cutting tool. Based on the ANOVA result range analysis, the best optimal cutting conditions were achieved with longest tool life. Zhirong et al [13] studied a novel approach for tool wear condition monitoring (TCM) which is based on the multi-scale hybride hidden Markov model (HHMM) analysis of cutting force signal. As an example, CNC turning of Inconel 718 was examined. The result state the HHMM structure can distinctly separate the tool wear states and captures the tool wear process information efficiently for TCM. Wojciech et al [14] reported chip breakers reliability in local operating features. Inconel 718 alloy was used as sample material in turning and two different chip breakers were tested. This aims to check the efficiency of chip breakers. The simulation based on the FEM was applied to estimate chip groove filling. This approach show the mutual interference between the chip form and chip breaker geometry.

The optimum machinability is desired; however it should be economically justifiable. Bin et al [15] studied finish-turning of NiCr20TiAl nickel-based alloy using Al2O3/TiN-coated carbide tools under various cutting conditions. The result state that the plastic flow of NiCr20TiAl alloy was presented on the machined surface by the lower cutting forces. The tensile residual stress was endangered on the machined surface and increased with the cutting parameters. Thakur et al [16] experimented machinability of Inconel 718 when machined with cemented tungsten carbide (K20) insert tool. The analysis was done on the machinability indices such as chip compression ratio, shear angle, surface integrity and chip analysis. The result indicated that these indices are important and necessary to access the machinability of Inconel 718 material effectively during high-speed machining. Choudhary et al [17] presented a general review on machinability of nickel-base superalloys particularly for Inconel 718 when using different cutting tools. Result showed that Alumina-TiC ceramic tools are best suited for high speed machining or high feed rate, whilst whisker-reinforced alumina is suitable for a medium cutting speed with a low feed rate.

The purpose of this study is to analyze the significant factors of cutting time, tooling costs, cutting force and surface hardness. This helps in economic machinability in manufacturing and in practice, one of the most decisive factors in selecting the preferred cutting parameters is achieved.

2. PROPOSED ALGORITHM

2.1 Workpiece material used

Nickel-based alloy Inconel 625 superalloy round bar of 90 mm length and 30 mm diameter was used as the workpiece material. The chemical composition of the workpiece material is given in table 1.

Table 1: Chemical composition of workpiece material

Component	Weight %
C	0.0300
Si	0.0600
Fe	4.7600
Mn	0.1000
Ti	0.3590
Al	0.3400
Cr	20.8100
Mo	8.2800
Ni	61.5000
P	0.0050
Co	0.0030
Cb+Ta	3.6200
NB	3.6000

Image 1: Work specimen Inconel 625

Product specification: Ni Cr Mo Alloy 625 acc to ASTM B446-03 (UNS N06625) Grade 1 hot worked, bright, annealed.

Mechanical properties: Test report number/ Mill Certificate number AD A/G02/2733-2/AD Temp (ºC): 60º C, 0.2% Proof stress (MPa): 520.0, U.T.S. (MPa): 950.0, Elongation % on 4D: 48.0, Reduction of area %: 61.0, Hardness (HBW): 229/229, Impact (Charpy) (Joules): 124 131 136.

2.2 Cutting tool inserts

The PVD nano-multi-layered AlTiN coated with high Al cemented tungsten carbide inserts from Tungaloy company were used. The insert's ISO designation is TNMG 160408-HRM AH8015 for medium cutting to finishing (i.e. roughing) and CNMG 120408-HRM AH8005 for finishing the workpiece. These coatings are a combination of layers having a thickness of up to 50 nm.

