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TECHNICAL PAPER

Chip load sensitive performance in micro-face milling of engineering materials

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Abstract The miniaturization of machine component is perceived by many as requirement for the future technological development of a broad spectrum of products. High-accuracy miniaturized components are increasingly demanded for various industries. Micro-component fabrication requires reliable and repeatable methods, with accurate analysis tools. Surface roughness is one of the most important parameters in the machining process. This research discusses an experimental approach to the development of mathematical model for surface roughness prediction before the milling process. This mathematical model is validated by equivalence variance test, i.e., *F* test. This study also presents the results of test done with high-speed face milling tool. The experiments were performed to investigate the influence of chip load on surface roughness along with other cutting parameters such as cutting speed and depth of cut for different engineering materials.

Keywords High-speed machining · Micro-milling · Chip load · *F* test · Surface roughness

1 Introduction

Manufacturing has been one of the principal means by which wealth creation is influenced and shall remain in future too. However, manufacturing has changed radically over the course of the last 20 years and rapid changes are certain to continue. The emergence of new manufacturing technologies, spurred by intense competition, will lead to dramatically new products, processes and process pull. It is widely appreciated that the development of micro-machining has greatly changed human lives in terms of increased standards, as an example of process pull. Micromachining or miniature machining plays an vital role in machining of very small parts consisting of micro-features. Micromachining not only offers quality and reliability for conventional products, but also makes possible better performing products, especially where mechatronics, miniaturization and critical functionality are important. The uses of high-accuracy miniaturized components have been increased, such as aerospace, biomedical, electronics, environmental, communications and automotive components [1].

These days, miniaturization has gained importance since there is an increasing need for micro-components for swiftly changing industrial applications. Therefore, micro-machining as a process pull is in full expansion. One of them is micro-milling, whose applications are varied in terms of machinable materials (metallic alloys, components, polymers and ceramics). Micro-milling is a micro-manufacturing technology that makes possible by removal of material to produce parts and features ranging from several millimeters to a few micrometers [1].

It requires a miniature tool with a diameter between 100 and 500 µm, which is often made of tungsten carbide to allow ferrous material machining. Micro-milling seems to be most flexible and productive for making complex three-dimensional microforms including sharp edges. Using the same principle as macro-milling, the phenomenon of micro-cutting involved in micro-milling is not a simple

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scaling of macro-cutting. A significant difference between these two cutting processes is the chip formation involving the so-called 'minimum chip thickness' phenomenon [1].

Micro-milling is one of the technologies widely used for the manufacture of microstructures and tooling inserts for microinjection molding and hot embossing. For example, important application areas are the manufacture of micro-parts for watches, keyhole surgery, housings for micro-engines and also tooling inserts for fabrication of micro-filters, housings and packaging solutions for micro-optical and microfluid devices [2].

The ability to generate a quality surface in an economic and reliable fashion is vital for the widespread application of micro-end milling. It will require a thorough understanding of the fundamental mechanisms associated with surface generation in micro-milling. There are a number of phenomena that prevail in micro-milling that are fundamentally different from macro-milling and influence the underlying mechanisms of the surface generation process. Surface roughness is influenced by machining parameters, such as feed, cutting speed, depth of cut and difficult to control factors, such as nonhomogeneity of work piece and tool, tool wear, machine motion error, formation of chips and unpredictable random disturbances. It has been shown that both controlled and non-controlled parameters cause relative vibrations between the cutting tool and the work piece [3].

The conduction of experiments for the characterization of surface quality for the micro-end milling shows that the chip load is by far the most dominant factor of that study. Cutting speed and its interaction with chip load also have significant effect. Runout appears to play a significant role in the surface quality of micro-milled parts. The dominant cutting marks have a period of twice the chip load, meaning that one cutting edge makes a deeper cut than the other cutting edge. The cutting marks of the nondominant edge are also visible as small steps on the surface roughness profiles. This effect is most likely due to runout [4].

Tool runout mainly depends on the characteristics of the spindle and the tool holder. A small runout that affects cutting profiles of conventional end milling creates very little drastic force variation in micro-end milling. In micro-end milling, the tool runout to tool diameter ratio becomes very big compared to conventional end milling. It is very common to see that only one cutting edge of a two flute end mill performs machining operations alone, while the other edge does not touch the work piece at all. When one of the cutting edges starts performing all or most of the cutting operation, the force variation increases significantly, the tool wears out much more quickly and the probability of tool breakage increases [5].

