IMPROVING THE TOOL LIFE OF CERAMIC CUTTING INSERT WHEN MACHINING DIFFICULT-TO-CUT ALLOY STEEL

NÂNG CAO TUỔI BỀN CỦA MẢNH DỤNG CỤ CẮT GỐM KHI GIA CÔNG HỢP KIM KHÓ CẮT GỌT

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ABSTRACT

Inconel is a nickel-based super alloy with a promise in industrial applications requiring high specific strength and corrosion resistance, namely, automobile, aerospace, jet engine, waste processing, marine equipment and oil and gas extraction. However, unlike traditional materials such as steel and aluminum, its machinability rating is poor, that is, it is very difficult to machine. Accordingly, the tool life in machining of Inconel is substantially less than traditional materials. This article proposes various techniques employed in improving the tool life of ceramic cutting insert as compared to commercial cutting tool. Experimental tests were carried out to check the efficiency of one of the proposed techniques using ISO 3685 standard. The results revealed that notch and flank wears were dominant morphology during cutting process. Furthermore, the tool life of the designed inserts could be remarkably improved 76.47% over the commercial cutting tool.

Keywords: *Ceramic cutting tool; difficult-to-cut steel alloy; tool life; high speed machining; Scanning Electron Microscopy (SEM).*

TÓM TẮT

Inconel vốn là siêu hợp kim nền niken có triển vọng trong những ứng dụng công nghiệp cần độ bền và độ chống mòn cao, chẳng hạn, công nghiệp ôtô, hàng không, động cơ phản lực, thiết bị hàng hải, xử lý chất thải và thiết bị khai thác dầu và khí. Tuy nhiên, không giống như các vật liệu thông thường như thép và nhôm, khả năng gia công của Inconel là kém, nghĩa là, nó rất khó gia công. Theo đó, tuổi bền của dụng cụ khi gia công Inconel khá thấp so với khi gia công vật liệu thông thường. Bài báo này đề xuất một số giải pháp kỹ thuật nhằm nâng cao tuổi bền của mảnh cắt gốm khi gia công Inconel và được so sánh với mảnh cắt gốm thương mại. Các thí nghiệm được thực hiện theo tiêu chuẩn quốc tế ISO 3685 để kiểm tra hiệu quả của các giải pháp kỹ thuật đã đề xuất. Các kết quả thí nghiệm cho thấy, mòn khía dạng chữ V và mòn mặt sau là dạng mòn chính trong quá trình cắt. Ngoài ra, tuổi bền của mảnh cắt gốm được thiết kế chế tạo theo giải pháp kỹ thuật đề xuất được tăng đáng kể khoảng 76,47% so với mảnh cắt gốm thương mại.

Từ khóa: *Dụng cụ cắt gốm; hợp kim khó gia công; tuổi bền; gia công cao tốc; Scanning Electron Microscopy (SEM).*

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1. INTRODUCTION

Nickel-based alloys (Inconel), known as the most difficult-to-cut materials in mechanical cutting process, are widely applied in the manufacture of mechanical components in the aerospace, automobile, rocket and jet engine, petrochemical equipment and other high temperature industrial applications [1]. To name a few, nickel-based alloys, which constitute 45 - 50% of the total material expected, are the optimal choice in the manufacture of hot sections (e.g., combustion chamber and turbine) of aircraft engines due to their outstanding strength and oxidation resistance at elevated temperatures in excess of 550°C [2]. To meet more stringent and/or severe operating conditions of modern airplane engines wherein higher complexity and higher operating temperature are required, up-to-date Inconels have developed from the simple nickel-chromium matrix to the multi-element, multiphase systems. And thus, Inconels now contain various doped materials of chromium, aluminum, titanium, cobalt, molybdenum and niobium in varying quantities to give higher performance (high strength at elevated temperature). Unfortunately, with a material of such composition, the problems of short tool life and metallurgical damage to the workpiece during machining are much more prominent, in other words, the now Inconels are much more difficult to cut.

The poor machinability of Inconel materials have been explored by many scientific literature, namely: (i) outstanding high-temperature strength, hardness and toughness are retained during machining require higher cutting forces, thereby resulting in degraded tool life [3]; (ii) severe work hardening during machining due to the austenitic nature of Inconel contributing to notching wear imprint usually at the depth of cut region and/or tool tip [4]; (iii) the presence of very hard phases/particles in the microstructure, such as carbides, nitrides, oxides, etc., cause high abrasive wear to cutting tools; (iv) chemical reactions with commercial cutting inserts at high cutting temperature leading to a high diffusion wear rate; (v) the generation of tough and continuous chips further exacerbating the degradation of the cutting tool by cratering; and (vi) the poor thermal diffusivity of Inconel often results in high temperature at the tool tip as well as large thermal gradient within the cutting tool [5].

