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Research Article

A Numerical Approach on the Design of a Sustainable Turning Insert

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Abstract: To decrease the energy footprint of a machined product, a novel turning insert design is reported in this article. Two geometrical models of the turning inserts, i.e., a commercially available design of insert; and proposed design of insert, were used to numerically simulate the turning operation. FEM-based coupled temperature displacement simulations were carried out for orthogonal turning operations for A2024-T351. Reasonable associations of numerical results with experimentation were found. Numerical simulation results showed the efficacy of the new design of the insert in quantitative reduction of energy inefficient byproduct of machining named as "Burr". Additionally, an improved tool life was also predicted.

Keywords: Machining simulation, Burr formation;, turning, aluminum alloy 2024-T351

1. INTRODUCTION

The US Department of Commerce explicitly defines sustainable manufacturing as "the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities and consumers"[1]. Developments of engineering products through smart sustainable manufacturing processes is the focus of manufacturing engineering related engineers and researchers for last some decades. These generic and specific product based processes and techniques encompass various methods (non-polluting methods, energy efficient methods, fast production methods, etc.) to achieve sustainable products. Amongst these methods cost effective and energy effective techniques have been more spotlighted and investigated in literature [2, 3]. In this continuation, to get sustainable production through machining process a new design of an eco-friendly turning insert has been proposed. Some direct and indirect advantages attributed to the newly proposed design of the insert are:

- Reduced side burr formation;
- Fewer resources requirement for deburring process to get final product (including machines, man, money and time);
- Longer cutting insert life (with lesser chances of chipping and fracture);
- Lesser emission of CO_2 (Indirect advantage: less energy is required to get final finished product and less energy is required with longer tool life).

In the current study, an FE-model for 3D-orthogonal turning operation has been developed. Initially, the FE model was validated with experimental results [4, 5] for turning of an

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aluminum alloy 2024-T351 using the commercially available turning insert (Sandvik uncoated carbide insert CCGX 12 04 08-AL H10). Turning numerical model was exploited subsequently to perform cutting simulation using newly proposed design of insert.

2. FINITE ELEMENT MODEL FOR TURNING SIMULATION

Geometrical model for 3D-orthogonal turning operation realized in ABAQUS software is shown in Fig. 1. In the orthogonal cutting conditions the tool cutting edge is simultaneously orthogonal to the cutting velocity and the feed velocity.

During machining material plasticizes and onwards fracture occurs and chip is separated from the workpiece. Throughout, this cutting process high stress, strains, temperatures, damage and other associated multiphysical phenomena occur at tool-workpiece interaction regions. This promotes severe mesh distortions (based on Lagrangian formulation). Furthermore, as chip detaches from workpiece a new surface (machined workpiece surface) is generated. In the present work to smooth the operation of chip formation and its detachment from workpiece an un-machined workpiece is geometrically modeled in three parts: predefined chip, machined part and chip separation zone. These parts are assembled through tie constraint algorithm (ABAQUS built-in algorithm), so that they behave like single identity "un-machined workpiece". Thermally coupled continuum brick elements C3D8RT with an average size of 30µm have been used to mesh various parts of model. Tool and workpiece were constrained as shown in Fig. 1.

To model the friction between tool and workpiece, Zorev`s friction model was employed [6]. Whereas, to model material`s elasto-plastic behavior, Johnson-cook thermo-elasto-visco-plastic model (Eq. 1) was employed [4, 5]. Furthermore, to simulate ductile damage for Al2024, Johnson-Cook damage model (Eq. 2) was used [4, 5].

$$\bar{\sigma}_{JC} = \underbrace{\left(A + B\bar{\varepsilon}^{n}\right)}_{\text{Elasto-plastic term}} \underbrace{\left[1 + Cln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]}_{\text{Viscosity term}} \underbrace{\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{m}\right]}_{\text{Softening term}} \quad (1)$$

Table 1. Physical properties of various materials [4].