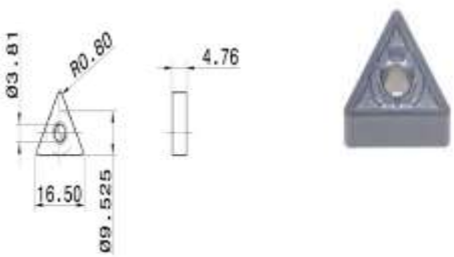

Image 2: TNMG 160408-HRM AH8015 cutting tool insert

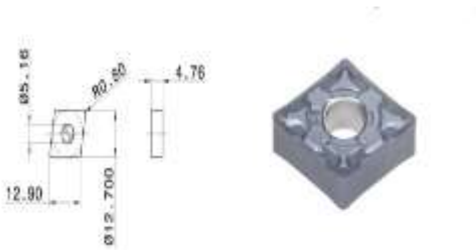

Image 3: CNMG 120408-HRM AH8005 cutting tool insert

3. WORKING MACHINERY

3.1.Computer Numerical Control (CNC) Lathe Machine for turning the specimens:

Turning experiments were carried out on HAAS model TL-1 CNC lathe machine with the following specifications:

Voltage 440V, 3-Phase, 50/60 Hertz, Full load 13AMPS, Largest load 21AMPS, Maximum spindle power 7.5KW, Maximum spindle speed 3000rpm, X/Z-axis stroke 203mm/762mm, Maximum feed rate both on X and Z-axis 11.4m/min.

Image 4: CNC graphic control unit

Image5: Turning process

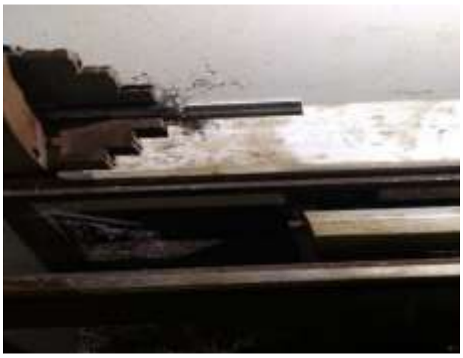

Image 6: CNC turned Inconel 625

3.1.2 Digital Universal Testing Machine Used for Surface Hardness Test:

The surface hardness test was done on the Digital UTM machine, make FIE model UTE-40 (SPL). Capacity 400KN. Least count 40N. The value for each specimen was obtained according to Brinell hardness (HB) test method.

Image 7: Operating surface roughness test on UTM

4. EXPERIMENT AND RESULT

4.1 Project Optimization Using Taguchi's Design of Experiment

Experiments were conducted according to Taguchi L_9 experimental design. Cutting speed (V), feed rate (f) and depth of cut (d) were selected as cutting parameters. With three control factors each in three levels. This is shown in table 2. According to Taguchi L_9 orthogonal array, there should be 9 experimental tests.

Table 2: Experimental control factors and their levels

Control factors	Symbol	Level 1	Level 2	Level 3
Cutting speed (m/min)	V	80	70	60
Feed (mm/rev)	F	0.10	0.15	0.20
Depth of cut (mm)	D	0.3	0.4	0.5

The machining is of step turning. The total turning length is 55 mm, facing of 1.7 mm done. The step is taken at 30 mm distance from front. This 30 mm length of rod is reduced to 25 mm diameter and the next remaining part out of 55 mm length i.e. 25 mm length is reduced to 27 mm diameter. The finished machining obtained is of smooth surface. Table 3 shows experimental design arrangement and the reading of cutting time with cutting force and surface hardness incorporated were noted and examined for optimum cutting parameters.

4.2 The CNC Turning Program As an Example for All Specimens Was As Follows

```
041063
T101;
G50 S3000;
G97 S1200 M03;
G96 S120 M08;
G00 Z20;
G00 X32 Z2.5;
G40;
G72 P1 Q2 D___ U___ W___ F___;
N1 G00 Z0;
G01 X-1.7;
N2 G00 W2.5;
G71 P1 Q2 D___ U___ W___ F___;
N1 G01 X25;
G01 Z-30;
G01 x27;
G01 Z-55;
N2 G01 F___;
G97 S1200 M09;
G28;
M01;
N2;
T202;
G50 S3000;
G97 S1200 M03;
G96 S120 M08;
G00 Z20;
G00 X32 Z2.5;
G40;
G72 P1 Q2 D___ U___ W___ F___;
N1 G00 Z0;
G01 Z-30;
G01 X27;
G01 Z-55;
N2 G01 F___;
G97 S1200 M09;
G28;
M30;
```