In the previous works, many researchers have reported various options with an objective to improve the tool life during machining of Inconel 718. Because of high toughness and resistance to thermal shock, to date, carbide cutting tools are the most widely used tool materials for machining Inconel. It is worth to note that most published work on the machining of Inconel is performed at low cutting speed V_c (e.g., 50 - 70m/min) and feed f (e.g., 0.15mm/min) using carbide cutting tools [6, 7]. Devillez et al [6] disposed that the tendency of nickel base alloys to galling and welding especially on the tool rake face and the tendency to form built-up-edge (BUE) at lower speed conditions can accelerate the carbide tool wear. Mohsan et al [8] researched the influence of cutting fluid conditions and cutting parameters during high pressure jet assisted machining of Inconel 718. It was concluded that higher cutting speed of 140m/min and a coolant pressure of 150 to 200bar are the optimum levels to produce a satisfactory surface quality. Bushlya et al [9] made an attempt to cut Inconel 718 using cemented carbide tools at a cutting speed of V_c = 60m/min and observed that 20% of tool life is improved by the protective coating available on the tool. From the literature, it is understood that quite a few work on machining of Inconel 718 using ceramic cutting tool has been reported. Ceramic tool materials with high thermal resistance, high hardness, high melting point, high abrasive wear resistance, high compression strength and poor affinity with Fe elements had been developed to cut the Inconel more effectively by using high speed machining (HSM) [10]. However, one of drawbacks of ceramic materials is their low thermal conductivity. This low thermal conductivity decreases the amount of heat flowing into cutting tool and, so, makes the regions of the tool close to the chip-tool and workpiece-tool interfaces hotter. Another typical property of ceramics is the low toughness, which makes cracks and breakages occurrence easier [11].

In this paper, to overcome these above-mentioned problems, the parameters relating to the design and fabrication process of ceramic cutting insert including tool materials, tool geometry, manufacturing route, cutting speed (V_c), feed (f), depth of cut (a_p), etc. were proposed and controlled in order to achieve adequate tool live, thereby improving the cutting performance during HSM of Inconel. The cutting performance of the designed cutting insert was studied during continuously dry turning Inconel. At the same time, a commercially available Ti(C,N) ceramic cutting tools was used for comparison with the same cutting conditions.

2. EXPERIMENTAL PROCEDURES AND MEASUREMENTS

2.1. Design and fabrication of ceramic cutting insert

The fabrication process of ceramic insert includes three major steps. At 1st step, a credible route for manufacturing raw ceramic cutting inserts was illustrated in Fig. 1. Firstly, a suitable amount of very fine, high purity Si_3N_4 powders (average diameter of 100 nm) with the required proportion of additives are mixed homogenously by ball milling. The mixed composition are then pressed into a pellet and followed by hot pressed sintering at 1600°C and 30MPa to promote the developments of strong bonds between the given powder grains. Next, the cutting inserts were ground into a size of 12.7mm × 12.7mm × 4.76mm. The edge preparation of ground inserts was made by microblasting technology after grinding and chamfering. At last, the cutting inserts were polished to improve the surface finish. In this manufacturing process, silicon carbide (SiC) whiskers added to Si_3N_4 matrix in random orientation in order to produce a ceramic tool material with very high toughness. Meanwhile, other additives were added to enhance hot hardness and abrasive wear resistant characteristics of the inserts.

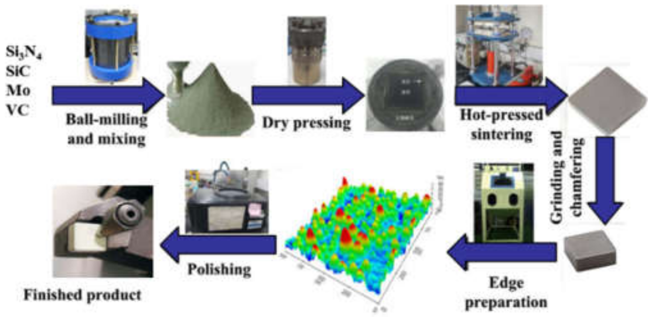

Fig. 1. Manufacturing route of raw ceramic cutting inserts

At 2nd step, micro-grooves in parallel to the main cutting edge on the rake face of the raw cutting insert were produced by a focused ion beam (FIB; Helios NanolabTM 600, FEI, USA) using gallium as the ion source. The FIB system was operated at an accelerating voltage of 30kV with beam current of 50pA. As shown in Fig. 2, the size (width×depth) of the micro-grooves is 100μm × 50μm and period is 150μm are captured by using SEM.

