Modelling and validation of Surface Roughness in Micro Turned Nickel based alloys (Nimonic 90)

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Abstract

Nickel based alloys (Nimonic 90) are one of the most used material for aircraft parts, gas turbine components and fasteners due to its inherent properties such as high strength at elevated temperature, good corrosion resistance, high stability, high wear resistance and low thermal conductivity. This paper proposes a mathematical model for prediction of surface roughness using fundamental geometrical properties of tool and workpiece. The corner radius is assumed as a straight line for developing mathematical equation, comprising mainly depth of cut, principal cutting edge angle, nose radius and feed. In micro turning, surface roughness increases with increase in feed and depth of cut. A rough surface compared to conventional turning is produced while micro tuning due to edge ploughing and rubbing when the chip thickness is lesser than edge radius. The principal cutting-edge angle is introduced in the model. This model is validated by conducting micro turning experiments on Nickel based superalloy using PVD coated Tungsten Carbide inserts. The surface roughness is significantly affected when the cutting-edge angle comes in contact with workpiece due to imperfect geometry of nose of the cutting tool. The authors observed a good surface finish at 12,000 rpm spindle speed, 8μm/rev feed and 5μm depth of cut. A good correlation is observed between the predicted value and experimentally measured roughness values.

Keywords: Micro Turning, Surface Roughness, Mathematical Relation

1. Introduction

With the advancement of technology, the demand for miniature and intricate components is increasing in industries. Miniaturization of mechanical systems in industries, defence and medical fields are enhancing which require fine threaded lead screw or fasteners for actuation and assembly of its micro components or system. Micromachining will play a vital and significant role for the upgradation of industries' work in precision engineering. Micromachining allows reliably, precise, and efficient production of tiny and intricated components with high accuracy. Nimonic alloys are extensively used in gas turbine components and extremely high performance reciprocating internal combustion engines. Micro turning and micro milling are the main technology for manufacturing the micro parts. Micro turning operation generates minute crests and vales with micro-geometric exclusivity known as surface roughness due to friction, breakage, or plastic deformation during chip separation.

A real time measurement of the surface roughness in the range of large roughness ensemble averaged coherence function i.e., the correlation function, of the scattered field is measured by using a two-waves interferometer. Interference fringes resulted from interference between two correlated field distributions. The visibility of these fringes depends on the degree of correlation between these two field distributions which was depend on the surface roughness [1]. An algorithm was developed to compute the depth of the surface points by adopting the classical phase shifting approach to evaluate the surface height. A deformed computer-generated grating pattern was projected on to the surface which allowed the pitch and intensity distribution to be varied using the software [2]. The workpiece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness are statistically significant in the finish hard turning of AISI H13 steel [3].

A mathematical model was generated by using the data collected from a sequence of turning experiments to explore the influences of cutting parameters on the surface roughness. The authors had used regression analysis for mathematical modelling with two different coating layers but same geometrical carbide inserts, considering surface roughness as output and cutting parameters as input [4]. The variation in average roughness values, due to the effects associated to the minimum chip thickness, was studied which showed a function of uncut chip area with machined surface [5]. A response model was proposed to predict average capacitive surface roughness using a capacitive sensor-based measurement system for different machining processes [6]. The experiments were performed and cutting forces, surface roughness was measured on developed micro turning setup considering Ti6Al4V as workpiece and coated carbide tool (TiN/AlTiN) as cutting tool insert. Surface roughness decreases by increasing cutting speed due to the decrease in the built-up edge at high speed and increases by increasing the depth of cut due to the increase in machine tool vibration which increases due to the increase in the cutting force [7],[8]. The minimum undeformed chip thickness, material spring back and plastic side flow play vital roles in the fabrication of turned surface with micro scale cutting condition which leads to poor theoretical roughness [9].

In Micro turning operation, the machined surface roughness is collectively affected by feed marks, cutting edge, sharp ended or rounded side cutting edge with same interaction, cutting tool geometry with round corner nose and adhesive interaction between the chip and the side cutting edge (material side flow). However, for theoretical analysis, there are many surface roughness predictive equations for turning which consists cutting parameters, generated from linear, exponential or multivariate regression methods but not by using geometrical properties of tool and workpiece. The responsible sources and dependency of surface roughness, waviness and other surface errors on the tool-tip vibration is not completely clarified.