Parameter	Workpiece (A2024-T351)	Insert (Tungsten carbide)
Density, ρ	2700	11900
Young`s Modulus, E	73000	534000
Poisson`s ratio, ν	0.33	0.22
Specific heat, C_p	$0.557T + 877.6$	400
Expansion Coefficient, α_d	$8.910^{-3}\ T + 22.2$	x
Thermal conductivity, λ	$25 \leq T \leq 300$: $\lambda = 0.247T + 114.4$ $300 \leq T \leq T_m$: $\lambda = -0.125T + 226$	50
Meting temperature, T_m	520	x
Room temperature, T_r	25	25

Table 2. Constitutive model parameters for A2024-T351 [4].

A	B	n	C	m	D_1	D_2	D_3	D_4	D_5
352	440	0.42	0.0083	1	0.13	0.13	-1.5	0.011	0

$$\bar{\varepsilon}_{0i} = \left[D_1 + D_2 exp\left(D_3 \frac{P}{\bar{\sigma}} \right) \right] \times \left[1 + D_4 ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[1 + D_5 \left(\frac{T - T_r}{T_m - T_r} \right) \right] \quad (2)$$

Further details on the numerical model are elaborated by Asad [4]. Material properties are given in Table 1 and Table 2.

3. TURNING EXPERMENTATION

Orthogonal turning experiments for cutting speed, V_C = 800 m/min, feed rate, f = 0.3 and 0.5 mm/rev, depth of cut, a_P = 4 mm were performed. Sandvik uncoated carbide insert with rake angle = 17.5° and clearance angle = 7° referenced CCGX 12 04 08-AL H10 was used. To get orthogonal conditions, it was made sure that the insert cutting edge was both orthogonal to the feed rate and cutting speed while edge inclination and entering angles were equal to 0° and 90°, respectively as illustrated in Fig. 2b. Cutting forces were registered by using a standard dynamometer. The measured average cutting forces for various cutting parameters are presented in Table 3. Chips were recovered, polished, etched and photographed as shown in Fig. 2c.

4. RESULTS AND DISCUSSION

Generation of various types of burrs for various machining processes and material properties has been reported in literature [7-9]. Side burr also called poisson burr is the main type of burr which produces during turning operations [7]. Schematic of side burr formation in orthogonal turning operation is shown in Fig. 3. In the present section numerical simulation work on qualitative and quantitative formation of side burr has been discussed. Initially, numerical model results (chip morphology and cutting forces) for cutting speed = 800 m/min, feed rate = 0.3 and 0.5 mm/rev, depth of cut = 4 mm for Sandvik insert have been validated with experimental results [4, 5]. Onwards, FE simulations have been reproduced with the new proposed geometry of cutting insert.

4.1 Simulation Results with Commercial Turning Insert

Fig. 2a shows the chip morphology produced for orthogonal turning operation for cutting speed = 800 m/min, feed rate = 0.5 mm/rev and depth of cut = 4 mm. The chip morphology has good corroboration with the experimentally produced [4] chip (Fig. 2c). In addition cutting forces shows good correlation (Table 3).

Table 3. Cutting forces results for V_C = 800 m/min, a_P = 4 mm.

	Feed rate *f* (mm/rev)	
	0.3	**0.5**
Experimental results [4]	738	1110
Numerically obtained	686	1090

Insight observation of chip and machined surface shows that material mainly plastically flows along x axis and y axis (in the form of chip), however some material flows along Z-axis because out of plane deformation. In addition surface contact conditions (e.g., contact pressure of tool and workpiece) are more sever at tool edges (Fig. 4) than at the central section of tool. This further enhances material flow towards edges. Consequently, after machining one finds a non-value added byproduct in the form of sharp side burr. Quantitative prediction of side burr is presented in Fig. 5.

4.2 Simulation Results with New Design of Turning Insert

A new geometry of the insert has been proposed (Fig. 1). The purpose is to reduce the non-value added byproduct “burr”. Orthogonal tuning simulation for cutting speed = 800 m/min, feed rate = 0.3 and 0.5 mm/rev, depth of cut = 4 mm, were reproduced. Considerable decrease in side burr was noticed as shown in Fig. 5. In addition, as geometry of the new insert requires less area of tool to contact with workpiece so less initial impact force is generated on tool. (Fig. 6). Later, characteristics of new insert geometry is useful in