At 3rd step, solid lubricants (Tungsten Disulfide-WS_2) with a mean diameter of 100nm were then filled into the micro-grooves by sputtering method. These self-lubricating micro-grooves have proved to be not only effective in reducing cutting force and chip-tool contact length but also facilitates chip removal. The finished cutting inserts were named as CeraKICET.

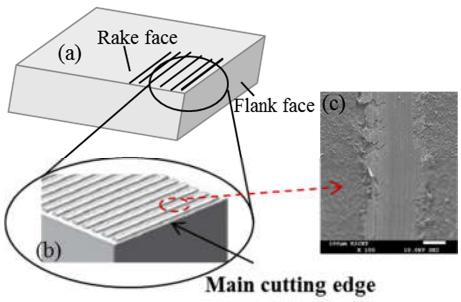

Fig. 2. (a) Fabricated micro-grooves on the rake face; (b) Magnified image of micro-grooves and (c) SEM image of micro-groove

2.2. Workpiece and cutting experiments

The experimental workpiece used was a 120mm diameter × 320mm long bar of Inconel 718 with a chemical composition (weight percent) and mechanical properties shown in Table 1.

Table 1. Chemical composition and mechanical properties of Inconel 718

Chemical composition	C	Si	Ni	Cr	Nb	Mo	Ti	Al	Mn	Fe
	0.25 %	0.04 %	53.8 %	18.1 %	5.5 %	2.9 %	1 %	0.55 %	0.06 %	Bal
Mechanical property	Hardness (HV)	Thermal conductivity ($W.m^{-1}.K^{-1}$)			Tensile strength (MPa)			Elastic modulus (GPa)		
	350	11.4			1600			205		

The experimental runs were performed on a turning CNC machine PUMA200MA, Korea with a maximum spindle speed of 3000rpm and a drive motor power of 15kW. The workpiece with one centre hole of 6.3mm diameter and 120° protecting chamfer firstly machined. A faceplate and a centre were then used to fix the workpiece.

The selection of appropriate cutting tools and machining parameters (V_c, f, a_p) depend on the machinability data of workpiece. The choice of tool involves various criteria like insert size, insert shape, geometry, and insert nose radius to achieve better tool life. Nose radius and shape, of the insert plays a key role during turning operations, which determines the surface quality of the machined components and its tool life. Fig. 3 shows the correlation between insert shape, productivity, and strength (Sandvik Coromant, 2015). Accordingly, square insert with rounded corner was selected and its dimension is defined to follow ISO 9361-1 in Table. 2.

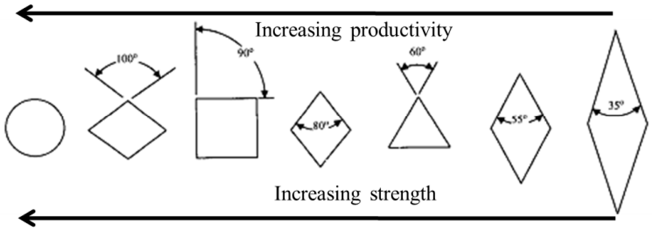

Fig. 3. Insert shape with respect to strength and productivity

Table 2. Standard ceramic insert angles (degree) and dimensions

Rake	Clearance	Cutting edge inclination	Cutting edge angle	Included angle	L×W×H (mm^3)	Corner radius (mm)
-6	6	-6	75	90	12.7×12.7×4.76	0.8

In this test, because of feed (f), depth of cut (a_p), or corner radius are not the prime test variables, the standard cutting conditions are selected according to Table 3 (ISO 3685). For comparative evaluation, a commercially-related Si_3N_4 ceramic tool (Type: CNGN120408S, SecoTool Korea) with the same specification was used. In this connection, 30 pieces of shafts have been turned using both CeraKICET and CNGN120408S tools in dry condition.

