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Depth Profiles of Residual Stresses in Inconel 718Machined with Uncoated and Coated Tools

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Inconel 718 is one of the super-alloy materials, belonging to nickel-chromium alloy family, which has major applications in aerospace sector such as engine parts and turbine components. Durability of these components during engineering performance is affected by residual stresses induced in them in the course of their manufacturing processes. The concept of the present paper is to provide an insight view of induced residual stresses in Inconel 718 work piece, when machined with coated (TiN) and uncoated tools at optimum conditions. For this purpose, turning experiments have been conducted on IN718 material through statistical approach using L9 orthogonal array. Taguchi optimization method is exercised with the emphasis on minimizing the cutting forces resulted during machining. The residual stresses generated in the work piece at the optimum conditions employed for both the tools have been evaluated using XRD method. Conditions such as cutting speed of 60 m/min, feed at 0.068 mm/rev and depth-of-cut of 0.10 mm have been optimized for achieving minimum cutting forces during machining of IN 718 using both coated and uncoated tools. However, tensile stresses on the initial surface layer and compressive stresses in the sub-surface layers are found higher in the work piece material machined with uncoated tool. Surface roughness and temperature developed on the surface of the machined bar are higher in case of uncoated tool than those with coated tool.

Keywords: Residual stresses, surface roughness, temperature, Inconel 718, TiN, coated tool

1 Introduction

Inconel 718 is a super-alloy that belongs to nickel-chromium alloy family with 50-55% of nickel and 17-21 % of chromium. Due to high proportions of chromium, it is designated as anti-corrosive, non-reactive and anti-iodizing alloy[1]. As Inconel 718 has some of the outstanding properties such as higher strength, greater corrosion resistance, low thermal conductivity and high temperature thermal stability, it is used as one of the major raw materials for manufacturing turbine blades, components of jet engine, aviation parts, cryogenic storage tanks, turbine casings etc.[2]. Residual stresses are one of the key properties affecting the durability of such components during their real-time performance. For example, surface tensile residual stresses of turbine components adversely affect their fatigue properties. Residual stresses in materials are caused due to the inhomogeneous plastic deformations of grain structures when loads or forces are applied on them, especially, during machining. Quality of these machined components is thus ensured by testing them for surface topology including presence of residual stresses as they have bearing on factor of safety in critical applications such as aero-engineparts[3]. Some of the oldest methods such as crack compliance technique proposed and developed by Cheng and Finnie[4] has been successfully used to find out the residual stresses in materials. In this process, there is a narrow cut made into the material, making the test a destructive method. Later, measurements of the induced stresses have been carried out using hole-drilling technique[5], which is considered a semi-destructive procedure. Currently, residual stresses are more conveniently measured by the non-destructive X-ray diffraction (XRD) method[6].

In conel 718 is a difficult-to-cut material[7]and so, high amounts of forces are evolved during its machining. These forces tend to increase the stress concentrations in the material. Meng Liu et al.[8], in their experimentation, have concluded that hard-to-cut materials need high thrust forces with outcomes of high tool wear and high induced stresses. Madariaga et al.[9] have studied the effect of tool wear on

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generation of residual stresses in Inconel 718 during turning operation. The authors conclude a direct proportionality between the tool's flank wear and surface residual tensile stress in the direction of cutting upto a threshold value and after that, there has been a decrement of the stresses with the increase in the flank wear. They have also found a noticeable rise in the depth of the sub-surface layers with compressive residual stresses when machined with the worn-out tools. In another study, Sharman et al.[10] have concluded that, an increase in cutting speed and the decrease in depth-of-cut induces less tensile residual stress. The authors also summarize that increasing tool wear increases the residual stresses.