Researchers have attempted to explicitly apply the minimum chip thickness concept in modeling the surface generation of the micro-end milling. The model successfully captured the feed rate trend of the surface roughness for single phase materials (pearlite and ferrite) and revealed the existence of an optimal feed rate in terms of the surface roughness due to the trade-off between the conventional feed rate effect and minimum chip thickness effect. The surface generation process for multiphase ductile iron is affected by the micro-burr formation occurring at the phase boundaries. The micro-burr formation is attributed to the interrupted chip formation process as the cutting edge moves from one phase to another. These micro-burrs increased the surface roughness by about 0.05–0.1 μm Ra [6].

Comprehensive surface generations of micro-end milling for both the side wall and floor surfaces have been developed. The models account for deterministic and stochastic surface roughness component. Kinematics (traditional feed rate effect) has negligible effect on the deterministic sidewall surface roughness. Larger edge radius results in higher surface roughness for both the sidewall and floor surfaces due to the increased influence of the plowing mechanism. Tool edge serration increases the deterministic sidewall surface roughness along the axial direction, but decreases the deterministic sidewall surface roughness along the feed direction. The vibrations reduce the total 3D surface roughness of the floor surface at feed rates [7, 8].

Experimental observations reveal that the interaction between cutting speed and the chip load (feed per tooth) is a major parameter deciding the roughness of micro-channels produced using micro-end milling. The drastic variation of specific cutting pressure and cutting forces at lower feed per tooth clearly indicates the effect of minimum chip thickness in microscale machining [9].

The simulation results show that, with an increase of tool edge radius, the cutting force increases, while the effective stress and mean cutting temperature of the micro-cutter decreases slightly. When the ratio of undeformed chip thickness to tool edge radius is less than about 40 %, increasing tool edge radius, the maximum effective stress and the cutting temperature zone of micro-cutter occur from the rake face to the corner on the tool edge and the flank face, with a distinct obvious size effect [10].

Based on this study, an attempt was made to generate experimental data for micro-machining of ETP copper, Al V-95 and HcHcr (D2) steel. In this investigation, the surface roughness correlates with chip load (feed/tooth) for high-speed face milling at the same machining conditions.

2 Experimental details

2.1 Machine tool

The experiments were performed at a machine shop of the Indo German Tool Room, MIDC Chikalthana Aurangabad

(Maharashtra), India. The Makino Japan make "Makino V33", 3 axis milling center was used for the experiment. The major capabilities of machine tool include: maximum spindle speed of 20,000 rpm and feed 20,000 mm/min; the machine tool has a 15KW motor. The system provides the reading of chip load in 'μm' unit.

2.2 Materials and tool

The work piece material was ETP copper, aluminum V95 (Al V95) and HcHcr (D2) steel. Cutting experiments were carried out in a block at ETP copper and HcHcr steel with dimensions 145 mm (length) × 57 mm (width) × 22 mm (height) and Al V95 with dimensions 154 mm (length) × 74 mm (width) × 28 mm (height). The chemical composition is given in Tables 1, 2 and 3, respectively, for ETP, Al V95 and HcHcr.

The cutting tool used for the experimentation was solid carbide end mill of 6 mm diameter, and four flutes CVD coated 30° helix and 12° rake angle, made by Hanita Cutting Tools, Israel with controlled 1 μm runout.

Minimum chip thickness is a major influencing factor in orthogonal cutting in micro-machining. Similarly, micro-burr formation plays an important role in surface generation in high-speed machining. Based on this literature survey, the pilot experiment is designed. The machining is carried out using 1, 2 and 3 μm depth of cut and single pass milling at continuously increasing spindle speed starting from 4,000 rpm (1.25 m/s) till micro-burr formation stage is achieved. High pressure dry air is used as coolant during experimentation. After the successful conduction of the pilot experiment, it is observed that the micro-burr formation stage is achieved beyond 8,000 rpm (2.51 m/s) spindle speed for the studied materials. So for the research experiment, spindle speed is selected in the range of 8,000–18,000 (5.65 m/s) rpm at a constant feed rate of 600 mm/min for 1, 2 and 3 μm depth of cut. Chip load is recorded at the first tool–work interaction. The levels of cutting parameters are as shown in Table 4.

