Precision milling of nickel-based single-crystal superalloy by TiAlN coated small diameter solid carbide end mill

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KEYWORDS

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Precision Milling,
Solid Carbide End Mill,
Cutting Forces,
Specific Energy.

ABSTRACT

Nickel-based superalloys pose cutting challenges due to their high strength, hot hardness, work hardening, and low thermal conductivity. Precision milling with small cutters is used for complex shapes and intricate profiles, but selecting appropriate machining parameters for these alloys is a challenging task. A set of machining conditions in slot milling with a TiAlN coated 1.5 mm diameter solid carbide end mills are investigated for dimensional accuracy, cutting forces, and specific energy. The dimensional accuracy in depth consists of within 10% of the depth of cut. The axial force and the feed force increase from 20 N to 106 N and from 17 N to 46 N, respectively with an increase in chip area from 0.8E-03 to 1.5E-03 mm^2/rev. Tool rotation caused a gradual increase of cutting forces in up-milling and decreasing of cutting forces in down-milling. The specific energy increases from 393 to 865 J/mm^2 steeply under higher chip areas.

1. Introduction

Superalloys are a class of metallic materials with superior properties of high-temperature strength, toughness, and resistance to corrosion and oxidation. The nickel-based superalloys are one of the prominent materials that can withstand thermal loads up to 80% of the melting temperature of the alloy in the service. Therefore, nickel-based superalloy components are exclusively used in the hot sections for turbine blades, vanes, and combustor components of advanced gas turbine engines in aerospace and power generation applications (Pollock & Tin, 2006). The single-crystal (SX) castings offer improved creep-rupture, fatigue, oxidation, and coating properties over equiaxed and columnar-grained components due to the absence of low melting grain boundary constituents and higher alloying of refractory elements (Reed, 2006).

During the application of nickel-based SX superalloys in manufacturing turbine blades, significant material removal by precision machining operations is necessary. But, nickel-based SX superalloys are considered as hard and ‘difficult-to-cut’ materials due to high strength, hot hardness, work hardening effect, and low thermal conductivity (Arunachalam & Mannan, 2000). Nickel-based superalloys show an increase in the flow stress with an increase in temperature up to about 650 °C due to Kear Wilsdorf lock by cross slip (Onyszko et al., 2009). High cutting forces and heat are generated while machining these alloys, which results in premature failure of cutting tools, lower material removal rate, and poor integrity of machined surfaces (Akhtar et al., 2014). Therefore, active research studies are under progress for the evaluation of optimal machining conditions for nickel-based superalloys. The milling process is one of the important machining processes, which is being used for the precision machining of complicated shapes and profiles. The geometries demand small diameter cutters for machining intricate features. But there is a dearth of published data available on the precision milling of nickel-based SX superalloy with small diameter cutters. Hence, in this work, an experimental investigation is performed on the nickel-based SX superalloy under precision

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Table 1
Nominal chemical composition of a nickel-based SX superalloy in wt.%.

Cr	Co	Mo	Ti	Al	W	C	Ta	Re	Ni
6.5	9.6	0.6	1.0	5.6	6.4	0.05	6.5	3.0	Bal.

slot milling operations with 1.5 mm diameter end mill cutters. The aim of this experimental investigation is to determine the suitable machining parameters for controlling the depth of machined geometry, as well as gaining insight into the machining mechanisms by analyzing the signals of cutting forces.

2. Experimentation

2.1. Work material and specimen preparation

The nominal chemical composition of nickel-based SX superalloy in weight % is shown in Table 1 (Harris et.al.,1990). The master alloy of the nominal composition was vacuum melted and cast with <001> crystallographic direction along the length of 120 mm by directional solidification technique. The details on the work material and detailed specimen preparation are illustrated by the author in their previous publication (Nandam et al., 2023). The specimens were of length of 45 mm, width of 16 mm and thickness of 13 mm having a flatness of 20 µm, and average surface finish, Ra of 0.2 µm on all the surfaces.