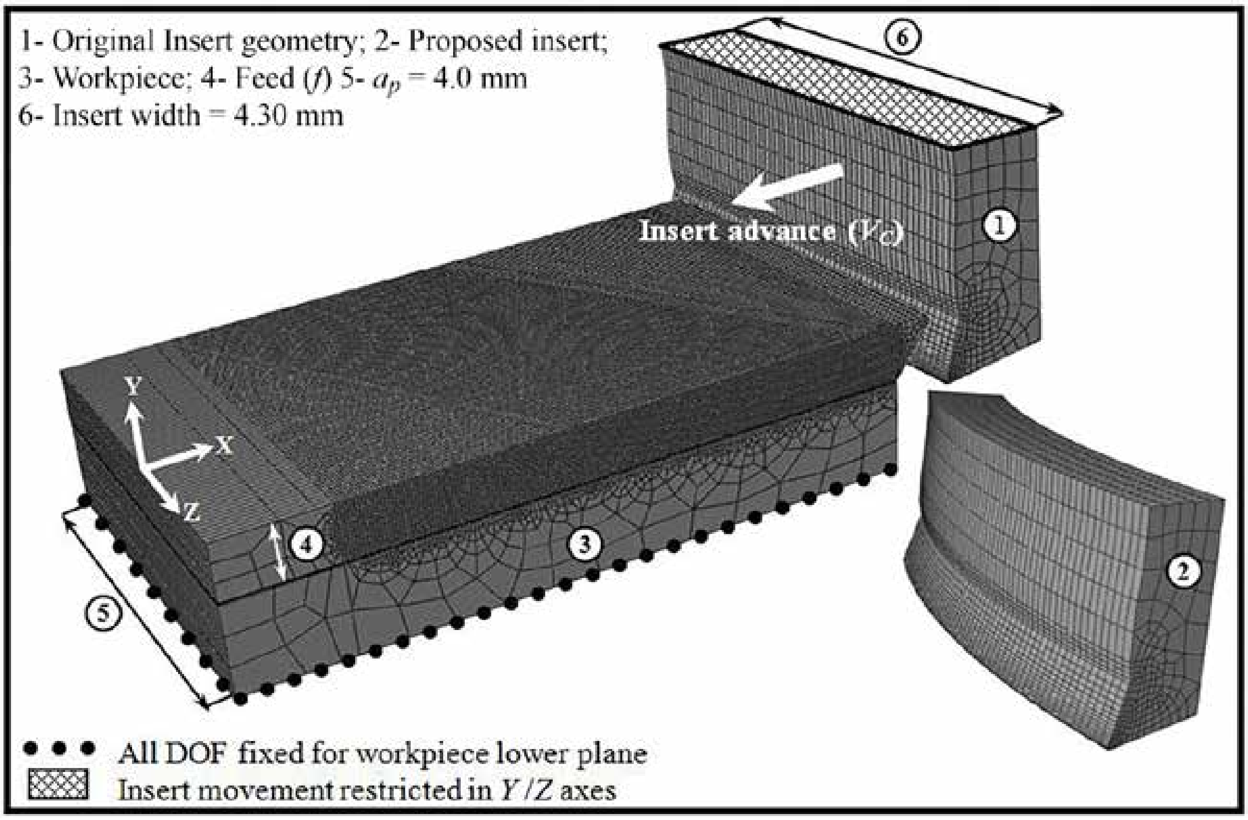

Fig. 1. Three-dimensional work-piece and turning inserts models.

