Journal of King Saud University – Engineering Sciences (2012) **24**, 85–94

King Saud University

Journal of King Saud University – Engineering Sciences

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ORIGINAL ARTICLE

Thermal-stresses in carbide-tip bonded face milling cutters

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Received 3 October 2010; accepted 20 March 2011
Available online 3 April 2011

KEYWORDS

Milling cutter;
Bonded cutting tools;
Adhesively bonded tool

Abstract Bonded composite cutting tools has been introduced to enhance surface finish and reduce cutting forces. The main objective of the current study is to assess factors that influence the thermal stresses developed in adhesively bonded carbide tip face milling cutters using numerical analysis. Both plain, copper filled adhesives, dry and coolant factors are considered in current study. It is found that thermal stresses developed in bonded carbide tip face milling cutter decrease tremendously with applying cutting coolant and little effect was reported when adding copper filler to adhesive.

1. Introduction

The majority of modern cutting tools are complex structures comprising a hard, wear resistant cutting inserts which are supported by a shank or holder generally manufactured from low or medium alloy steel. The insert, with which the actual cutting operation takes place, is generally kept as small as possible in order to reduce the cost and may be made in a variety of hard materials, commonly cemented carbide at different grades. Brazing and mechanical clamping are the common mounting methods on the tool holder (Schwartz, 1979; Al-Samhan, 2004; Alsamhan and Darwish, 2003; Darwish and Al-Samhan, 2004a; Darwish and Al-Samhan, 2004b; Darwish and Davies, 1989a; Darwish and Davies, 1989b; Kilik et al., 1990; Davies and Darwish, 1991; Darwish et al., 1991; Maekawa et al., 1996; Darwish, 2000a; Darwish, 2000b; Alsamhan and Darwish, 2005; Darwish and S.M., 2004).

When cemented carbide inserts are brazed, micro-fissures are often developed due to the high temperature of the brazing operation. The proportion of rejects in brazing due to cracks in cemented carbide inserts often reach 10–20% (Darwish and Davies, 1989a). Mechanical clamped cutting inserts does not always ensure a contact stiffness that is sufficiently high to prevent vibrations usually developed in cutting operation. When tool manufacturing technology is converted from brazed to bonding, the advantages expected are reduction in scrapped inserts due to the lower temperature necessary during assembly, hence, less skilled labor is required and also improved tool quality and surface finish due to the high damping of adhesive layers (Darwish and Davies, 1989a; Darwish, 2000a; Darwish, 2000b).

The main problem with bonded tools is the heat flow in tool holder which is restrained due to low thermal conductivity of the adhesive material. Different researchers investigate the

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Peer review under responsibility of King Saud University.
doi:10.1016/j.jksues.2011.03.009

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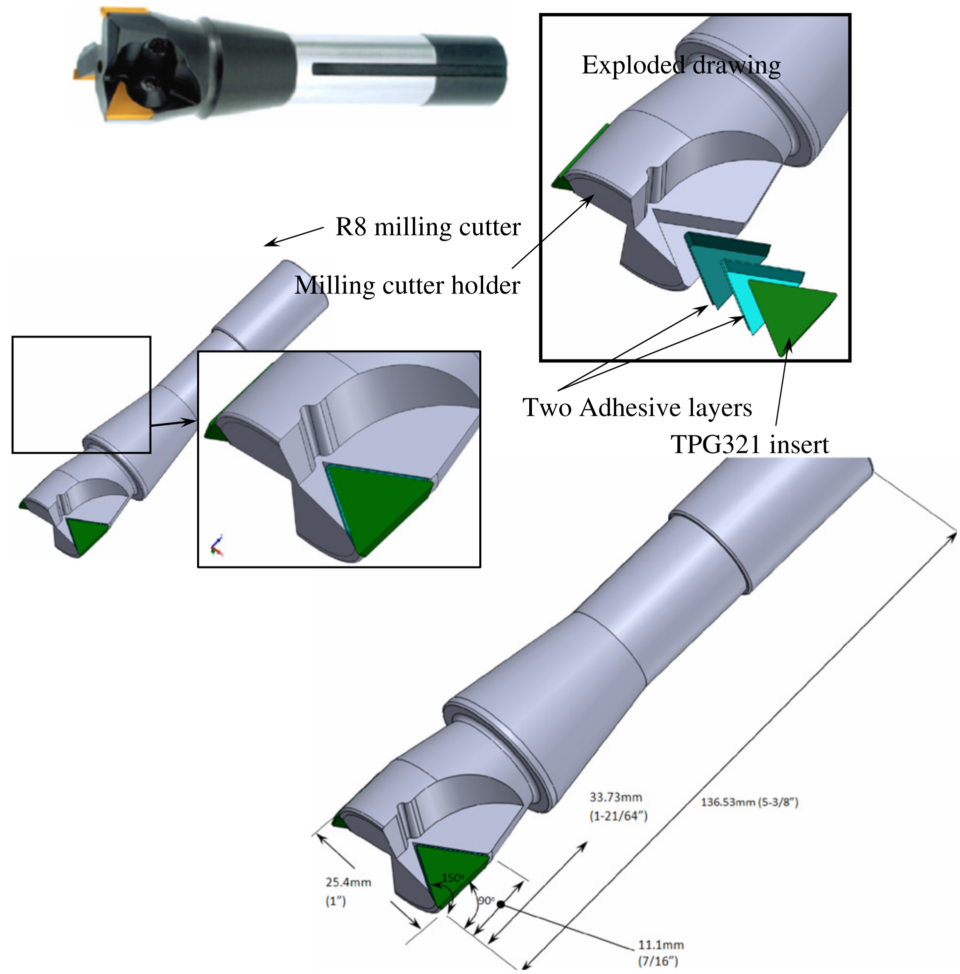