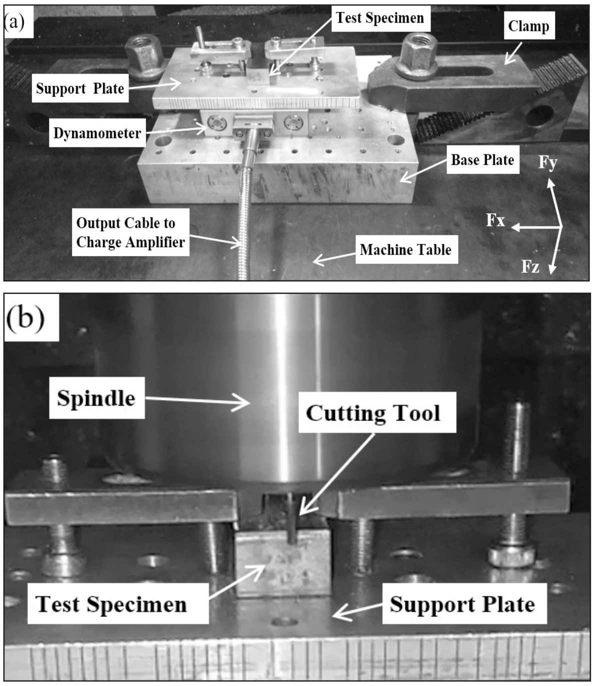

Fig. 1. Experimental set up for measurement of cutting forces (a) position of test specimen on the dynamometer, and (b) slotting operation with a small diameter end mill.

2.2. Experimental setup

A 3-axis precision CNC (computer numerically controlled) vertical machining centre, model VMC 600 II from M/s Hardinge, USA with rated spindle power of 25 kW and maximum spindle speed of 8000 RPM was used for slot milling experiments. Solid carbide tools are most widely used in the industry mainly due to their high toughness and resistance to thermal shock. PVD- TiAlN coated tungsten carbide end milling cutting tools of 1.5 mm cutter diameter and four fluted geometry of short length series No. G9A69015 from M/s YG1 Co., Ltd., South Korea was chosen from the manufacturer's product catalogue for precision machining of nickel-based superalloys. The cutting tool has a cutting length of 5.0 mm and 30 °helix angle with a straight shank of 3.0 mm diameter and overall length of 39 mm. The cutting tool was inserted into the spindle of the machine tool through BT 40 taper collets. A piezoelectric based multi-component precision cutting force dynamometer, model Minidyn 9256C1 from M/s Kistler, Singapore having the measuring range of plus or minus 250 N in x, y and z- directions with the sensitivity of -26 µC/N in x and z- directions and -13 µC/N in y-direction was used for measurement of cutting force signals. The specimens were held by clamps on the support plate and the support plate was fitted to the cutting force dynamometer. The complete cutting force dynamometer setup was fixed on the base plate, which was fitted to the machine tool as shown in Fig. 1. The output cables of the cutting force dynamometer were connected to the charge amplifier. The signals of the charge amplifier are connected to the data acquisition system, which consists of the Labview software interface in a personal computer (PC) system. The data acquisition rate of the cutting force signal was selected as 2k Hz.

2.3. Machining parameters

López De Lacalle et al. (2000) found that cutting speeds of over 30 m/min cause mechanical hardening effect on a nickel-based superalloy. The range of machining parameters was derived from the recommendations of the cutting tool manufacturer, the feasibility of the machine tool, and trial and error machining operations on the work material for higher tool performance without any tool breakage. The chip area is calculated as the product of table feed and depth of cut. The values of the machining parameters used for the slot milling operations are shown in Table 2. The machining experiments were performed on the surfaces of the test specimen along the length under a dry machining environment by developing CNC part programs. The machining condition at a higher chip area was replicated for validation of results.