In a metal cutting process, temperature and roughness of the machined surfaces are the other two supplementary attributes influenced by the machining parameters such as cutting speed, feed rate, depth-of-cut, edge radius, rake angle etc. Temperature generated during turning of Inconel 718 is the most influential factor for variation of residual stresses. While machining, high temperatures are reached in the cutting zone and during the cooling-down period, the upper layers tend to contract elastically more than the inner part, creating tensile residual stresses in the uppermost layer[11]. Friction coefficient is another parameter that influences the temperatures developed in the job material during machining, as reported by Migumao[11]. According to him, the low friction coefficient generated by the coated tool limits the high raise in temperature leading to a slight decrease in surface stresses and in the thickness of the tensile layer. Araghchia et al.[12], after their novel cryogenic experimentation on turning of aluminium 2024, have stated that the cryogenic liquid as coolant reduces the residual stress in the material. While experimenting with coated and uncoated inserts, Outeiro et al.[13] have proved that residual stresses evolved during machining with coated tools are low when compared to those with uncoated tool. Surface roughness of the material when combined with surface residual stresses affects fatigue strength and corrosion resistance of the engineering part[14-15]. In general, best fatigue properties are obtained for the specimens with lower surface roughness and higher compressive residual stresses[16].

Generation of cutting forces, which influences the residual stresses, in a material depends on the type of the material and the parameters used for machining, such as turning. Since, there are varied parameters associated with a turning operation, building a relationship between the turning conditions and residual stresses developed in the material during turning is challenging, due to the complexity of the spread of the induced residual stresses[17]. To ease such situations and minimize large parametric window, the optimal setting of parameters, where minimum cutting forces are achieved, may be performed to establish a relationship between machining conditions and residual stresses distributed across the materials from their machined surfaces[18]. Taguchi analysis has been followed with a minimum number of experiments to optimize the process parameters for a chosen attribute[19-20] such as the cutting force. Usually, the conditions, which provide less tensile stresses and more compressive stresses in the materials after machining are preferred.

The present work is, therefore, aimed to study the distribution of residual stresses along the depth from the machined surface resulted during turning of Inconel 718 with TiN coated and uncoated tungsten carbide inserts using optimum conditions evaluated from Taguchi method of machining experiments, and accordingly, to grade the performance of the tools. Analysis of the roughness values and the temperatures of the machined surfaces is also attempted to gauge the functioning of the tools used for machining.

2 Materials and Methods

2.1 Selection of materials

Inconel 718 round bars of 60mm diameter and 160mm length were selected as job materials for machining. Prior to machining, the bars were heat treated in an electric furnace at 950°C for 1h and then conventionally air-cooled to room temperature[21]. Uncoated and TiN coated WC-Co turning inserts of CNMG120408 grade (Widia India Pvt. Ltd, India) were used for machining the bars. The manufacturer used a CVD coating process to deposit a 4 µm thick TiN layer on the carbide inserts.

2.2 Turning operation

The turning operation of any material usually involves many parameters such as cutting speed, feed, depth-of-cut, tool material, tool geometry, rake angles, etc. However, to facilitate collection of the experimental data, only three predominant factors, namely, cutting speed (v), feed (f) and depth-of-cut (d), were considered in planning of the experimentation. The ranges of these factors used in the study are shown in Table 1.

The levels of the machining parameters presented in the table are based on the design of the equipment and the data provided by the manufacturer. The turning experiments were conducted on a precision lathe setup (MA-1430, Magnum Pvt Ltd., India) as shown in Figs (1 and 2) for machining of the Inconel 718 round bars. Figures (1 and 2) represent the experimental layout and the experimental set-up, respectively, for measuring the cutting forces. During turning operations, cutting force generated is a resultant force that combines tangential, feed and radial force components. Of the three cutting force components, the tangential force (F_z) is the greatest, the feed force (F_y) is less in magnitude and the radial force (F_x) is the least in magnitude. Therefore, during experimentation, greatest magnitude of the force i.e., tangential force (F_Z) was assessed. While machining, the cutting forces were measured with a four-component piezoelectric tool-post dynamometer (Kistler 9272, Kistler Group, Switzerland). The force signals generated during machining were fed into a charge amplifier connected to the dynamometer. This amplifier converted the analog signal to digital signal, which was continuously recorded by the data acquisition system connected to the charge amplifier.