Image 8: Work specimens after turning

Image 9: Work specimens after surface hardness testing

5. CALCULATIONS

5.1 Calculations for Cutting Force (Fc) for All Specimens

Cutting force was calculated from the formulae. The formulation procedure is as follows:

$$\text{Power (P)} = (\text{Energy at drive motor}) \times MRR$$

$$MRR = \pi D_{avg}\, d\, f\, N$$

D_{avg} is the average diameter of workpiece that is machined.
D_f → Final machined diameter
D_i → Initial diameter of raw material

$$D_{avg} = \frac{Df + Di}{2}$$

$$P = \text{Torque(T)} \times \omega$$

$$P = T \times 2\pi N$$

$$T = \frac{Fc\ Davg}{2}$$

$$F_c = \frac{2 \times T \times 1000}{Davg} \text{ in N}$$

Approximate range of the Machine tool (specific energy) i.e. energy at drive motor is = 4.8 – 6.7 W-s/mm^3.

The average of 4.8 and 6.7 is taken for calculations i.e. 5.75 W-s/mm^3.

In the machining the value of revolution per minute (N) is kept at 1200 rpm.

The final diameter (D_f) is = 25mm and
The initial diameter (D_i) is = 30mm.

Calculations

V = 80m/min, f = 0.1mm/rev, d = 0.3mm P = (Energy at drive motor) × MRR

Now,

$$MRR = \pi\, D_{avg}\, d\, f\, N$$

$$D_{avg} = \frac{Df+Di}{2}$$

$$\therefore D_{avg} = \frac{30+25}{2}$$

$$D_{avg} = \frac{55}{2}$$

$$D_{avg} = 27.5 \text{ mm}$$

$$\therefore MRR = \pi \times 27.5 \times 0.3 \times 0.1 \times 1200$$

$$MRR = 3110.176727 \text{ mm}^3/\text{min}$$

$$P = (\text{Energy at drive motor}) \times MRR$$

$$\therefore P = 5.75 \times 3110.176727$$

$$P = 17883.51618 \text{ N-m/min}$$

$$T = \frac{P}{2\pi N}$$

$$T = \frac{17883.51618}{2\times\pi\times1200}$$

$$T = 2.371875 \text{ N-m}$$

$$F_c = \frac{2 \times T}{Davg}$$

$$F_c = \frac{2\times2.371875\times1000}{27.5}$$

$$\therefore F_c = 172.5 \text{ N}$$

V = 80m/min, f = 0.15mm/rev, d = 0.4mm

$$MRR = \pi \times 27.5 \times 0.4 \times 0.15 \times 1200$$

$$MRR = 6220.353454 \text{ mm}^3/\text{min}$$

$$P = 5.75 \times 6220.353454$$

$$P = 35767.03236 \text{ N-m/min}$$

$$T = \frac{35767.03236}{2\times\pi\times1200} = 4.74375 \text{ N-m}$$

$$F_c = \frac{2\times4.74375\times1000}{27.5} = 345 \text{ N}$$

V = 80m/min, f = 0.2mm/rev, d = 0.5mm

$$MRR = \pi \times 27.5 \times 0.5 \times 0.2 \times 1200$$

$$MRR = 10367.25576 \text{ mm}^3/\text{min}$$

$$P = 5.75 \times 10367.25576$$

$$P = 59611.7206 \text{ N-m/min}$$

$$T = \frac{59611.7206}{2\times\pi\times1200} = 7.90625 \text{ N-m}$$