Figure 1 General layout of the bonded carbide tip face milling cutter with general overall dimensions.

heat flow in bonded tools and suggest different solution for this problem. Darwish and Davies (1989b) investigate the heat flow through bonded and brazed single point metal cutting tools when turning a cylinder pipe using experimental (thermocouple and infra-red camera) and numerical techniques. High temperature concentration were reported at the tool-chip interface for bonded cutting tools when compared with brazed tools, they recommend that cutting fluids should always be used with bonded tools to increase the heat dissipation. Later Davies and Darwish (1991) study different techniques to increase the heat dissipation of the bonded single point cutting tools by using adhesive with atomized copper powder fillers to increase the thermal conductivity of adhesives. They found that the effect of coolant on the temperature distribution is more pronounced than the effect of copper powder mixed with adhesive. They reported that the cutting fluids always to be used with bonded tools whether or not a metallic powder is mixed with the adhesive.

The concentrated high temperature of bonded-cutting tool may result in destabilization in the micro-structure of machined workpieces, especially if the workpiece material is sensitive to temperature changes like Duralumin material. Darwish, Niaz and Ghaneya (Darwish et al., 1991), machined Duralumin with both bonded and brazed single point tools. The correlation between cutting temperature, microhardness and photomicrographs reveals that phase stability of Duralumin is always maintained with bonded cutting tools. Finally, they reported that bonded tools are safe for machining temperature-sensitive heat treatable alloys.

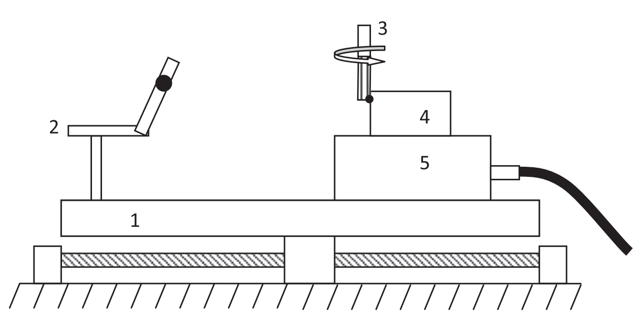

Figure 2 Experimental set-up used to measure the chip-tool interface temperature and cutting forces of the bonded carbide-tip face milling cutter (Darwish and Alsamha, 2004).

Machining of difficult-to-cut metals with bonded tools like nickel-based supperalloy is studied by Darwish (2000b), his work demonstrates the favorable effect of bonded tools on surface roughness when compared with mechanically clamped tools.

The aim of the present study is to assess the effect of different factors that improve the heat dissipation in bonded carbide tip of a face milling cutter on thermal stresses (thermo-mechanical stresses) developed during cutting. A standard one inch face milling cutter with two adhesively bonded triangle inserts, type TPG321, is modeled as bonded carbide tip face cutter, where the finite-element technique used in current study. The investigated factors covers, using two type of adhesive materials, plain adhesive and copper filled adhesive material. Dry cutting and cutting with coolant factors are also included in current study.