2.3 Taguchi method

Taguchi concept of quality design utilizes an uncommon design of orthogonal arraysto examine the whole parameter space with modest number of trials[22]. Performance characteristics are divided into three categories in the examination of the desired attribute, namely, LTB (lower-the-better), HTB (higher-the-better) and NTB (nominal- the-better). The LTB criterion for the cutting forces was chosen for acquiring optimum process parameters during the experiments. Taguchi method recommended the use of a parameter termed signal-to-noise (S/N) ratio linked to a chosen attribute,y_i, to measure the quality characteristics deviating from the desired values of the attribute. The values of S/N ratio were determined from the Eq. 1 using cutting force as y_i.

$$\frac{S}{N} = -10 \log\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \quad \ldots (1)$$

where, 'n' is the number of tests and 'y_i' is the value of F_z of the i^{th} test.

A total of nine experimental runs were planned based on Taguchi L_9 orthogonal array as shown in Table 2 and machining was carried out under dry conditions. Later, the mean values of the S/N ratios were calculated for each parameter level. Further, the level of the given parameter and its value were

Table 1 — Turning parameters and their levels

Turning parameters	Notation	Units	Level of factors 1	2	3
Cutting Speed	v	m/min	60	90	120
Feed	f	mm/rev	0.068	0.103	0.120
Depth-of-cut	d	Mm	0.10	0.20	0.30

Table 2 — Orthogonal array L_9 of the experimental runs

Actual parameter values			Coded parameter levels		
v	f	d	v	f	d
60	0.068	0.10	1	1	1
60	0.103	0.20	1	2	2
60	0.120	0.30	1	3	3
90	0.068	0.20	2	1	2
90	0.103	0.30	2	2	3
90	0.120	0.10	2	3	1
120	0.068	0.30	3	1	3
120	0.103	0.10	3	2	1
120	0.120	0.20	3	3	2

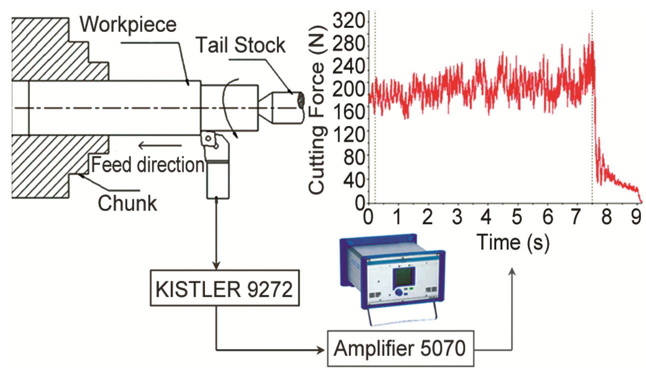

Fig. 1 — Experimental layout for measuring cutting forces.

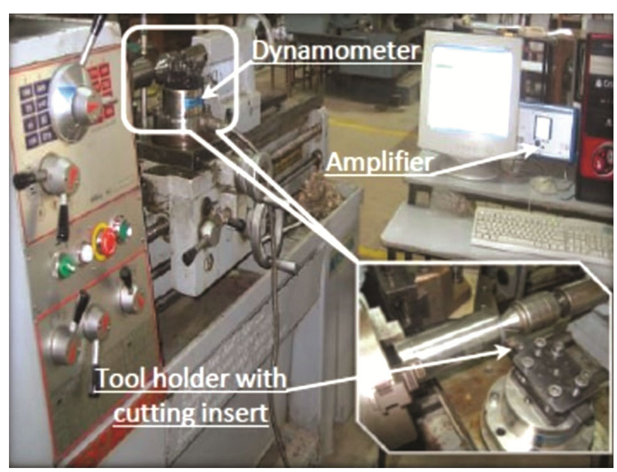

Fig. 2 — Experimental set-up for measuring cutting forces.

optimized for which a higher mean S/N ratio was observed.