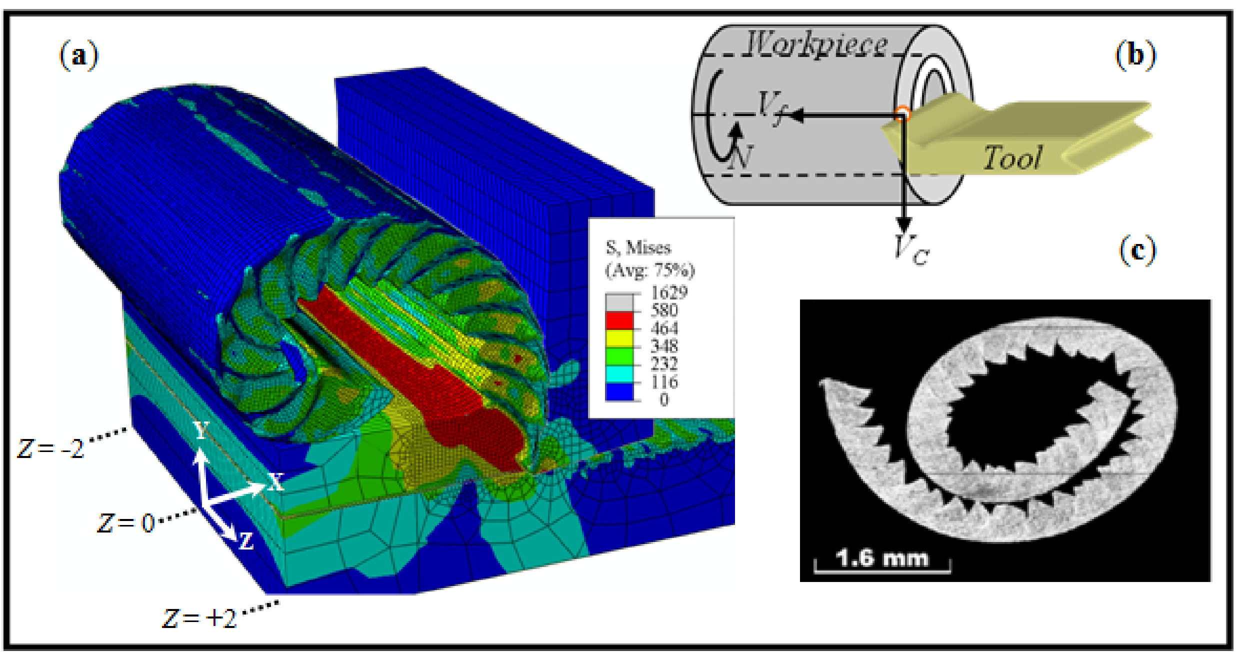

Fig. 2. Chip morphology for orthogonal turning for V_C = 800 m/min, f = 0.5 mm/rev, a_P = 4 mm.