The experiments were carried out with a combination of a selected range of depth of cut and cutting speed at a constant feed rate of 600 mm/min. The chip load value was observed during machining on the milling center and was recorded when the tool interacted (contact) first time with the work material for cutting. Figure 1 shows the sample of workpiece of the studied material.

Homell Tester made in Germany was used for surface roughness measurement in the experimental work at the National Accreditation Board for Testing and Calibration Laboratories (NABL) certified Dimensional Metrology Lab of IGTR. Five small regions on the machined surface were determined for measurement and the average value of these measurements was recorded as the Ra value.

The generated experimental data are recorded in Table 5.

Using the above experimental result, the relationship between the factors and the performance measures was modeled by using multiple linear regressions for the prediction of surface roughness. The regression process is done with the help of S/W MINI-TAB 16 (software for data analysis). The obtained mathematical models for all three materials are as follows:

For ETP copper:

$$\mathrm{Ra} = 1.0631 + 0.0227\mathrm{Vc} - 0.2458\mathrm{ft} + 0.4258d \quad (1)$$

$$R^2 = 0.9808$$

For Al V-95:

$$\mathrm{Ra} = 1.5643 + 0.0285\mathrm{Vc} - 1.1887\mathrm{ft} + 0.22505d \quad (2)$$

$$R^2 = 0.9018$$

For HcHcr steel:

$$\mathrm{Ra} = 0.0359 + 0.0592\mathrm{Vc} - 2.1515\mathrm{ft} - 0.0025d \quad (3)$$

$$R^2 = 0.9152$$

where Ra is the surface roughness, d is the depth of the cut, Vc is the cutting velocity, ft is the chip load (feed/tooth) and R^2 is the coefficient of determination.

Table 1 Material composition for ETP copper

Alloys	Ti	Pb	Zn	Cu (%)
ETP copper 80 BHN	Nil	Nil	Nil	99.96

Table 2 Material composition for aluminum (V95)

Alloys	Zn (%)	Mg (%)	Cu (%)	Mn (%)	Cr (%)	Fe	Al (%)
V95 120 BHN	6.0	2.3	1.7	0.4	1.18	–	88.42

Table 3 Material composition for HcHcr steel

Alloy	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Mo (%)	V (%)	W (%)	Fe (%)
HcHcr 615 BHN	1.46	0.65	0.3	0.021	0.015	12.80	0.91	0.81	0.50	82.53

2.3 Validation of the empirical mathematical model

F test has been used to test the equality of variances of two normal populations. *F* test is also used in the context of analysis of variance (ANOVA) for judging the significance of more than two sample means at one and the same time. It is also used for judging the significance of multiple correlation coefficients. Test statistic, *F*, is calculated and compared with its probable value for accepting or rejecting the null hypothesis. *F* test was initially used to verify the hypothesis of equality between two variances, but is now mostly used in the context of analysis of variance [11, 12].

The *F* test evaluates hypothesis that involves multiple parameters. An example is a simple setup,

Table 4 Value of levels and cutting parameters

Level	1	2	3	4	5	6
Depth of cut, *d* (μ)	1	2	3	–	–	–
Cutting speed (m/s)	2.51	3.14	3.78	4.40	5.03	5.65