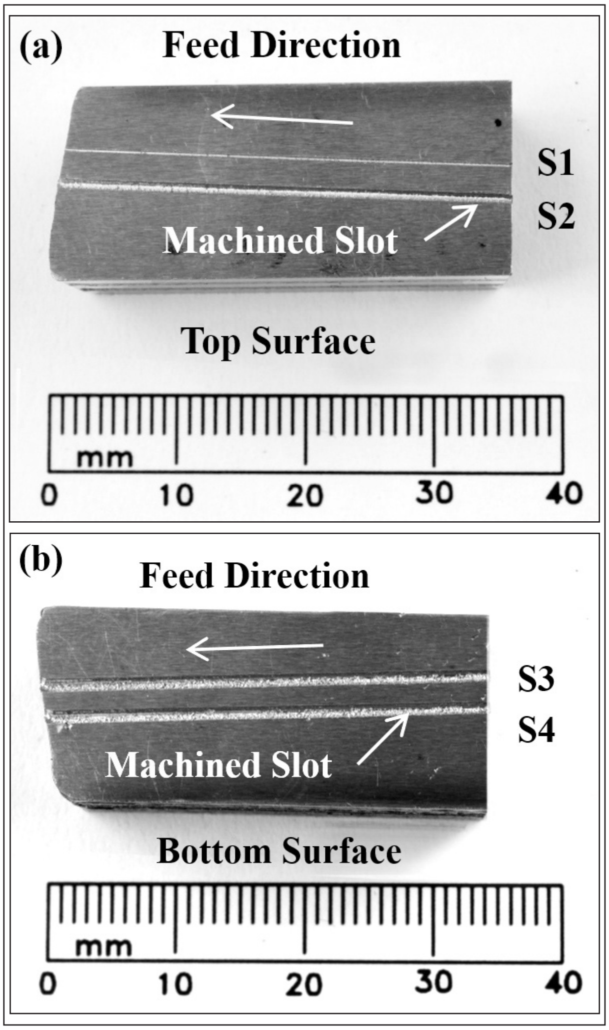

Fig. 2. The machined slots on the test specimen's (a) top and (b) bottom surfaces.

The machined slots on the top and bottom surfaces of the test specimen are shown in Fig. 2. Figure 2.a. shows the slots machined with 0.05 mm and 0.1 mm depth-of-cut and Figure 2.b. shows the slots machined with 0.15 mm depth-of-cut.

Samples were cut across the length at 10 mm from the end of the test specimen by using a precision Wire EDM process. These samples were mounted into the 1-inch size Bakelite moulds to observe the cross-section of the machined slots. The moulds were polished using a series of silicon carbide emery papers followed by diamond paste. The cleaned surfaces were etched by a commercial Kalling's 2 regent. The slotted geometry was measured on the digital micrographs of an optical stereomicroscope by using image processing software, Image J.

3. Results and Discussions

3.1. Dimensional accuracy and surface quality

The optical micrographs of the cross-section of the machined slots are shown in Fig. 3. The formation of slots were not proper under all machining conditions. The machined surfaces have burrs under machining conditions of medium and higher chip area. The machining condition of higher chip area at repeatability test (S4) consists of similar observations of the surface quality and machined geometry as that of initiation condition (S3).

The geometry such as the width and depth of the slot was measured. The deviation in width was calculated as the difference between the measured slot width and the cutting tool diameter. The deviation in depth was calculated as the difference between the measured depth at the middle of the slot and the given depth of cut.

Table 2
The machining parameters for slot milling operations.