2.4 Surface roughness and temperature

To measure the temperature during turning, an experimental layout and the test set-up as shown in Figs (3 and 4), respectively, were used. The temperature was measured using a K-type thermocouple, which had a measuring capacity of 1000°C. The K-type chromel thermocouple is the most common general-purpose thermocouple with a sensitivity of approximately 41µV/°C. It is inexpensive and available in a wide variety of temperature ranges from -200°C to +1260°C. The thermocouple was connected to the tool holder between shim and the insert as shown in Fig. 4 for both the coated and uncoated inserts. The temperatures were recorded digitally as depicted in Fig. 5 using an Arduino based microprocessor as shown in Fig. 3. Surface roughness (Ra) of the machined surfaces was measured using a portable surface roughness tester (Surf test SJ310, Mitutoyo, Japan).The ISO 4287:1997 standard was followed for measuring surface roughness of the specimens using a diamond probe with a speed of 0.5mm/sec scanned over a length of 4mm.

As the emphasis was given in measuring the cutting force as the main characteristic of the turning operation for optimization studies and, surface roughness and temperature are the supplementary characteristics, the latter characteristics were not recorded for every experimental run. However, they were considered and studied for the optimum machining conditions.

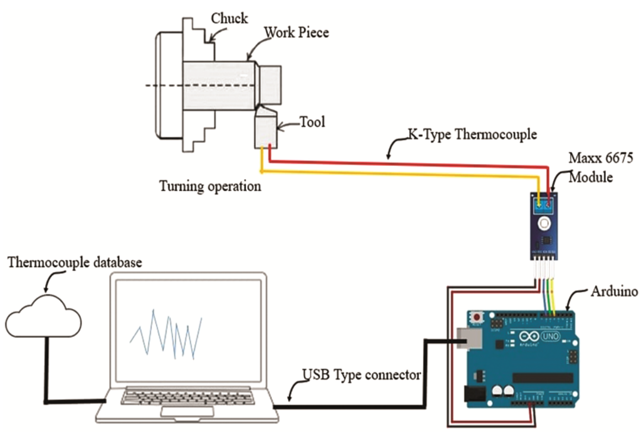

Fig. 3 — Temperature measurement layout.

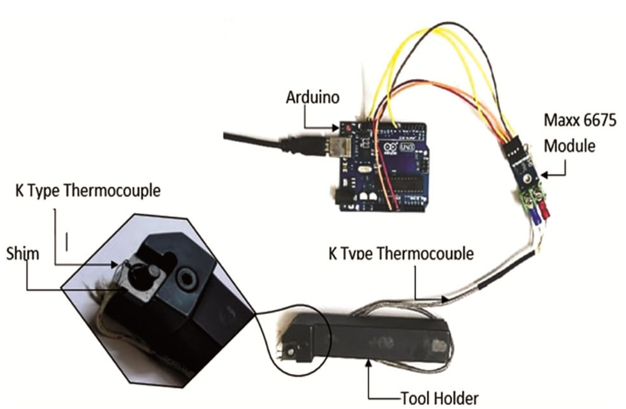

Fig. 4 — Temperature measurement set-up.

2.5 Residual stresses

In order to measure the residual stresses induced in work piece material through XRD technique, the machined surface of Inconel 718, with optimized parameters, was cut to a 5 mm thick slice by using wire cut EDM process. Generally, residual stresses are distributed up to a depth of 500µm from the surface of a material, after machining and, therefore, cutting a 5mm thick slice from the surface should not be problematic. For measuring the stresses along the depth from the machined surface, it was necessary to remove the layers, one after the other, from the machined surface in such a way that it should not affect the subsequent layer, i.e., not altering the stress state that was originally present in the material. Electro-polishing was the preferred method for removing surface layers for the purposes of depth profiling of the residual stresses[23]. Electro-polishing of the machined surfaces was carried out on Lectropolish 5 (Struers, Denmark) polishing unit. The stresses were measured on the cut slices for both the samples of Inconel 718 (machined with coated and uncoated tools) before and after electro-polishing. The stress measurements were carried out in an XRD unit