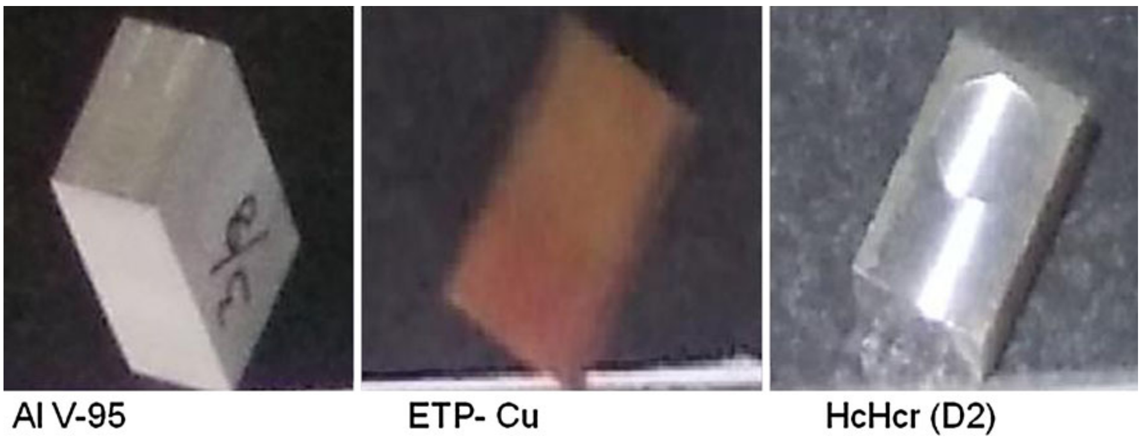

Fig. 1 Sample workpiece of studied materials

Table 5 Experimental recorded data for chip load and Ra (measured)

Sr. No.	Depth of cut (μ)	Cutting speed (m/s) (rpm)	ETP Copper			Aluminum V-95			HcHcr (D2) Steel		
			Chip load (μm)	Ra measured (μ)	Ra predicted (μ)	Chip load (μm)	Ra measured (μ)	Ra predicted (μ)	Chip load (μm)	Ra measured (μ)	Ra predicted (μ)
1	1	2.51	1.16	1.24	1.26	1.01	0.72	0.66	0.02	0.12	0.14
2	1	3.14	1.04	1.26	1.30	0.94	0.74	0.76	0.02	0.18	0.18
3	1	3.78	0.97	1.30	1.34	0.90	0.80	0.83	0.01	0.22	0.23
4	1	4.40	0.93	1.35	1.36	0.87	0.85	0.88	0.01	0.28	0.27
5	1	5.03	0.89	1.34	1.38	0.84	0.87	0.93	0.01	0.3	0.31
6	1	5.65	0.87	1.36	1.40	0.83	0.88	0.96	0.01	0.34	0.35
7	2	2.51	1.16	1.76	1.69	1.01	0.88	0.89	0.02	0.14	0.14
8	2	3.14	1.04	1.82	1.73	0.94	0.95	0.99	0.02	0.18	0.17
9	2	3.78	0.97	1.82	1.76	0.90	1.10	1.05	0.01	0.26	0.23
10	2	4.40	0.93	1.84	1.79	0.87	1.22	1.11	0.01	0.28	0.27
11	2	5.03	0.89	1.86	1.81	0.84	1.26	1.16	0.01	0.32	0.31
12	2	5.65	0.87	1.90	1.83	0.83	1.30	1.19	0.01	0.36	0.34
13	3	2.51	1.16	2.06	2.11	1.01	1.10	1.11	0.02	0.12	0.13
14	3	3.14	1.04	2.10	2.16	0.94	1.10	1.21	0.02	0.19	0.17
15	3	3.78	0.97	2.18	2.19	0.90	1.38	1.28	0.01	0.23	0.23
16	3	4.40	0.93	2.18	2.21	0.87	1.30	1.33	0.01	0.28	0.27
17	3	5.03	0.89	2.20	2.24	0.84	1.32	1.38	0.01	0.32	0.30
18	3	5.65	0.87	2.24	2.25	0.83	1.36	1.41	0.01	0.36	0.34

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \quad (4)$$

To test the null hypothesis, all of the slopes are assumed to be zero.

$$H_0 : \beta_1 = \beta_2 = \beta_3 = 0$$

This implies the alternative hypothesis

$$H_0 : \beta_1 \neq 0 \text{ or } \beta_2 \neq 0 \text{ or } \beta_3 \neq 0$$

This is the test of the null that none of the independent variables has predictive power, so our Ra experimental and Ra theoretical values in logarithmic form were considered.