$$F_c = \frac{2\times7.90625\times1000}{27.5} = 575 \text{ N}$$

V = 70m/min, f = 0.1mm/rev, d = 0.4mm

$$MRR = \pi \times 27.5 \times 0.4 \times 0.1 \times$$

$$MRR = 4146.902303 \text{ mm}^3/\text{min}$$

$$P = 5.75 \times 4146.902303$$

$$P = 23844.68824 \text{ N-m/min}$$

$$T = \frac{23844.68824}{2\times\pi\times1200} = 3.1625 \text{ N-m}$$

$$F_c = \frac{2\times3.1625\times1000}{27.5} = 230 \text{ N}$$

V = 70m/min, f = 0.15mm/rev, d = 0.5mm

$$MRR = \pi \times 27.5 \times 0.5 \times 0.15 \times 1200$$

$$MRR = 7775.441818 \text{ mm}^3/\text{min}$$

$$P = 5.75 \times 7775.441818$$

$$P = 44708.79045 \text{ N-m/min}$$

$$T = \frac{44708.79045}{2\times\pi\times1200} = 5.9296875 \text{ N-m}$$

$$F_c = \frac{2\times5.9296875\times1000}{27.5} = 431.25 \text{ N}$$

V = 70m/min, f = 0.2mm/rev, d = 0.3mm

$$MRR = \pi \times 27.5 \times 0.3 \times 0.2 \times 1200$$

$$MRR = 6220.353454 \text{ mm}^3/\text{min}$$

$$P = 5.75 \times 6220.353454$$

$$P = 35767.03236 \text{ N-m/min}$$

$$T = \frac{35767.03236}{2\times\pi\times1200} = 4.74375 \text{ N-m}$$

$$F_c = \frac{2\times4.74375\times1000}{27.5} = 345 \text{ N}$$

V = 60m/min, f = 0.1mm/rev, d = 0.5mm

$$MRR = \pi \times 27.5 \times 0.5 \times 0.1 \times 1200$$

$$MRR = 5183.627878 \text{ mm}^3/\text{min}$$

$$P = 5.75 \times 5183.627878$$

$$P = 29805.8603 \text{ N-m/min}$$

$$T = \frac{29805.8603}{2\times\pi\times1200} = 3.953125 \text{ N-m}$$

$$F_c = \frac{2\times3.953125\times1000}{27.5} = 287.5 \text{ N}$$

V = 60m/min, f = 0.15mm/rev, d = 0.3mm

$$MRR = \pi \times 27.5 \times 0.3 \times 0.15 \times 1200$$

$$MRR = 4665.265091 \text{ mm}^3/\text{min}$$

$$P = 5.75 \times 4665.26509$$

$$P = 26825.27427 \text{ N-m/min}$$

$$T = \frac{26825.27427}{2\times\pi\times1200} = 3.5578125 \text{ N-m}$$

$$F_c = \frac{2\times3.5578125\times1000}{27.5} = 258.75 \text{ N}$$

$$V = 60\text{m/min},\ f = 0.2\text{mm/rev},\ d = 0.4\text{mm}$$

$$MRR = \pi \times 27.5 \times 0.4 \times 0.2 \times 1200$$

$$MRR = 8293.804606 \text{ mm}^3\text{/min}$$

$$P = 5.75 \times 8293.804606$$

$$P = 47689.37648 \text{ N-m/min}$$

$$T = \frac{47689.37648}{2\times\pi\times1200} = 6.325 \text{ N-m}$$

$$F_c = \frac{2\times6.325\times1000}{27.5} = 460 \text{ N}$$

5.2 Calculations for Surface Hardness for All Specimens

The load (P) is given on the specimen was 3000 N for 10 seconds.

