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Simulation led Performance Evaluation of a Hybrid Al_2O_3/SiC/cBN Composites for Cutting Tool Inserts

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Abstract

A computational material design approach is used to design a novel ceramic material with improved thermal and structural performance for cutting tool inserts. Many competing requirements are inherent in material design, necessitating careful consideration of critical considerations in terms of material phase composition, reinforcement size, morphology, and distribution in order to attain the intended properties. When compared to commercial stand-alone alumina (Al_2O_3), the hybrid alumina/silicon carbide/cubic boron nitride composite (Al_2O_3/SiC/cBN) employed for cutting inserts is found to be the suited design among other alternatives with enhanced thermal and structural properties. In order to study the performance characteristics and the effects of the new ceramic composite with improved properties, a fully coupled thermal and structural analysis of the cutting tool insert during cutting of high strength steel alloy is evaluated using finite element method and compared with Al_2O_3 inserts. Stress distribution and temperature profile are observed as a function of time during dry cutting conditions. Improved thermal performance of a cutting insert made of Al2O_3/SiC/cBN is found due to better resistance to thermal shock which can be associated with better flow of temperature through the insert. The stresses generated due to the combined effect of the heat flux and mechanical loading on the cutting edge

are analyzed and it is found that the newly proposed hybrid composite is a potential substitute for commercially available ceramic inserts.

Keywords: finite element method, cutting simulation, tool inserts, performance.

1 Introduction

Intricate manufacturing involved in the development of complex designs has driven the demand for an improved industry standard for cutting tool inserts. Innovation in the design of materials has been focused on the reduction of cost and optimization of performance during high-speed cutting scenarios. Ceramic-based cutting tools are being considered for high-speed cutting for a wide range of workpieces. The incorporation of reinforcements tends to improve thermal performance without significant reduction in structural integrity. For a cutting tool to be at its most effective, it should be having enhanced wear resistance and resistance to fracture and thermal shock. Ceramic-based cutting tools possess certain limitations for which ceramic-based composites are considered. Deficiencies such as low resistance to thermo-mechanical shock can be improved by the inclusion of suitable reinforcements. The additional phases can improve the targeted characteristics of the cutting tool such as resistance to cracking and enhancement of “field” properties such as thermal conductivity and elastic modulus. An alumina composite reinforced with silicon carbide resulted in longer tool life in comparison to standalone alumina. The presence of a hard secondary phase enhances the overall hardness of the tool insert [1-2]. Reduction of overall stresses generated during the cutting process can also help improve the life of an insert. The main objective of this work is to assess the performance of a newly introduced hybrid alumina-silicon carbide-cubic boron nitride composite under predetermined cutting conditions by means of simulations.

This paper discusses the performance evaluation of the proposed ceramic-based hybrid Al_2O_3/SiC/cBN composite when considered for the application of cutting tool inserts under predetermined cutting conditions by means of simulations. The newly proposed alumina-based composite material is analyzed and compared with its fellow cutting tool insert competitors, such as standalone alumina inserts. The new composite material possesses enhanced thermal and structural properties in accordance with the cutting tool insert design while also possessing the economic and environmental benefits of alumina [3, 4]. The performance evaluation of the composite cutting tool inserts when considered for the turning of high-strength steel is performed using the FEM through a 3D steady-state coupled thermal-structural analysis. A steady-state thermal stress analysis will allow the simulation of the heat flux being generated at the cutting edge due to frictional forces occurring during machining and the flow of heat within the insert. This flow of heat into the system results in an increased temperature and greater stress gradients throughout the body. In addition, a high CTE can result in greater deformation of the insert which can lead to thermal shock failure due to the fluctuation of temperature.

2 Methods

2.1 Problem Description

For the thermal part of the analysis, the basic energy will be utilized to determine the temperature field as shown in eq. (1):

$$C_p u.\nabla T = \nabla(k\nabla T) + Q \quad (1)$$

Where C_p is the heat capacity, k is the thermal conductivity of the constituents present within the system, ∇T and Q are the temperature difference and the heat source within the system.
The general heat flux into and out of the body is defined by the following equation:

$$-n(-k\nabla T) = h_c(T_c - T) \quad (2)$$

Where hc is the convective heat transfer coefficient and T_c is the temperature of the surrounding environment respectively. T is defined as the initial temperature at any given point on the surface of the boundary.
Regarding the steady-state structural analysis, the stress-strain constitutive behavior is defined by:

$$-\nabla \mathrm{u} * \sigma = F * v \quad (3)$$

$$\sigma_y - \sigma_0 = c: (\varepsilon - \varepsilon_0 - \varepsilon_{Th} - \varepsilon_p) \quad (4)$$