For evaluating the 'R^2' (coefficient of determination) and 'F' ratio, the relations were used as follows:

$$S_{yx} = \sqrt{\sum[(\mathrm{Ra}_{(\mathrm{Exp})} - \mathrm{Ra}_{(\mathrm{tho})})^2]/(N-2)}$$

where N is the number of observation.

$$\text{Total sum of square (SST)} = \sum[(\mathrm{Ra}_{(\mathrm{Exp})} - \text{mean of } \mathrm{Ra}_{(\mathrm{Exp})})^2] \quad (5)$$

$$\text{Error sum of square (SSE)} = \sum[(\mathrm{Ra}_{(\mathrm{Exp})} - \mathrm{Ra}_{(\mathrm{tho})})^2] \quad (6)$$

$$\text{Group sum of square (SSR)} = \sum[(\mathrm{Ra}_{(\mathrm{tho})} - \text{mean of } \mathrm{Ra}_{(\mathrm{Exp})})^2] \quad (7)$$

$$\text{Coefficient of determination} = R^2 = 1 - [\mathrm{SSE}/\mathrm{SST}] \quad (8)$$

$$F \text{ ratio} = F = (\mathrm{SSR}/K)/(\mathrm{SSE}/N - K - 1)$$

where N is the number of observations and K is the number of variables.

The result of this F test is given in Table 6.

3 Result and discussion

For ETP copper, Al V-95 and HcHcr steel, the standard error Syx and the coefficient of determination R^2 are determined. This shows that regression models for these materials as a whole are suitable estimating models which have less standard error of the estimate. At 5 % level of significance, the critical value for F distribution is 3.34, as the calculated value for the same is much greater than critical F value as reported in Table 6, so that regression as a whole is significant.

Using the theoretical models for the studied materials, the predicted roughness value is mentioned in Table 5 showing the increasing trend when chip load was reduced for ETP, Al V-95 and HcHcr steel, respectively. We can observe from the data that the roughness value increases with increase in cutting speed and decreasing chip load. For all the three material, the same trends were observed in these plots.

The chip load values showing the decreasing trend as spindle speed increases. This trend is observed for the studied materials as shown in Fig. 2 in HSM. For very low chip loads, chatter can occur due to the small chip thickness. Hence, even if small vibrations occur, the tool can easily jump out of the cut, which can result in chatter. Therefore, up to a certain level increasing the chip load has a stabilizing effect.

From Fig. 3, the variation in chip load for ETP copper and Al V95 is very close as compared for HcHcr steel when increase in cutting speed is same. This is due to the

Table 6 Values of R^2 and F

Material	Syx	SST	SSE	SSR	Value of R^2	Value of F
ETP	0.0149	0.8005	0.0036	0.7998	0.9955	1,046.62
Al V95	0.0569	0.8366	0.0517	0.7841	0.9404	70.71
HcHcr	0.0745	0.1028	0.0087	0.0941	0.9152	71.9574