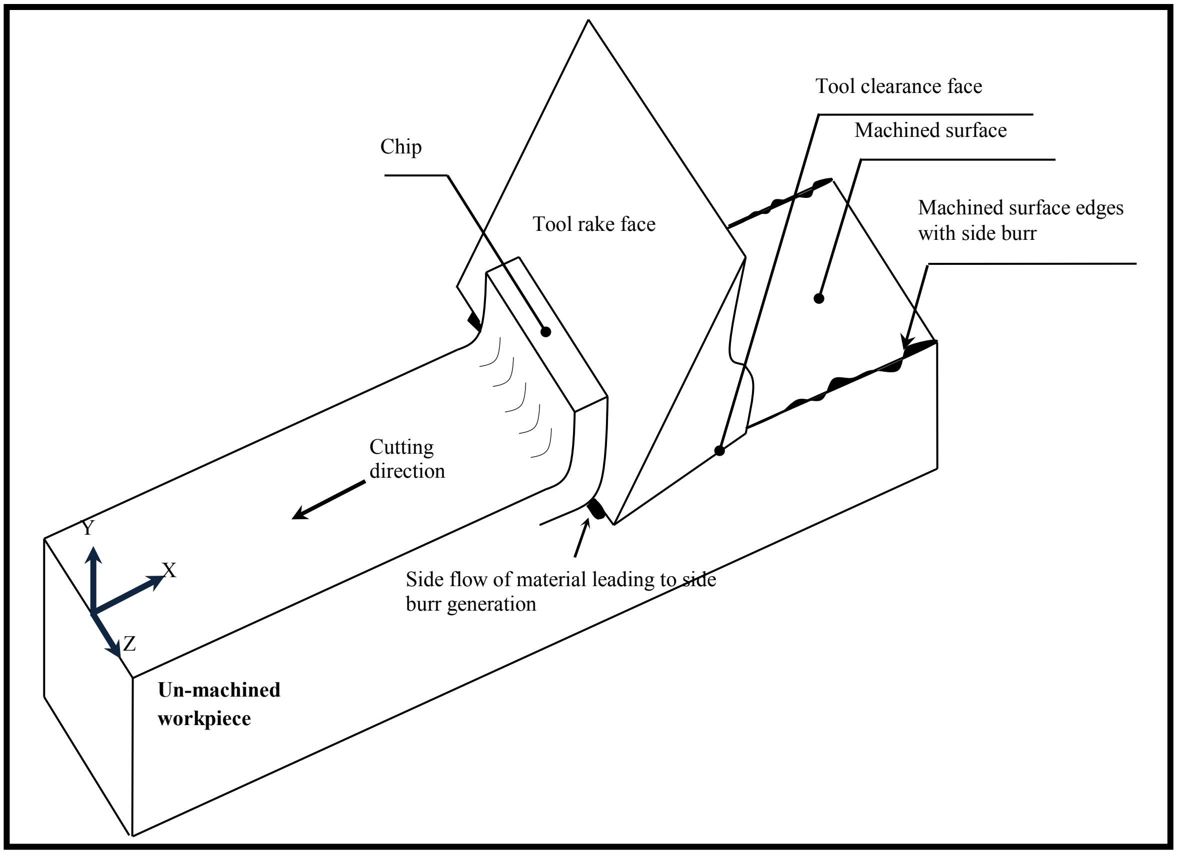

Fig. 3. Side burr formation in turning operation.

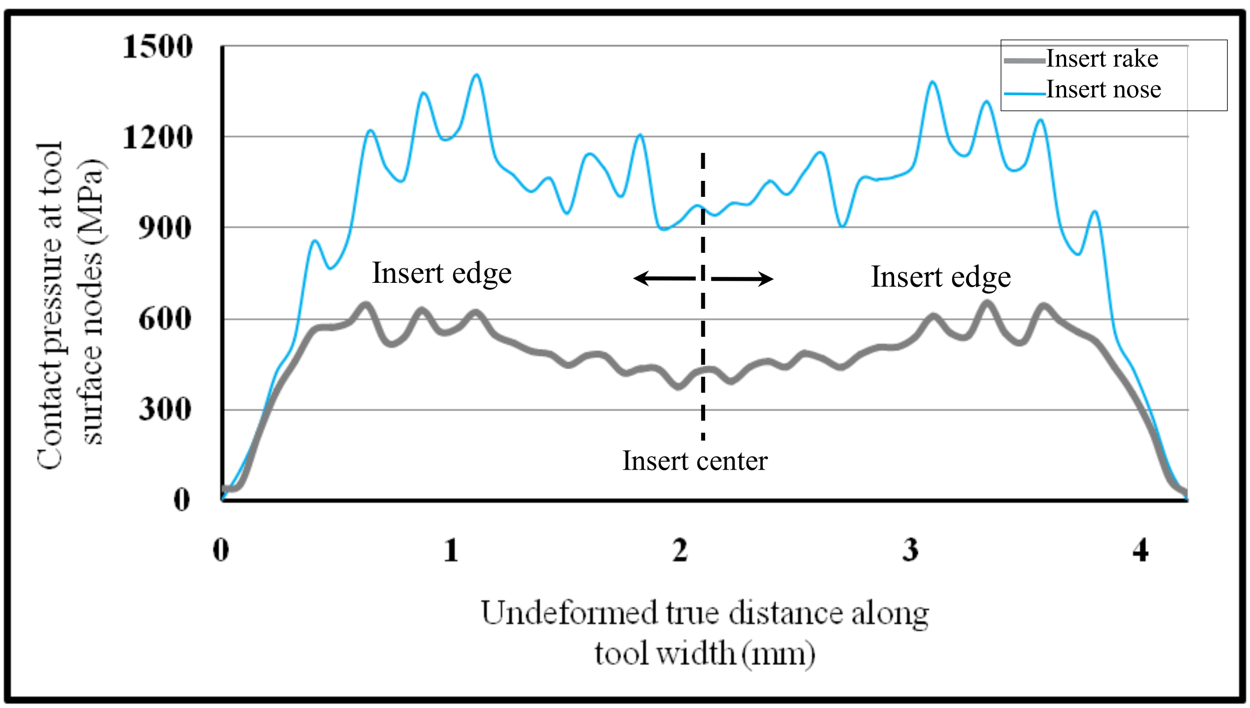

Fig. 4. Profiles of contact pressure at various contact sections of cutting insert for V_C = 800 m/min, f = 0.5 mm/rev, a_P = 4 mm.