Machining Condition	Cutting Speed, m/min	Table Feed, mm/min	Depth-of-Cut, mm	Chip Area mm^2/rev
S1	25	85	0.05	0.8 E-03
S2	25	69	0.1	1.3 E-03
S3	25	53	0.15	1.5 E-03
S4	25	53	0.15	1.5 E-03

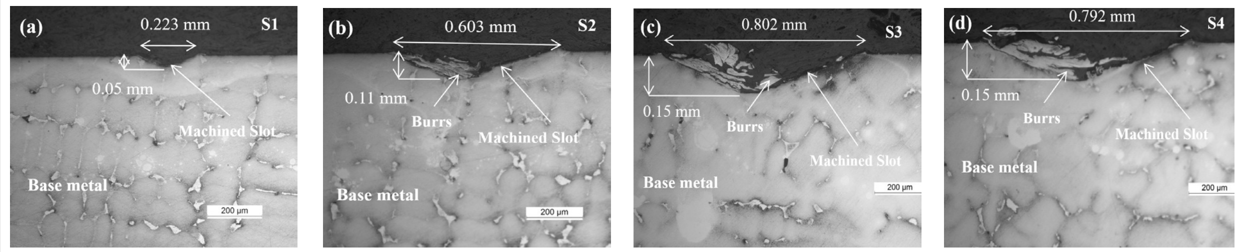

Fig. 3. Cross-sectional images of the slots under machining conditions of (a) S1, (b) S2, (c) S3 and (d) S4.

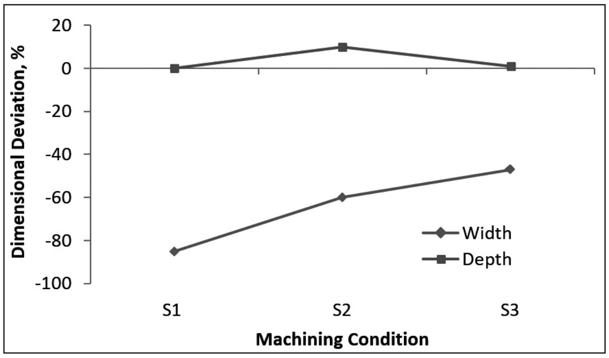

Fig. 4. Dimensional deviation of the slots under various machining conditions.

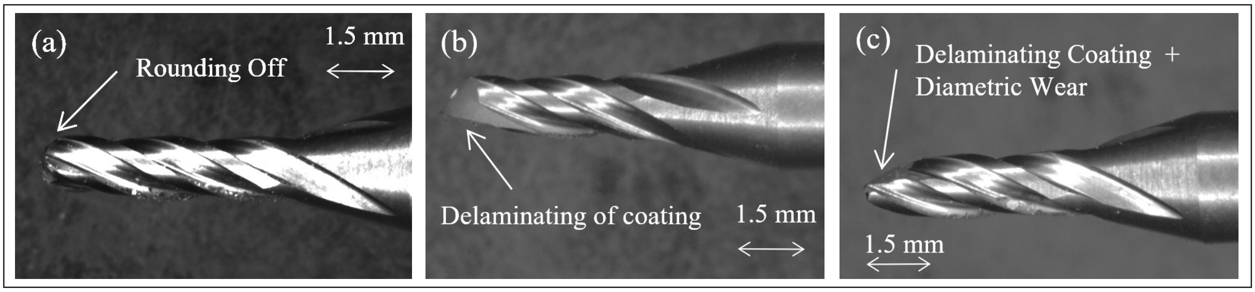

Fig. 5. Optical micrographs of the used tools under machining conditions of (a) S1, (b) S2, and (c) S3.

The percentage of deviation was calculated as a ratio of the deviation value and the initial value. The results of percentage deviation in width and depth for the observed machining conditions are shown in Fig. 4. It is observed that the variation in depth has significantly lower values than the width and is nearer to zero.

The tools used for slot milling operations were inspected under the digital microscope. The micrographs of the cutting tools are shown in Fig. 5. It is observed that the progress of tool wear advances from the rounding-off of cutting edges to the delamination of coating, and ultimately to diametric wear, as the work materials undergo the machining conditions from S1 to S3 through S2. This progress of tool wear could be due to an increase in chip load.