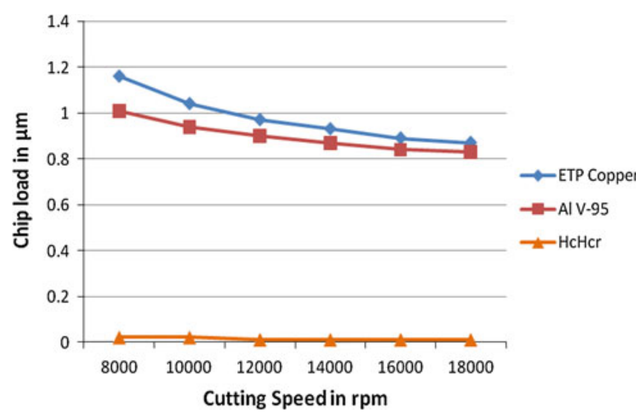

Fig. 2 Chip load and cutting speed for ETP copper, Al V-95 and HcHcr

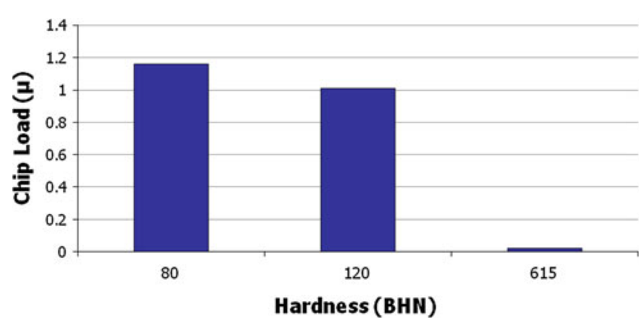

Fig. 3 Effect of hardness on chip load

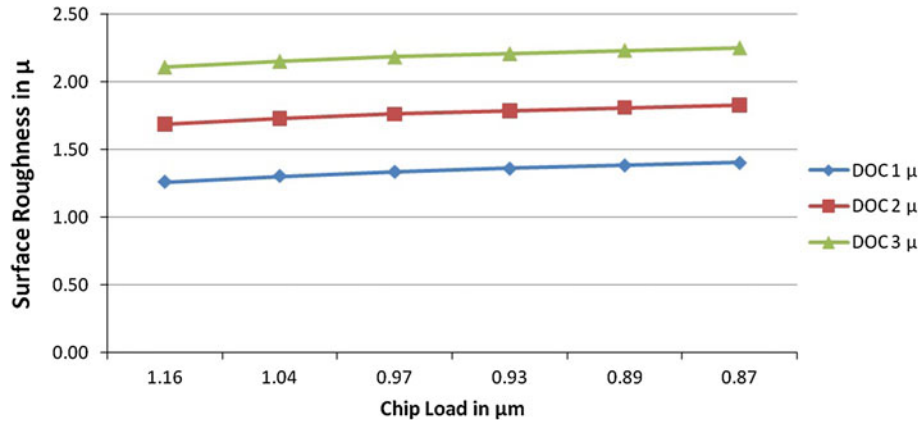

Fig. 4 Predicted Ra and chip load for ETP copper

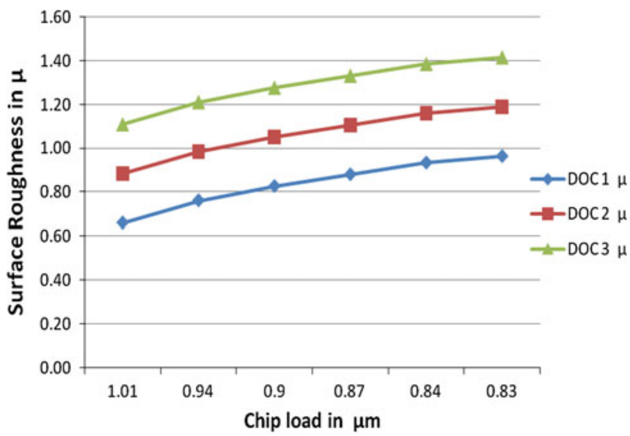

Fig. 5 Predicted Ra and chip load for aluminum V-95

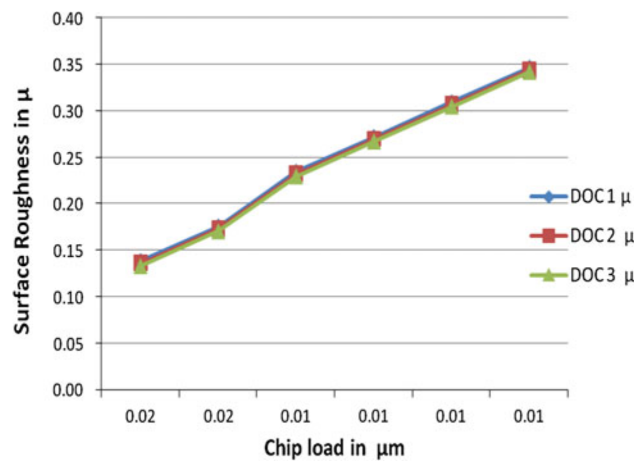

Fig. 6 Predicted Ra and chip load for HcHcr steel

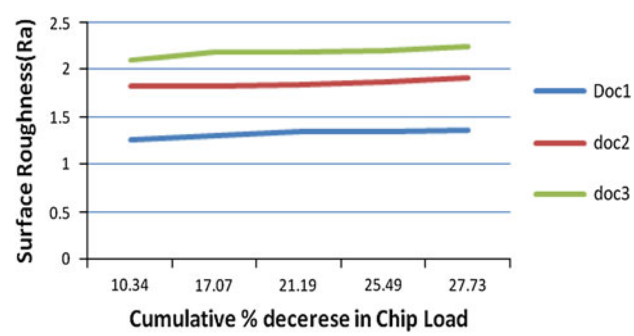

Fig. 7 Cumulative percentage decrease in chip load versus surface generation for ETP copper

hardness of the studied materials. The hardness value of HcHcr is much larger than the other two. The shear strength of HcHcr is also greater than that of ETP copper and Al V-95. The chip load mostly depends on shear strength and hardness, as cutting speed at the same time chip load is independent of depth of cut. The reasons for this variation of surface roughness at high speed is not only attributed to the geometrical consideration, but also the effect of minimum chip thickness, elastic recovery, plowing action and microstructure of the workpiece when the uncut chip thickness is in the order or less than the average grain size.