Table 3. Standard cutting conditions

Cutting condition	B
Cutting speed, V_c, m/min	150
Depth of cut, a_p, mm	2.5
Feed rate, f, mm/rev	0.25
Corner radius, r_ε, mm	0.8

2.3. Evaluation methods

Testing was done in accordance with ISO 3685 - 1993 (Tool-life testing with single point cutting tools). The cutting process was carried out in dry cutting condition. A cutting tool was rejected or the machining process stopped based on the following criteria: (i) maximum flank wear land VB_{max} = 0.5mm; (ii) nose wear ≥ 0.5mm; (iii) Notching at the depth of cut line ≥ 0.5mm; (iv) excessive chipping (flaking) or catastrophic fracture of the cutting edge. If the 30th sample was machined and the critical value of tool wear was not reached, the tests were stopped. The tool life was determined as the below equations:

$$T = t_m \times K \quad (1)$$

$$t_m = \frac{L}{n \times f} \quad (2)$$

where: T - tool life (min); t_m - machining time (min); K - number of machined pieces; L - length of cut (mm); n - spindle speed (rev/min); f - feed (mm/min).

Microscope (Model: IMTcam3, IMT i-Solution Inc., USA) was utilized to examine any defect existence of the inserts prior to the machining operation. Field emission scanning electron microscopy (FE-SEM; JSM-7610F, JEOL, Japan) with operating voltage of 10kV was used to determine the worn morphology of the cutting inserts after every cut.

3. RESULTS AND DISCUSSION

3.1. Tool life

As can be seen in Table 1, the machinability of workpiece affected by its mechanical property. The high tensile strength of workpiece (1600MPa) implies high specific cutting force on one hand, and brings the risk of severe tool edge chipping on the other hand. Meanwhile, the rather high hardness of Inconel 718 (350HV) together with its low thermal conductivity ($11.4W.m^{-1}.K^{-1}$), can lead to marked plastic deformations and to an accelerated wear on the cutting tool during machining [12]. The tool life of self-designed and commercial ceramic inserts was monitored at the same cutting parameters. The set criterion of tool wear was = 0.5mm (ISO 3685) or 30 pieces of machined sleeves. After at least one of the mentioned parameters was achieved, the tests were stopped and evaluated by SEM. The number of pieces machined by CeraKICET and CNGN120408S inserts is indicated in Fig. 4. Then, formula (1) and (2) were used to calculate the tool life of ceramic inserts (Table 4). The results revealed that the tool life of the designed insert (CeraKICET) was increased remarkably about two times as compared to commercially available cutting tool insert

(CNGN120408S). CNGN120408S insert did not reach the maximum number of 30 machined workpiece. Its tool life was impaired due to its size of notching wear reached the prescribed criterion of 0.5mm (Fig. 5). In contrast, the cutting temperature can be decreased due to the self-lubricant film, the notching wear was less compared to CNGN120408S insert. This means the tool life of CeraKICET insert can be redoubled.

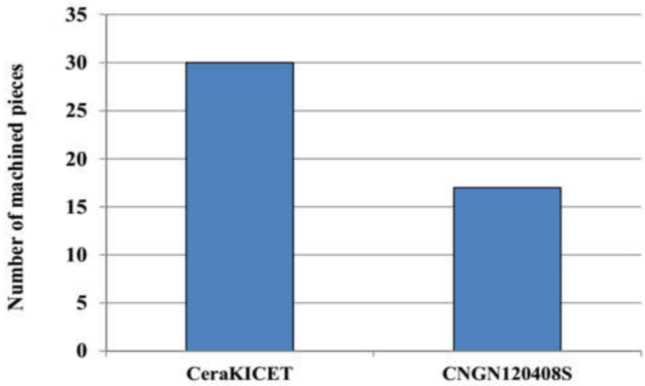

Fig. 4. The number of Inconel workpieces turned by ceramic inserts

Table 4. Tool life of cutting inserts

	Length of cut L (mm)	Cutting speed V_c (m/min)	Spindle speed n (rev/min) $n=\frac{1000V}{\pi D}$	Feed rate f (mm/min)	Machining time t_m (min)	Number of machined pieces (K)	Tool life T (min)
CNGN120408S	300	150	400	0.25	3	17	51
CeraKICET	300	150	400	0.25	3	30	90
Improvement (%)							76.47