3.2. Cutting forces

The cutting forces in x, y, and z-directions as a function of the machining time under slotting operations along the length are shown in Fig. 6. It is observed that the cutting forces for each rotation have a similar trend under individual machining conditions. It indicated that the material is not undergone mechanical hardening. The cutting forces in the x-direction are near 'zero'. It could be due to the unidirectional movement of the cutting tool in the y-direction while the slotting operation. The maximum values (17 N to 40 N) and smoothness of the cutting force profiles in the y-direction (feed force) increase with a decrease in feed speed. The maximum cutting forces in the z-direction (axial force) increase from 22 N to 107 N with increases in the depth of cut.

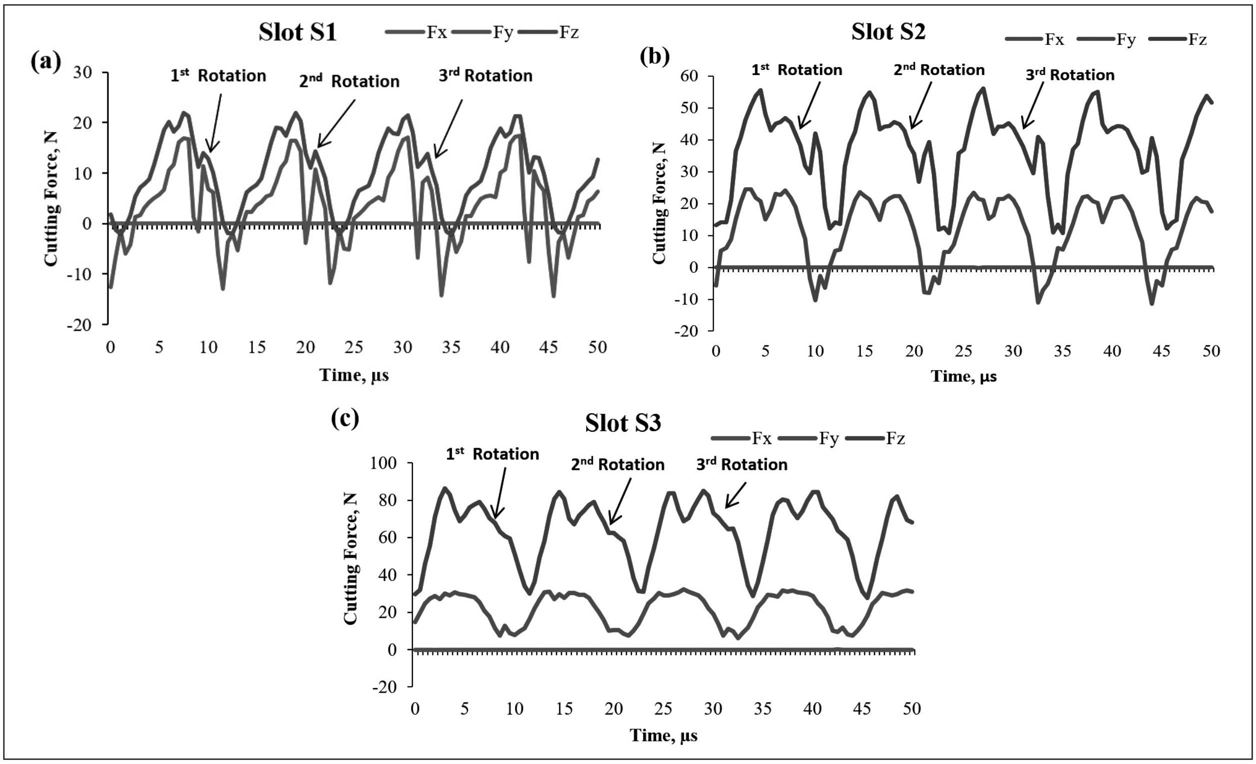

Fig. 6. The cutting forces in x, y and z-directions while slotting operations under machining conditions of (a) S1, (b) S2 and (c) S3.