2. Mathematical Modelling

Chip flow is extensively influenced by the principal cutting edge angle Ø. The value of Ø varies starting from zero over the curved portion of the principal cutting edge for the single point nosed radius tool. So, bc can be considered as curved and bd as a straight line for the tool (see Fig. 1). Therefore, Ø can be written as $Ø_{avg}$ to incorporate the effect of tool nose radius [10].

$$Øavg = \frac{\left(\frac{Ø}{2} + \left[\frac{t}{R} + cosØ - 1\right] \frac{1}{\sin Ø}\right)}{\left(1 + \frac{\left[\frac{t}{R} + cosØ - 1\right]}{Ø}\right)} \quad ......(1)$$

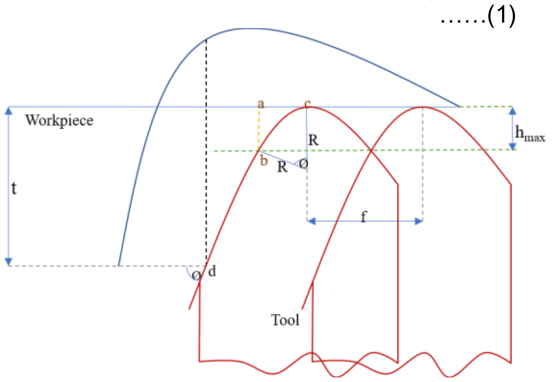

Fig. 1: Schematic diagram for tool and workpiece interaction

From Fig. 1, for micro tool insert curved ‘bc’ can be considered as straight line and a ∆ abc (see Fig. 2) is shaped. So, peak-to-valley heigh for the regime can be calculated as:

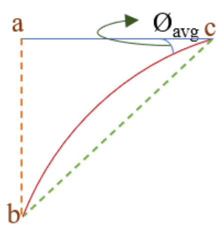

Fig. 2: Magnified view of tool tip interaction

From ∆ abc –

$$\sin Ø_{avg} = \frac{ab}{bc} = \frac{hmax}{RØ}$$

$$h_{max} = RØ \sin Ø_{avg} \quad ......(2)$$

Also, the roughness height or peak-to-valley height for micro turning operation considering feed per revolution and cutting-edge radius is given as follows:

Also -

$$h_{max} = f^2/8R \quad ...(3)$$

Putting the value of ‘R’ from Eq. 2 to 3 –

$$h\ max = \frac{f\sqrt{Ø}\ \sin Ø_{avg}}{2\sqrt{2}} \quad ...(4)$$

The distance travelled by workpiece in one minute during machining is πDN, where D is diameter of the workpiece and N is the spindle speed. If ‘de’ is considered as roughness peak to valley height i.e., h_{max}, a ∆ cde (see Fig. 4) can be imagined (see Fig. 3)

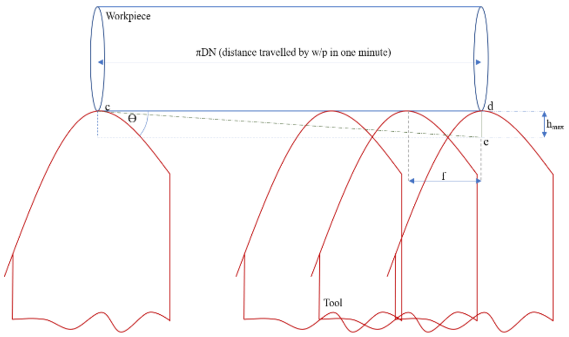

Fig. 3: Schematic diagram of tool and workpiece interaction

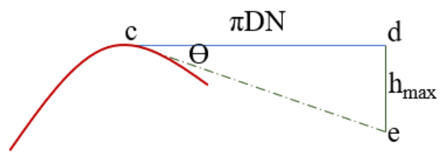

Fig. 4: Magnified view of tool-tip interaction

From ∆ cde –

$$\tan Θ = \frac{h\ max}{πDN}$$

$$h_{max} = πDN \tan Θ \quad ....(5)$$

where, Θ is auxiliary cutting-edge angle

Considering above equations-

$h_{max} = f^2 / 8R$

$h_{max} = RØ \sin Ø_{avg}$

$h_{max} = πDN \tan Θ$

$$\frac{f^2}{8πDN \tan Θ} = R = \frac{h_{max}}{Ø \sin Ø_{avg}}$$

$$h_{max} = \frac{f^2\ Ø \sin Ø_{avg}}{8πDN \tan Θ} \quad ....(6)$$

3. Experimental Details

The experimental work to validate the proposed model was conducted by means of micro turning developed by Jagadesh and Samuel [8] after some modifications, (see Fig. 5)