3.2. Wear morphology and wear mechanism

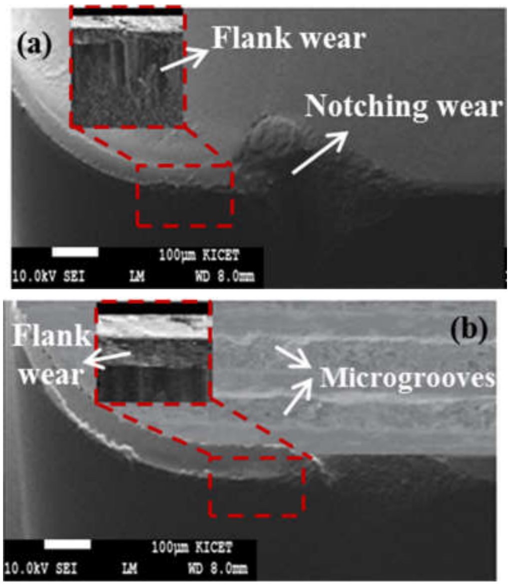

Fig. 5. Wear morphology and wear mechanism of: (a) conventional insert and (b) CeraKICET insert

Generally, cutting tools wear predominantly in different ways, depending on cutting conditions (principally cutting speed V_c, cutting tool material and coolant condition). The test results that, in dry cutting condition, average flank wear was developed very close to the cutting edge, while notching wear appeared at the end of depth of cut (Fig. 5). As can be found that, notching wear is a domineering wear mechanism for both conventional and designed inserts. However, for conventional CNGN120408S insert, accelerated notch wear developed on both flank and rake faces, thereby weakening the cutting edge rapidly.

Notching wear has a "V" shape at the end of depth of cut due to the presence of a work-hardened layer on the previously cut surface as shown in Fig. 6, or stress concentration, or flow of built-up edge material parallel to the cutting edge [13-15].

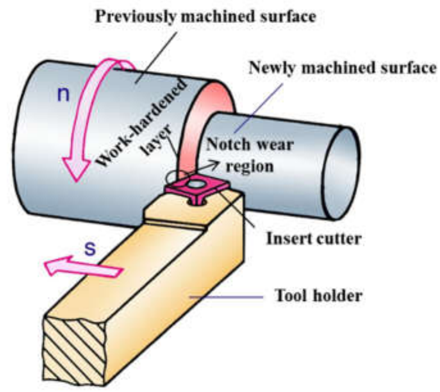

Fig. 6. The notching wear appeared due to a work-hardened layer

As widely known that, the origin of tool wear phenomenon is friction. For two surfaces in sliding contact under load in dry condition, the friction force will be [16]:

$$F=\tau\times A_R \quad (3)$$

where A_R is the actual contact area of the tool-chip and τ is the shear length of the weaker of the two sliding surfaces. Here, A is the product of the contact length of the tool-chip (L_{tc}) and the cutting width (W_c) ($A_R= L_{tc}\times W_c$). The energy generated per unit time is derived from the friction force and sliding speed between cutting tool and workpiece. The energy is then converted into heat in the cutting zone. High temperature is very important to notching wear rate and rate of wear-land development [17]. Accordingly, for improving the tool life of cutting insert, the friction force or temperature at cutting zone must be minimized. To aim at minimizing the friction force, therefore, either reducing contact length of the tool-chip contact surface or reducing the shear length of the cutting tool must be considered. Based on this argument, the tool life of designed insert (CeraKICET) was significantly improved in comparison with conventional cutting insert can be explained as follows. First, with the solid lubricants filled into the micro-grooves on the rake face of CeraKICET, thus a layer of lubricating film having low shear strength is released during machining process. In other word, the original friction between the chip and the rake face will turn into friction between the chip and the lubricating film, so the temperature at the tool tip was relatively decreased and hence improving its tool life. Second, the contact length between tool-chip intersectional surface was reduced due to the designed micro-grooves, resulting in less frictional force in the contact area, which will also eventually enhance the tool life.

4. CONCLUSION

In this paper, the authors developed a design and fabrication method for improving the life time of ceramic cutting insert when machining difficult-to-cut super alloys. From the results of this work, the following conclusions may be concluded:

a. Notch wear, average flank wear prevailed for both conventional and designed ceramic inserts. Wears depended on the cutting conditions, friction force, temperature at the cutting zone.

b. Overall, the designed ceramic tool exhibited the better tool life performance. Micro-textures not only enhance tribological properties over cutting tool surfaces, but also reduce the friction force between the chip-tool intersection face, thereby minimizing temperature at the tool tip zone and increase the tool life.