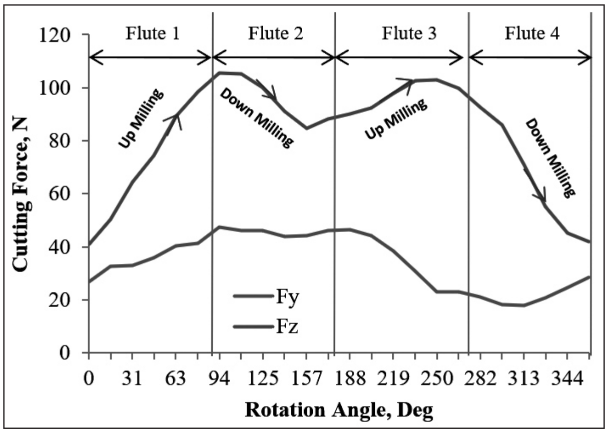

Fig. 7. Cutting forces under complete rotation depicting the up-milling and down-milling on the flutes.

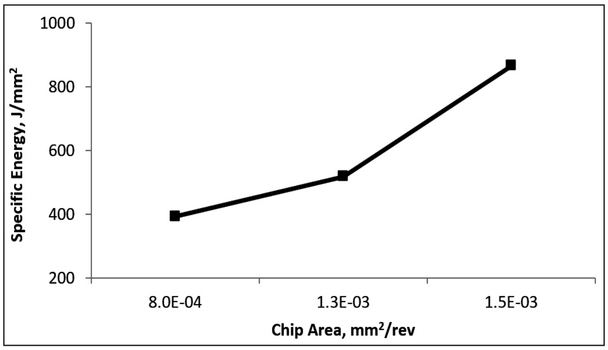

Fig. 8. Specific cutting energy as a function of chip area.

The cutting force in z-direction under machining condition of higher chip area was further analysed with respect to cutting flutes under a full rotation. The evolved cutting forces as a function of tool rotation angle is shown in Fig. 7.

3.3. Specific energy

The resultant cutting force (F_c) was calculated from the below equation (Varghese et al., 2021):

$$F_c = \sqrt{{F_x}^2 + {F_y}^2 + {F_Z}^2} \qquad \text{......................(1)}$$

The cutting force in x-direction (Fx) was neglected in the calculation due to their lower significance. The specific energy (p_s) for slotting operation is calculated as given by using below equation (Varghese et al., 2021):

$$p_s = \frac{F_c}{a_p f_s} \qquad \text{......................(2)}$$

where, α_p is depth-of-cut and f_s is feed speed. The result of specific energy under observed machining conditions is shown in Fig. 8. The specific energy per a unit area of uncut chip thickness increases steeply under higher chip area. It could be due to higher resultant cutting forces by the higher chip area and tool wear.

4. Conclusions

Precision slot milling experiments were conducted on a nickel-based SX superalloy in as-cast condition with TiAlN- PVD coated solid carbide end mill cutters of 1.5 mm diameter under a set of machining conditions.

The dimensional inaccuracy in width increases with an increase in chip area due to progressive diametric tool wear. The cutting forces have a similar trend under individual machining conditions due to negligible mechanical hardening of work material. The cutting force in the z-direction (axial) has the highest value among the other two. The axial force increases proportionally with an increase in depth-of-cut. The cutting force in the y-direction (feed force) increases with a decrease in feed speed. The cutting tool has undergone both up and down milling operations under a full rotation. The cutting forces increase gradually in up-milling and decrease gradually in down-milling operations due to variations in the engagement of chip thickness. The specific energy per unit area of uncut chip thickness increases steeply under higher chip area due to higher resultant cutting force.

The selected machining conditions are appropriate for the precision milling of nickel-based SX superalloy with small diameter cutters for maintaining reasonably constant depth from the surface. The variations in the width can be addressed through the incorporation of advanced machining techniques or the appropriate step-over distance in surface milling operations.

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