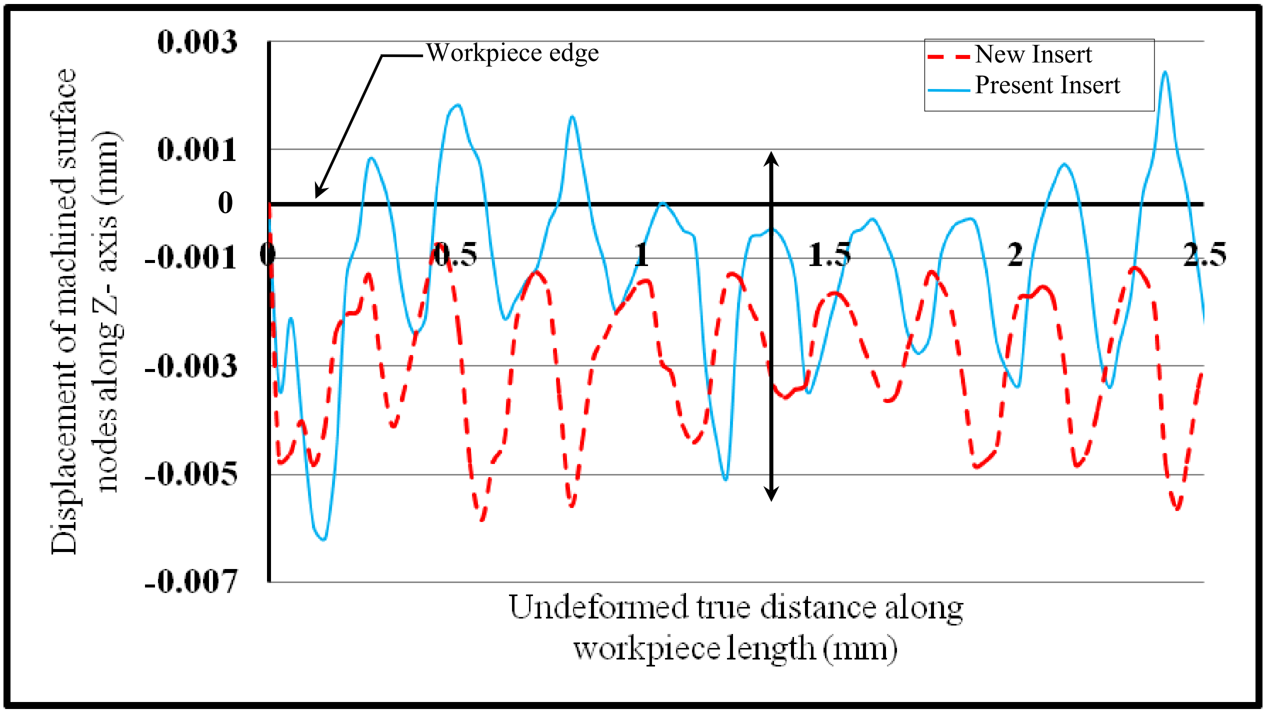

Fig. 5. Quantitative prediction of side burr for V_C = 800 m/min, f = 0.5 mm/rev, a_P = 4 mm.