As shown in Figs. 4, 5 and 6, the roughness value showed an increasing trend when chip load was reduced for ETP, Al V-95 and HcHcr steel, respectively. In Table 4, we can observe that the roughness value increases with increase in cutting speed for all the three materials, the plots of which will show the same nature as shown in Figs. 4, 5 and 6.

When the chip load reduces in the rage of 10 to 35 %, the surface finish is degraded by 2 to 3 %. This cumulative effect is proved by trend of Ra value in Fig. 7 for ETP Copper. When the chip load reduces in the rage of 5 to 20 %, the surface finish is degraded by 4 to 10 %. This cumulative effect is proved by trend of Ra value in Fig. 8 for Al V95 For HcHcr D2 due to the high hardness and high cutting speed at low depth of cut the chip load will remain nearly constant. The surface finish is degraded by 25 to 45 %. This cumulative effect is proved by trend of Ra value in Fig. 9 for HcHcr (D2). The results are given in Table 7.

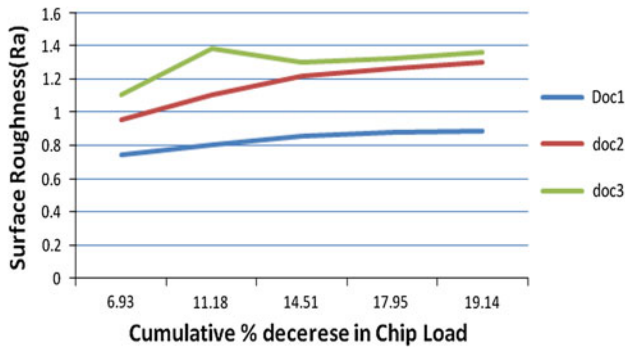

Fig. 8 Cumulative percentage decrease in load versus surface generation for Al V95

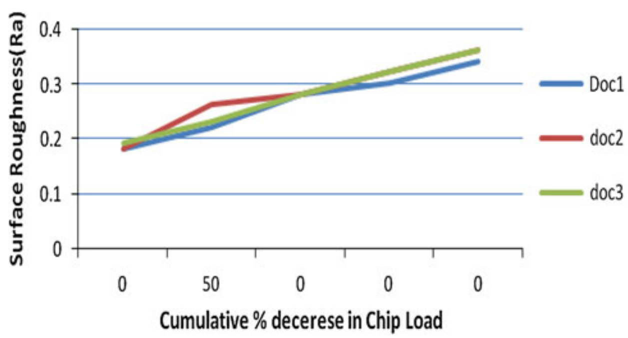

Fig. 9 Cumulative percentage decrease in chip load versus surface generation for HcHcr

Table 7 Cumulative percentage decrease in chip load versus surface finish degradation

Material	Cumulative % decrease in chip load	% Degradation surface finish
ETP Copper	10–35 %	2–3 %
AlV95	5–20 %	4–10 %
HcHcr	Due to high hardness remain constant	25–45 %

4 Conclusion

- When the spindle speed increases, the chip load decreases to a maximal of 25 % for ETP copper and Al V-95; for HcHcr, the decrease is 50 %, due to high hardness.
- The chip load values observed for high-speed machining of metallic workpieces are in the order of 0.5–1.0 μm and compared with other machining is above 10–20 μm.
- Surface finish is degraded by 10–20 % for ETP copper and Al V-95 with increase in cutting speed at constant depth of cut from 1 to 3 μm, while the deterioration is 50 % for HcHcr for the same cutting speed range.
- At high chip loads, the contribution of cutting speed was 30–40 % in surface generation, which is a considerably more prominent factor.
- The actual chip load decreases with the increase in cutting speed for a constant feed rate. This is usually referred to as chip thinning and one of the major advantages of high-speed milling.
- The relationship between chip load and surface roughness appears slightly non-linear, particularly at high cutting speed.

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