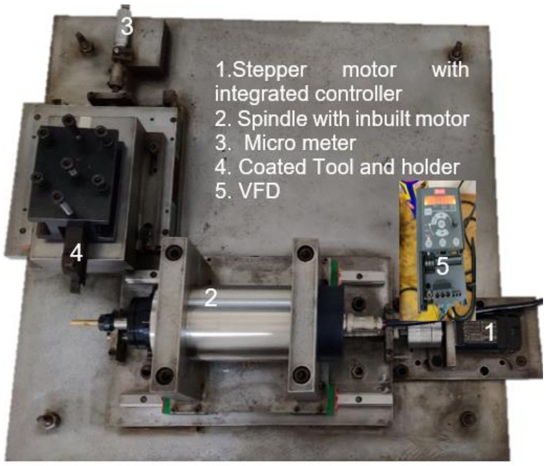

Fig. 5: Developed Micro Turning setup

3.1. Material Selection

Nimonic 90, cylindrical workpieces of 5.5 mm diameter and 60mm length were used for machining, composition of the alloy is given in Table 1.

Table 1: Nimonic 90 Material Composition

Ni (%)	Co (%)	Cr (%)	Ti (%)	Fe (%)	Zn (%)	Mn (%)	Pb (%)
58.35	17.78	18.92	1.91	1.29	1.26	0.16	0.02

3.2. Cutting Tool and Edge Geometry

S graded PVD AlTiN coated Tungsten Carbide inserts of 0.4 mm corner radius and 20μm edge radius were used for the machining of Nimonic alloy as workpiece. The cutting tool inserts is placed in the tool holder having approach angle of 95°. The cutting-edge length and thickness of the insert is 6.45 mm and 2.38 mm respectively.

3.3. Experimental Methodology

In order to keep the machining condition impassive, each experiment was conducted with new sharp tools. The cutting tests were carried out without coolant and, total 8 experiments were conducted according to full factorial design. In this study, three main cutting parameters, cutting speed (V), feed (f), and depth (d) of cut are selected. Two level tests for each factor were used. Table 2 shows the experimental data for validation of mathematical model for Nimonic 90 Nickel alloy.

Table 2: Experimental data for model validation

Ex. No.	V (RPM)	f (μm/rev)	d (μm)	Ra (μm)
1	12000	8	5	3.29
2	18000	8	5	0.60
3	12000	16	5	5.24
4	18000	16	5	3.48
5	12000	8	10	3.68
6	18000	8	10	0.47
7	12000	16	10	7.33
8	18000	16	10	2.65

4. Results and Discussion

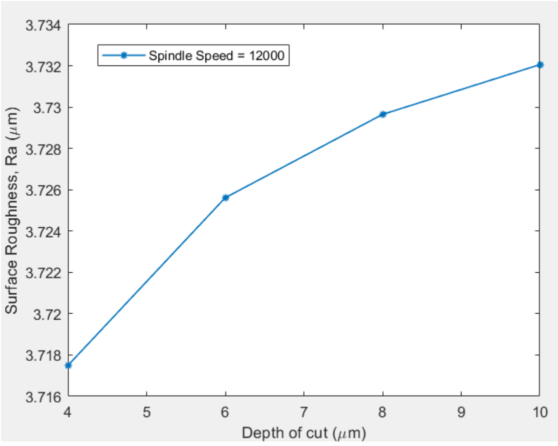

Fig. 6 : variation of surface roughness with depth of cut at 8μm/rev feed

Fig. 6 shows the variation of surface roughness with depth of cut at 8μm/rev feed. As depth of cut increases, there is a sightly increase in surface roughness.

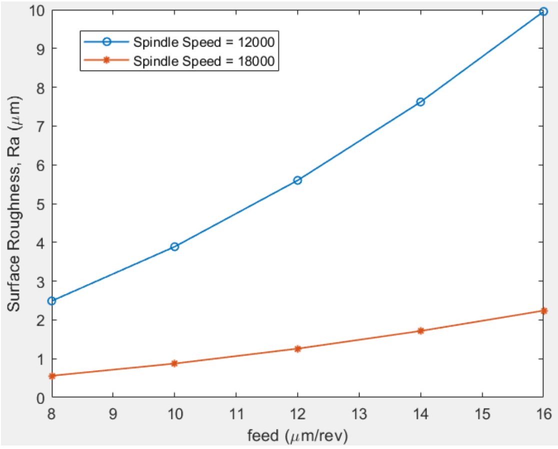

Fig. 7: variation of surface roughness with feed at 5 μm depth of cut

Fig. 7 shows the variation of the surface roughness with feed at 5μm depth of cut. Surface roughness is significantly increasing while increasing the feed.