Furthermore, this study also aims at sustainable manufacturing through dry cutting condition without using any harmful coolant materials, which are undesirable for environment and human health. Further works can be performed by assessing the cutting performance between wet and dry conditions. .

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REFERENCES

[1]. E.O. Ezugwu, Z. M. Wang, A.R. Machado., 1999. *The machinability of nickel-based alloys: a review.* Journal of Materials Processing Technology 86, pp. 1-16.

[2]. A. Gloria, R. Montanari, M. Richetta, A. Varone., 2019. *Alloys for Aeronautic Applications: State of the Art and Perspectives.* Metals, 9, 662; DOI:10.3390/met9060662.

[3]. R. Arunachalam, M.A. Mannan., 2007. *Machinability of Nikel-based high temperature alloys.* Machining Science and Technology, DOI: 10.1080/10940340008945703.

[4]. A. Suárez, L.N. López de Lacalle, R. Polvorosa, F. Veiga., 2016. *Effects of high-pressure cooling on the wear patterns on turning inserts used on alloy IN718.* Mater. Manuf. Process, DOI: 10.1080/10426914.2016.1244838.

[5]. R. Polvorosa, A. Suárez, L.N. López de Lacalle, I. Cerrillo, A. Wretland, F. Veiga., 2017. *Tool wear on nickel alloys with different coolant pressures: Comparison of Alloy 718 and Waspaloy*. Journal of Manufacturing Processes 26, pp. 44-56.

[6]. A. Devillez, G. Le Coz, S. Dominiak, D. Dudzinsk., 2011. *Dry machining of Inconel 718, workpiece surface integrity.* Journal of Materials Processing Technology, pp. 1590–1598.

[7]. Z. He, X. Zhang, H. Ding., 2016. *Comparison of residual stresses in cryogenic and dry machining of Inconel 718.* Procedia CIRP 46, pp. 19-22.

[8]. AUH Mohsan, Z. Liu, X. Ren, W. Liu., 2018. *Influences of cutting fluid conditions and cutting parameters on surface integrity of Inconel 718. under high-pressure jet-assisted machining (HPJAM)*. Lubrication Science, pp 1-16, DOI: 10.1002/ls.1418.

[9]. V. Bushlya, J. Zhoua, J.E. Stahl., 2012. *Effect of Cutting Conditions on Machinability of Superalloy Inconel 718 during high speed turning with coated and uncoated PCBN Tools.* Procedia CIRP, Vol. 3, pp. 370–375.

[10]. Z. Bin, L. Hanlian, H. Chuanzhen, W. Jun, W. Bo, H. Yao., 2019. *Cutting performance and crack self-healing mechanism of a novel ceramic cutting tool in dry and high-speed machining of Inconel 718*. Int J Adv Manuf Technol, DOI: 10.1007/s00170-019-03386-x.

[11]. I.R. Pashby, H. Khamsehzadeh, 1988. *The Machining of Waspaloy With Various Ceramic Tools.* First Intrna. Conf. on The Behaviour of Mat. in Eng., pp. 6.1-6.5.

[12]. A.K. Parida, K. Maity, 2018. *Comparison the machinability of Inconel 718, Inconel 625 and Monel 400 in hot turning operation*. Eng. Sci. Tech., Int. J., pp. 1-7.

[13]. K.E.H. Moltrecht, 1964. *Tool Failure When Turning Nickel Base High Temperature Alloys.* ASTME, V. 64 (2), pp. 1-31.

[14]. H.K. Tonshoff, S. Bartsch., 1988. *Wear Mechanisms of Ceramic Cutting Tools.* Ceramic Bul., Vol.67, No.6, pp.1020-1025.

[15]. M.C. Shaw, 1984. *Metal cutting principles.* Oxford University Press, New York, pp. 154-183.

[16]. E. Dow Whitney, 1994. *Ceramic cutting tools: Materials, Development, and Performance.* ISBN: 0-8155-1355-0, Noyes Publications, pp. 1-10.

[17]. A. R. C. Sharman, J. I. Hughes, K. Ridgway, 2006. *Workpiece Surface Integrity and Tool Life Issues When Turning Inconel 718™Nickel Based Superalloy*. Machining Science and Technology: An International Journal, pp. 399-414.

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