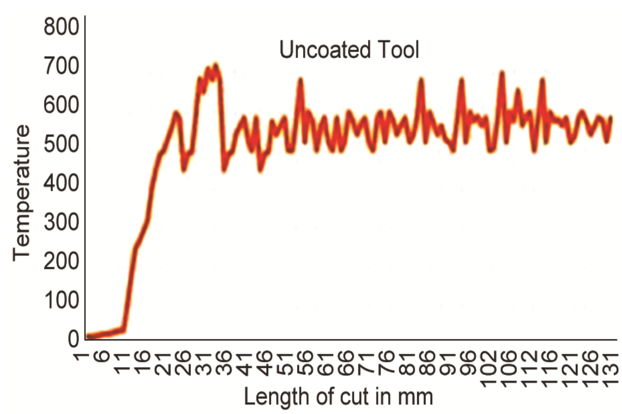

Fig. 5 — Temperature measurement graphs for (a) coated, and (b) uncoated tool.

(X'pert PRO MRD, Panalytical, The Netherlands) with a target power of 40 mA current and 45kV voltage by applying classical "d vs $\sin^2\psi$" method. The target radiation used for the analysis was Cu Kα. It has been referred erstwhile[24] that while carrying out the residual stress analysis using X-ray diffraction technique, a high 2θ >125º should be used so that small changes in d-spacing, due to strain, can be measured more precisely. Therefore, during the experimentation, the stress analysis was carried out on (420) atomic plane of Inconel 718 at the diffraction angle of 145 degrees.

3 Results and Discussion

3.1 Taguchi analysis

The three components of the cutting forces, namely, F_x, F_y and F_z resolved along x-, y-, and z-axes, respectively, as exemplified in Fig. 6, have been measured using the dynamometer. It is clear from the figure that F_z>>F_x and F_y and hence, the force component F_z with highest magnitude is selected in the present study for Taguchi analysis. The values of the cutting force (F_z) and S/N ratios determined from the Eq. 1 are listed in Table 3 after machining Inconel 718 with coated and uncoated tools. Depending up on the sets of machining parameters used, the cutting force ranges from the minimum of 102.8 N to the maximum of 415.3 N and the S/N ratio varies from -40.3 at minimum to -52.3 at maximum in the case of coated tool. Similarly, the uncoated tool, the variation in cutting force ranges from 392.2 N to 455.3 N and that of S/N ratio ranges from -51.8 to -53.16. Table 4 shows the mean values of S/N ratio calculated for each parameter and its corresponding levels. For example, for a cutting speed, v, an S/N ratio of -44.01 in Table 4 is obtained from the mean of -40.23, -45.27, and -46.54 for level 1 of the cutting speed from Table 3 in the case of coated tool. Similarly, for the

Table 3 — Cutting forces and corresponding S/N ratios obtained during machining of Inconel 718 using coated and uncoated tools

Coded parameter levels			Cutting forces (Fz) and S/N ratios			
			Coated tool		Uncoated tool	
v	f	d	F_z (N)	S/N	F_z (N)	S/N
1	1	1	102.8	-40.2	392.2	-51.8
1	2	2	183.6	-45.3	444.4	-52.9
1	3	3	212.4	-46.5	522.1	-54.3
2	1	2	141.7	-43.0	451.4	-53.1
2	2	3	198.4	-45.9	535.7	-54.5
2	3	1	155.5	-43.8	472.2	-53.4
3	1	3	366.9	-51.2	566.6	-55.1
3	2	1	371.5	-51.3	495.1	-53.9
3	3	2	415.3	-52.3	455.3	-53.2

Table 4 — Mean S/N ratios for coated and uncoated tools at different levels of machining parameters

Cutting parameters	Mean S/N ratios					
	Coated Tool			Uncoated Tool		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
v	-44.0	-44.2	-51.6	-53.0	-53.6	-54.0
f	-44.8	-47.5	-47.5	-53.3	-53.7	-53.5
d	-45.1	-46.8	-47.9	-53.0	-53.0	-54.6