In these equations, σ is the Cauchy stress, $F * v$ is the body load, ε is the total strain value, ε_{Th} is the strain generated due to the thermal loading and ε_p is the effective plastic strain generated. σ_y is the yield stress of the material, ∇u is the displacement gradient and c is the elastic stiffness matrix. The mathematical relationships for the strains as a result of the time-dependent structural analysis with appropriate constitutive behaviour is used. To remove the possibility of rigid-body motion, the area where the insert is fitted onto the tool arm is considered to be constrained in all directions.

The equations are summarized by the following,

$$[f_{Thermal}] = [K_1][t] \quad (5)$$

$$[f] = [K_2][d] - [f_{TF}] \quad (6)$$

Where $f_{Thermal}$ is defined as the thermal load which may be applied as a heat source, heat flux or conduction or convection of heat. K_1 is function matrix of the effective thermal conductivity of the material and geometry dimensions. t is the temperature distribution matrix which contains the unknown variables. f_{TF} is defined as the thermal force and is a function of the temperature distribution t, CTE and the effective elastic modulus of the composite. f is the applied nodal forces which will be varied based on the cutting tool machining experimental data extracted from literature. K_2 is a matrix defined as a function of the elastic modulus of the composite and geometry dimensions; d is the nodal displacement matrix which is also an unknown.

2.2 Geometry Model and Boundary Conditions

To simulate real-life dry cutting heat transfer cutting conditions, free and natural convective heat transfer has been applied to the entire body of the model with a heat transfer coefficient of air, which is 10 W/m^{2}-K as shown in Figure 1 [3].

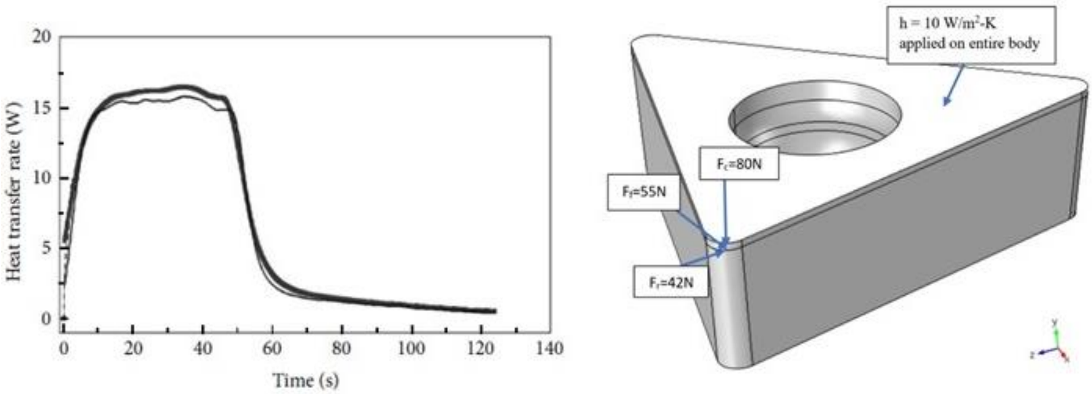

Figure 1: Heat transfer loading applied onto cutting edge as a function of time and the description of the additional boundary conditions applied onto the insert [3].

2.3 Material Model

The material properties used for the ceramic based composite material model have obtained for the experimental material characterization and testing reported by authors earlier [4, 5] as shown in Table 1. The selected ceramic based composite consists of an alumina matrix with 30% silicon carbide and 20% cubic boron nitride inclusions. The benchmark material which was selected as pure alumina was also developed in this work and the determined properties have been used for comparative analysis.

Material	Elastic Modulus [GPa]	Poisson's Ratio	Thermal Conductivity [W/m^2-K]	CTE [1/K]	Fracture Toughness K_{IC} [MPa-m$^{1/2}$]
Al_2O_3	147	0.22	25	7.06	4.0
Al_2O_3/SiC/cBN Composite	189.4	0.21	36.86	5.41	4.42

Table 1: Material properties used to define the material model [4, 5].