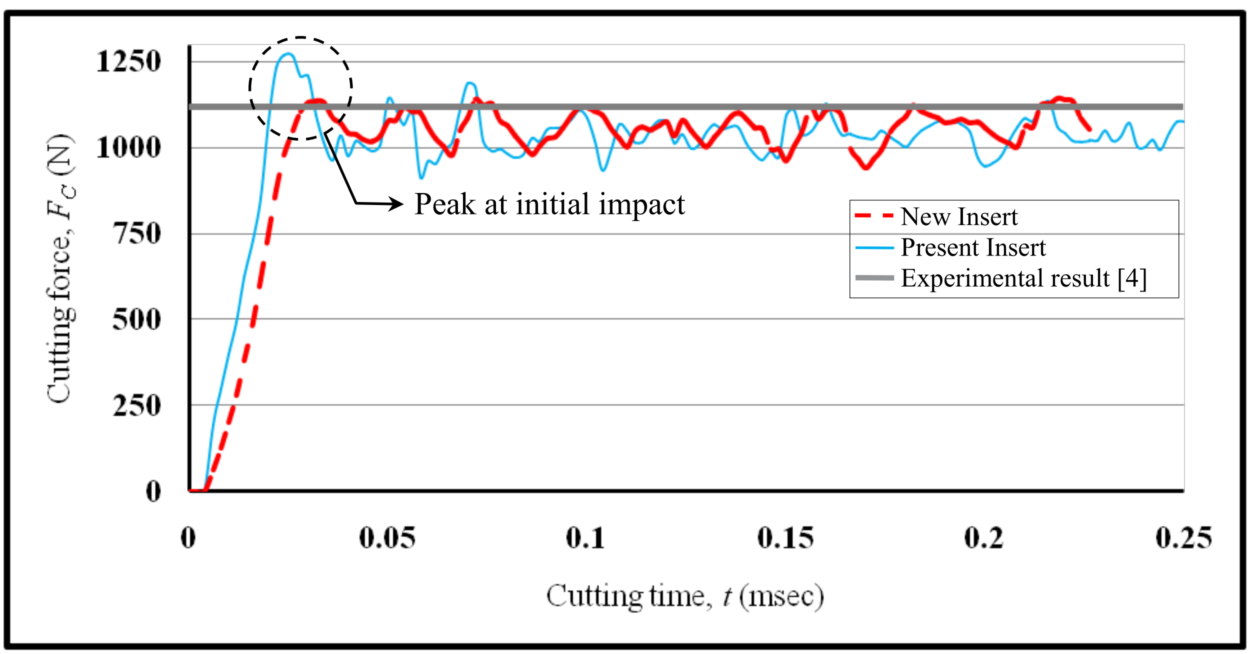

Fig. 6. Plots of cutting forces for V_C = 800 m/min, f = 0.5 mm/rev, a_P = 4 mm.

decreasing early failure of tools because of chipping and fracture.

5. CONCLUSIONS

The 3D orthogonal turning simulations showed that, out of plane deformation and severer contact conditions at tool work, piece edges produce and enhance side burr formation. The proposed design of turning insert is helpful in reducing burr formation. Therefore, less resources are required for deburring process to produce the final product. As lesser initial tool-workpiece contact is required to initiate cutting, so longer cutting insert life (with fewer chances of chipping and fracture) has been predicted. Also, lesser emission of CO_2 would be produced to get the final machined product. In future, further numerical and experimental tests shall be produced to realize the insert design for onward actual machining.

NOMENCLATURE

A	Initial yield stress (MPa)
a_P	Cutting depth or axial depth of cut (mm)
B	Hardening modulus (MPa)
C	Strain rate dependency coefficient
C_p	Specific heat (J kg^{-1}° C^{-1})
$D_1 ... D_5$	Coefficients of Johnson-Cook material shear failure initiation criterion
E	Young's modulus (MPa)
f	Feed rate (mm/rev)
m	Thermal softening coefficient
n	Work-hardening exponent
P	Hydrostatic pressure (MPa)
T	Temperature at a given calculation instant (°C)
T_m	Melting temperature (°C)
T_r	Room temperature (°C)
V_C	Cutting speed (m/min)
$P/\bar{\sigma}$	Stress triaxiality
$\bar{\varepsilon}$	Equivalent plastic strain
$\dot{\bar{\varepsilon}}$	Plastic strain rate (s^{-1})
$\dot{\bar{\varepsilon}}_0$	Reference strain rate (10^{-3} s^{-1})
$\bar{\varepsilon}_{0i}$	Plastic strain at damage initiation
σ_{JC}	Johnson-Cook equivalent stress (MPa)
ν	Poisson's ratio
α_d	Expansion coefficient (µm m^{-1}° C^{-1})
λ	Thermal conductivity (W m^{-1} C^{-1})
λ_s	Mill helix angle (deg)
ρ	Density (kg/m^3)

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