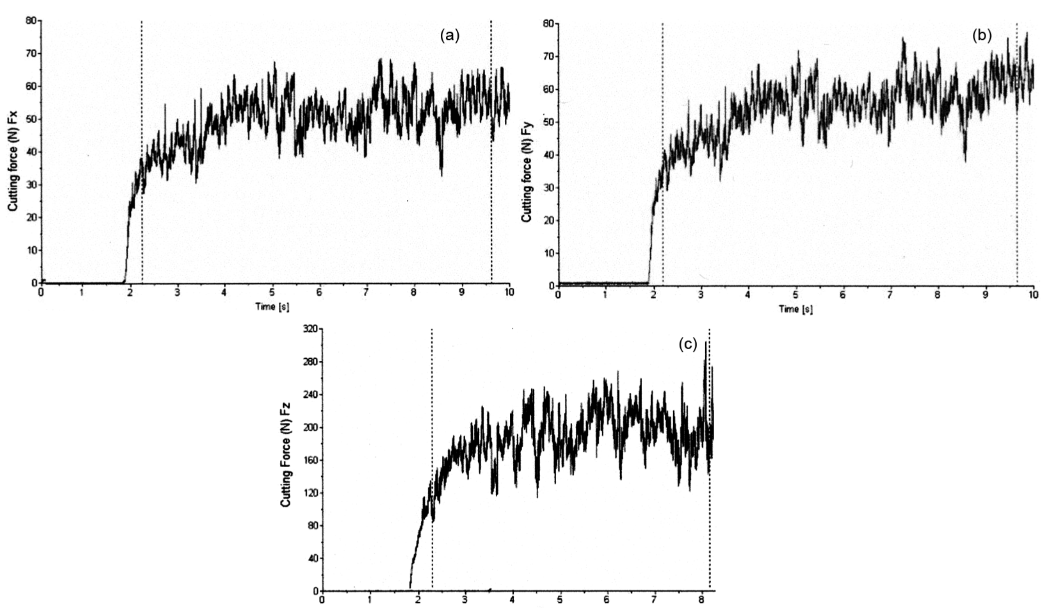

Fig. 6 — Components of the cutting forces (a) F_x, (b) F_y, and (c) F_z.

same cutting speed at level 2 for the coated tool, the S/N ratio is -44.25 in Table 4, which is the mean of -43.02, -45.95 and -43.80 taken from Table 3, and so on. Table 4 shows the highlighted values of highest mean S/N ratio for each parameter and its level for both coated and uncoated tools. As the lower cutting forces and higher mean S/N ratio indicate better performance characteristic of the cutting tools, the best experimental run with optimum machining parameters, as shown in Table (1-4), for both the cases of coated and uncoated tools for machining Incone l718 is $v_1f_1d_1$, i.e., cutting speed of 60m/min, feed at 0.068 mm/rev and depth-of-cut at 0.10mm.

3.2 Surface roughness and temperature

The surface roughness and temperatures measured during the experiments are listed in Table 5. It is observed from the table that the surface roughness and temperature developed on the surface of the machined bar are higher in case of uncoated tool compared to that with coated tool. It is suggested by Arunachalam et al.[25] that machining tools with ceramic coatings such as TiN cause low friction coefficients generating lower surface temperatures compared to those with uncoated tools justifying the present finding. It is reported by Ucun et al.[26] that build-up edges are formed more in softer uncoated tools during machining compared to that in the tools with hard ceramic coatings and these build-up edges affect the surface quality, normally, increasing the roughness of the machined surfaces. This fact supports the observation from the table, where the surface roughness of the bar machined with the coated tool is found less than that machined with the uncoated tool

3.3 Residual stresses

A plot between the depth from the machined surface and residual stress measured along the depth from the surface of the machined bar is drawn, as shown in Fig. 7 to understand the depth profiling of residual stresses on the machined component. It is observed from the figure that the compressive stress values, which are obtained in the sub-surface level are higher in material machined with the uncoated tool (332 MPa) than that machined with coated tool (248 MPa). It is obvious from Fig. 7 that the tensile stresses in the starting layers are lesser on the surface to some extent in the case of the coated tool (265 MPa) than that with the uncoated tool (335 MPa). The range of the depth, in which compressive residual stresses are spread across, is approximately equal in both the cases, i.e., nearly 400 μm. The prime factor deciding such a distribution of residual stresses is the fatigue strength, which is initially tensile in starting layers in the surface followed by compressive in further deeper layers of the material. It is reported that the surface tensile stresses should be less and the compressive stresses should be high for a high fatigue strength material[27].