3 Results

Results have been obtained when the heat flux has been applied onto the cutting edge and the stresses distribution and temperature profile are observed as a function of time for each case. The duration of the dry cutting process was taken as 120 seconds with the results being recorded at every 0.1 second interval for better analysis. In addition, the surrounding temperature has been maintained at 25oC with the application of a convective heat transfer coefficient to allow heat to escape into the surrounding from the body, therefore, simulating dry cutting conditions. Three cases will be presented with each being comparatively analyzed in terms of temperature profile and stresses distribution

Results have been obtained as a function of time as the heat flux and the mechanical pressure loading is applied. Figure 2 shows a temperature variation at the cutting edge of inserts made of commercial Al_2O_3 and proposed Al_2O_3/SiC/cBN composite. Figure 3 (a-c) and (d-f) show the contour plots of temperature distribution in the two inserts, respectively, at 10s, 60s, and 90s after cutting. As can be observed, the heat flux begins to heat up the cutting edge and temperature increases rapidly and begins spreading around the edge. These frictional forces lead to the increase in temperature in cutting edge which spreads away from the edge as time goes on. The temperature is maximum at approximately 40 seconds in both cases; this is expected due to the heat flux boundary condition. As compared to Al_2O_3, a reduced level of temperature in the proposed insert attributed to the superior thermal conductivity of the designed composite which is allowing the temperature to quickly flow away from the cutting edge.

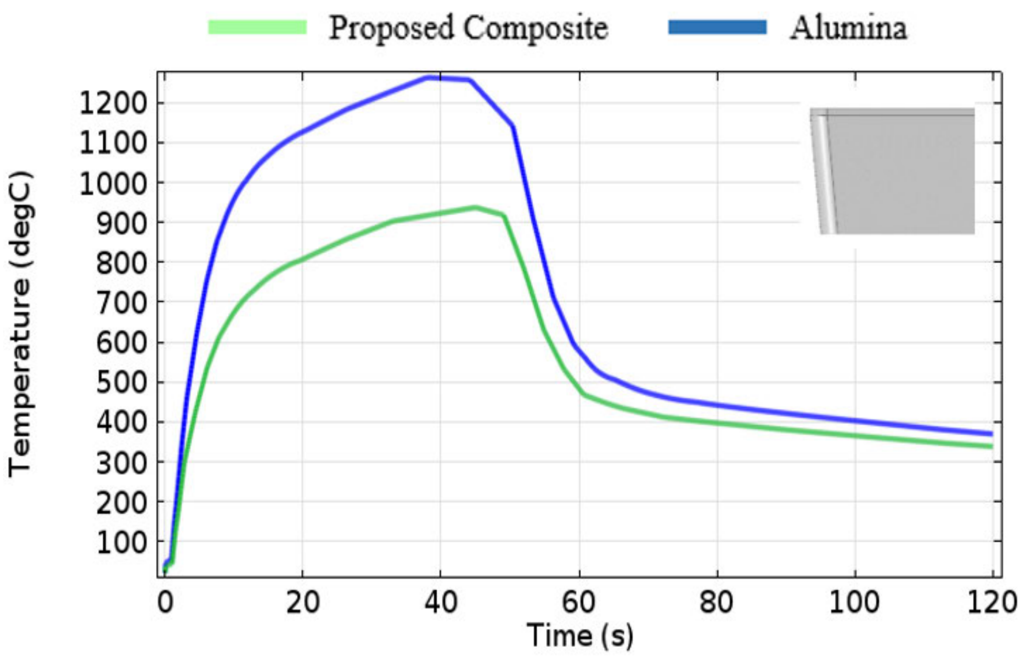

Figure 2: Temperature variation at the cutting edge of inserts made of commercial Al_2O_3 and proposed Al2O3/SiC/cBN composite.