Table 3: Comparison of Experimental and Mathematical relation Roughness

Sl No.	Exp. Ra (μm)	Math. Ra (μm)	Error	Error%
1	3.29	2.64	0.65	19.756
2	0.60	0.54	0.06	10.000
3	5.24	9.98	1.74	21.116
4	3.48	3.95	0.47	13.505
5	3.68	3.82	0.14	03.804
6	0.47	0.58	0.11	23.404
7	7.33	8.95	1.62	22.101
8	2.65	2.28	0.37	13.962

Table 3 shows the difference between experimental and mathematical model roughness values. Min 3.8% and Max 23.4% error is observed.

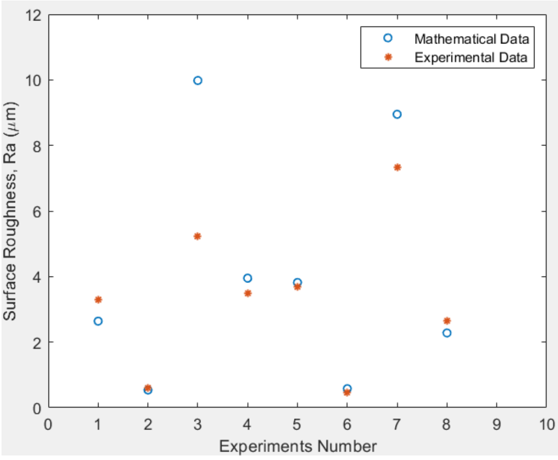

Fig. 8: Comparison of experimental and mathematical data

Fig. 8 shows the comparison of mathematical and experimental data.

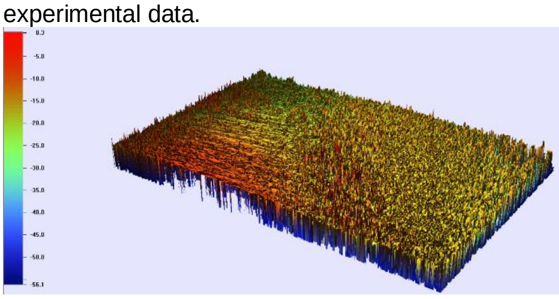

Fig. 99: 3D profile of surface turned at 12,000 rpm, 8 µm/rev, 5 µm depth of cut

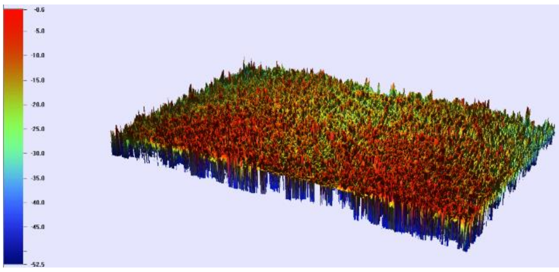

Fig. 10: 3D profile of surface turned at 12,000 rpm, 16µm/rev, 5 µm depth of cut

Fig. 10 and 10 shows the surface profiles measured using WYKO NT1100 optical 3D profilometer. the surface roughness values for the above samples is 3.29 and 5.24µm respectively and the other values are given in Table 2.

5. Conclusions

In this study, a mathematical model for surface roughness measurement were proposed for Nimonic 90 for high-speed machining. PVD AlTiN coated tungsten carbide inserts were used for experiments and effects of machining parameters onto the surface roughness were investigated. When depth of cut increases, there is a slightly increase in roughness because of high cutting forces while increasing feed, substantial increase in roughness, due to high friction and ploughing effect, is observed. Whereas mathematical model also illustrates the decrease in surface roughness value while increasing spindle speed but experimental study displays contrary effect for some samples. Surface roughness is mainly guided by edge radius of cutting inserts and uncut chip thickness. The future scope of this research is the upgradation of the model by comprising ploughing effect, vibration parameters, uncut chip thickness and tool tip temperature.

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