It is a well-known fact that the tensile stresses in a component favour crack formation and compressive stresses help reduce the crack propagation. Since, the surface tensile stresses in the case of coated tool in the present study is less than that for the case of uncoated tool, it is more likely that crack nucleation would initiate first for the component machined with the uncoated tool. Higher compressive stresses in material machined with uncoated tool may be more favourable for hindering the crack propagation in the subsequent inner layers when compared with that of coated tool. However, the extent for which the crack propagation would be hindered in the subsurface layers of the machined component due to compressive stresses depends on the crack nucleated in the initial machined surface due to the surface tensile stresses. Thus, taking into account the surface tensile stresses for initiation or nucleation of cracks, one can comprehend that machining with the coated tool is better than that with the uncoated tool.

Table 5 — Temperatures and surface roughness values obtained at optimum conditions of machining Inconel 718 with uncoated and coated tools

Optimum condition	Uncoated tool		Coated tool	
	Temperature (°C)	Surface roughness (μm)	Temperature (°C)	Surface roughness (μm)
v1f1d1	544	1.21	451	0.72

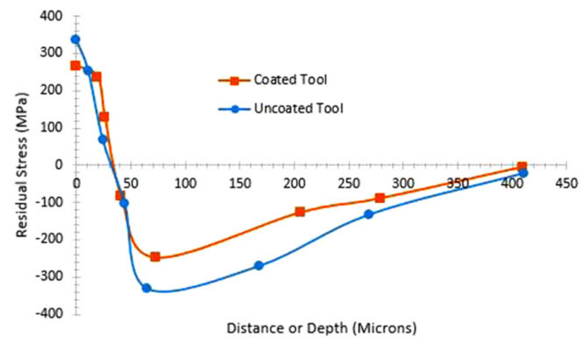

Fig. 7 — Depth profiles of induced residual stressesin Inconel 718 machined with coated and uncoated tool.

It is finally summarized from the present study that the machining performance of the TiN coated tool is better than the uncoated tool after comparing the surface residual stresses, surface roughness values and temperatures evaluated during turning of Inconel 718 bars.

Conclusions

The present work has successfully demonstrated optimization of machining parameters in turning Inconel 718 materials with TiN coated and uncoated tools for achieving minimum cutting force based on L9 orthogonalarray of experiments based on Taguchian alysis. Depth profiles of the residual stresses from the machined surfaces at optimum machining conditions have been evaluated. The following conclusions are drawn from the study:

a) The optimal combination of control factors and their levels for machining Inconel 718 with coated and uncoated tool are $v_1f_1d_1$, i.e., 60 m/min cutting speed, 0.068 mm/rev feed, and 0.10 mm depth-of-cut.

b) Tensile stresses in the starting layer of the machined surfaces are found lesser in the case of the coated tool (265 MPa) than that with the uncoated tool (335 MPa).

c) Compressive stress values, which are obtained in the sub-surface levels, are higher in material machined with the uncoated tool (332 MPa) than that machined with coated tool (248 MPa).

d) The range of depth, in which compressive residual stresses are spread across, is approximately equal in both the cases, i.e., nearly 400 µm.

e) Considering surface tensile stresses favour initiation or nucleation of the surface cracks, itis deduced that machining with the coated tool is better than that with the uncoated tool.

f) Surface roughness and temperature developed on the surface of the machined bar are higher in case of uncoated tool compared to that with coated tool

g) It is finally inferred from the present work, that the coated tool has performed better than the uncoated tool when comparing the tensile residual stresses, surface roughness and temperature of the machined surfaces of the Inconel 718 bars.

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