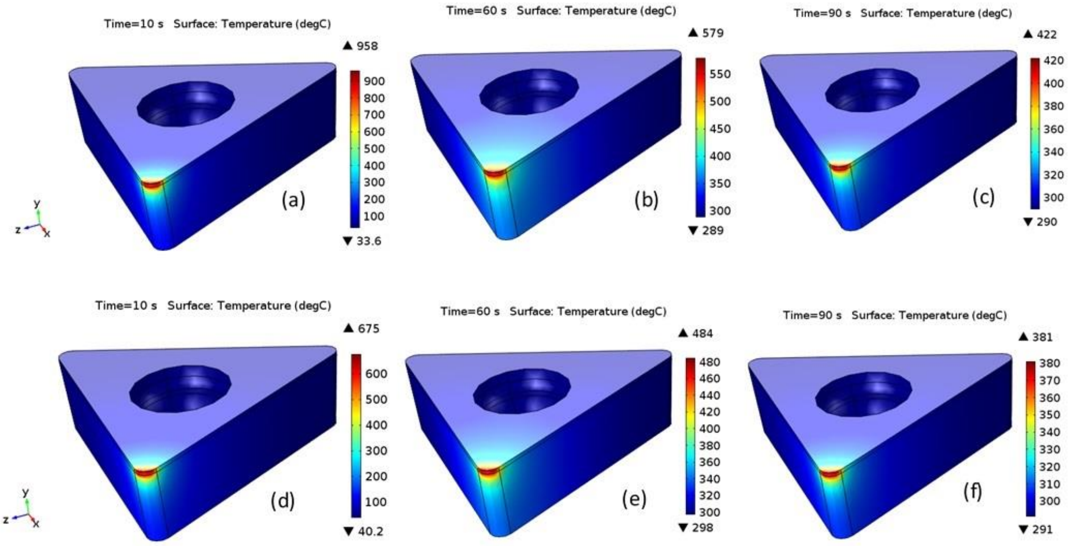

Figure 3: Temperature distribution captured at various cutting times at the cutting edge of inserts made of commercial Al_2O_3 and proposed Al_2O_3/SiC/cBN composite.

As can be observed in the temporal variation of von-Mises stress distribution in commercial Al_2O_3 and proposed composite (Figure 4), of the Al_2O_3-SiC-cBN composite insert during the cutting process, considerably less stresses are imposed on the designed insert, which is due to the enhanced elastic modulus of the composite along with the decreased CTE which is reducing the amount of deformation caused by the loadings imposed during the cutting process.

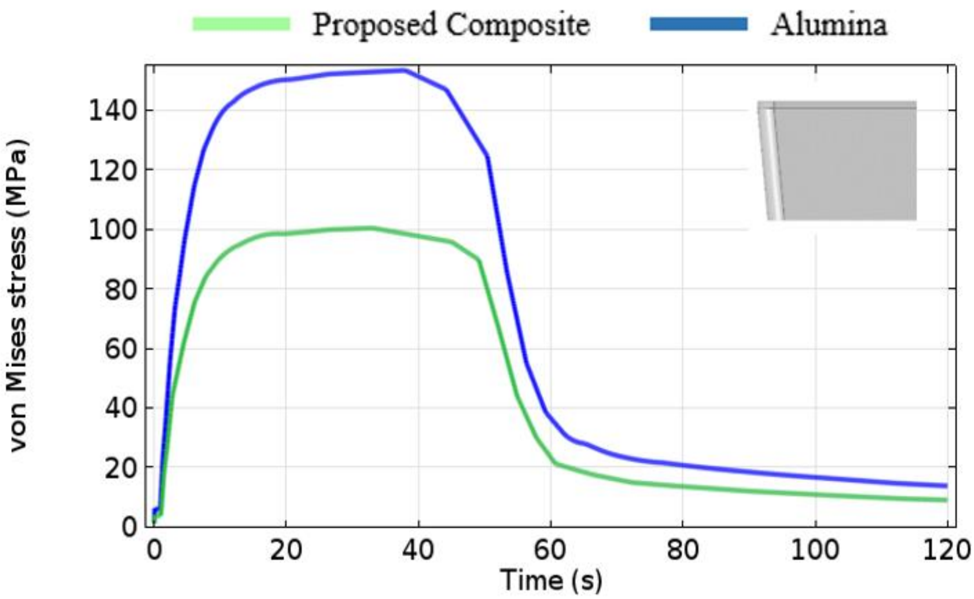

Figure 4: Stress variation at the cutting edge of inserts made of commercial Al_2O_3 and proposed Al_2O_3/SiC/cBN composite.

4 Conclusions and Contributions

The following conclusions can be drawn from this work:

- The performance of designed and developed Al_2O_3-SiC-cBN composite when considered for use as cutting tool inserts is evaluated.
- The finite element method (FEM) is considered to model the thermal performance of the composite when subjected to a cutting process of predetermined cutting speed, feed rate, and depth of cut.
- As a means of comparison, alumina inserts' performance is evaluated along with the designed composite.
- The thermal performance of the new proposed Al_2O_3-SiC-cBN composite is found to be better compared to the two other cases.
- Structural performance is also found to have been improved due to the presence of comparatively reduced stresses on the cutting edge of the designed composite.

The developed model has been implemented on the work done previously by Kisku [6] on the investigation of the temperature profile of a coated and uncoated cemented carbide insert due to the heat flux introduced during the cutting process. The same material model and boundary conditions have been used and the corresponding results are in good agreement with the reported results in reviewed work.

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