The value is calculated by the following formula of Brinell hardness test:

$$HB = \frac{2P}{(\pi D)(D-\sqrt{D^2-d^2})}$$

Where, P → Load
D → Ball diameter
d → Indentation diameter
P = 3000 N
D = 10 mm

Table 3: Experimental design arrangement using L_9 Taguchi and the results

Sr no.	Speed (V) [mm/min]	Feed (f) [mm/rev]	Depth of cut (d) [mm]	Cutting time (t) [min:sec]	Cutting force (F_c) [N]	Surface hardness [HB]
1	80	0.1	0.3	17:12	172.50	196.89
2	80	0.15	0.4	17:05	345.00	414.64
3	80	0.2	0.5	17:00	575.00	284.85
4	70	0.1	0.4	17:20	230.00	269.11
5	70	0.15	0.5	17:08	431.25	284.85
6	70	0.2	0.3	17:12	345.00	228.77
7	60	0.1	0.5	17:18	287.50	387.68
8	60	0.15	0.3	17:24	258.75	269.11
9	60	0.2	0.4	17:10	460.00	254.60

Calculations

d = 4.3 mm

$$HB = \frac{2P}{(\pi D)(D-\sqrt{D^2-d^2})}$$

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-4.3^2})}$$

$$HB = \frac{2\times3000}{(\pi\times10)(10-9.03)}$$

$$\therefore HB = 196.89$$

d = 3 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-3^2})} = 414.64$$

d = 3.6 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-3.6^2})} = 284.85$$

d = 3.7 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-3.7^2})} = 269.11$$

d = 3.6 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-3.6^2})} = 284.85$$

d = 4 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-4^2})} = 228.77$$

d = 3.1 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-3.1^2})} = 387.68$$

d = 3.7 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-3.7^2})} = 269.11$$

d = 3.8 mm

$$HB = \frac{2\times3000}{(\pi\times10)(10-\sqrt{10^2-3.8^2})} = 254.60$$

6. CONCLUSIONS AND FUTURE SCOPE

Conclusion

This research tried to investigate the optimization of one of the most important alloys from different aspects involved in turning process, i.e. workpiece, cutting tool and machining economics. For this purpose, cutting force, surface hardness, cutting time and tooling cost were investigated in turning of Inconel 625 nickel based superalloy. Optimization was carried to determine minimum values of cutting force, machining time and compatible value of surface hardness. According to the experiments and subsequently performed analyses, following conclusions can be drawn:

1. Increasing the cutting speed, decreases the cutting force due to an increased cutting temperature. This can be seen in the result of experiment calculations. High cutting force damages the tool and pile up the material from both workpiece and tool.
2. As feed rate and depth of cut increases, cutting force also increases. With increase in the depth of cut, the direction of chip flow changes.
3. For a good combination of machining efficiency, energy consumption, resultant surface integrity and cutting force, speed should be of medium range with low feed rate.
4. Hardness increases with decreasing particle size. This is known as the Hall-Petch relationship. However, below a critical grain size, hardness decreases with decreasing grain size. This is known as the inverse Hall-Petch effect.
5. Here the cutting force should be low and the surface hardness should be high enough to operate the workpiece material in applicable use.
6. So the experiment no. 4, i.e. cutting parameter set of $V_2 f_1 d_2$, i.e. 70m/min cutting speed, 0.1mm/rev feed rate and 0.4mm depth of cut was determined to be the optimum machining variables.

7. With these readings, the cutting force (F_c) calculated was less i.e. 230 N, surface hardness (HB) was compatible i.e. 269.11 with the efficient cutting time of 17 minutes 20 seconds.
8. The experiment sr. no. 1 gives less cutting force but its surface hardness value is less. So the experiment sr. no. 4 is selected as optimum machining variable.

Future scope

Machining economics has been neglected by most of the researchers; however, in practice, it is one of the most decisive factors in selecting the preferred cutting parameters. This work considered one of its factors. However, in future works, environment friendly machining of these alloys under minimum-quantity-lubrication (MQL) or cryogenic machining with the same parameters of operation can be considered. With this application temperature considerably reduces, tool hardness is maintained and hence the tool life is improved, thus allowing for higher cutting speeds. The chips also are less ductile, thus machinability is increased. There is no adverse environmental impact. This gives a new trend in machining.

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