2. Solid model development

The art of the finite-element analysis lies in the representation of a real structure and with its loading conditions, after importing the solid CAD system, by a mathematical model, which can be analyzed by numerical software in computer hardware. One factor affecting the result accuracy is the similarity between geometry of the real structure and the loading conditions considered in the finite-element model. In the current study, CATIA Ver. 5 software was used to develop the solid model of the composite carbide tip bonded face milling

Table 1 Material constituents and properties of bonded carbide tips face milling cutter.

Cutter Components	Material	Density ($kg/m^3 \times 10^{-6}$)	Specific heat (J/kg °C)	Thermal conductivity (W/m °C)	Thermal expansion coefficient (m/m °C $\times 10^{-6}$)	Young's modulus (Pa)	Poisson's ratio	Yield strength (N/mm^2)
Cutter Shank and holder	Steel	7870	458.48	35.3	12.1	2e11	0.3	282
Cutting edge (TPG321)	Carbide	19,300	458.48	110.0	4.0	6.3e11	0.22	21,000
Adhesive	Plain type	1300	1667.2	1.06	60.0	2.5e9	0.38	103.6
Adhesive	Copper power fill 30%	1500	1667.2	1.81	60.0	2.5e9	0.38	103.6

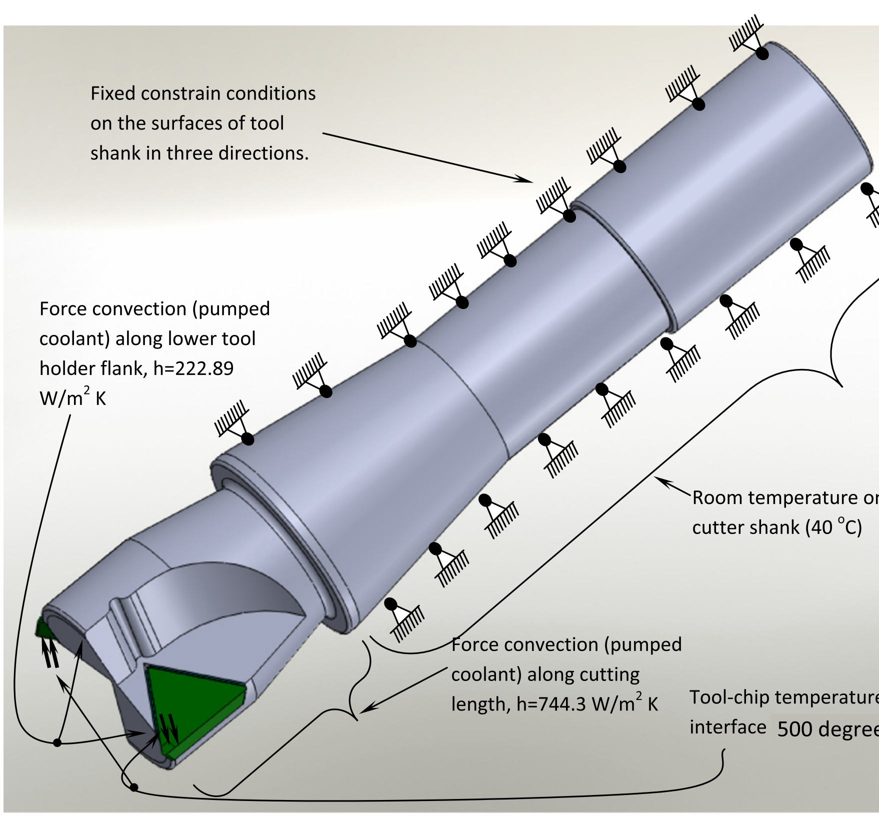

Figure 3 Assign thermal boundary and constrain conditions on the FE model of the bonded carbide tip face milling cutter.

cutter. Fig. 1, shows the actual photo of the milling cutter with R8 shank having three cutting edges. This type of cutters manufactured with one, two, three up to five cutting edges having same TPG321 carbide inserts, furthermore, milling cutter diameter increases with increase of number of cutting edges.

In the current study, CAD model was developed for face milling cutter with two bonded cutting inserts (see Fig. 1). The figure shows also the exploded drawing for the bonded milling cutter assembly. As illustrated in the figure, the bonded face milling cutter consists of two cutting edges with insert type TPG321, two adhesive layers 0.25 mm thickness each (0.5 mm total thickness) and milling cutter shank holder namely R8 shank type. It is worth noting that this type of milling cutters are standard type face milling cutter with mechanical clamped inserts, where modification was introduced in the CAD model after removing the mechanical clamping unit. Fig. 1, shows the general overall dimensions of the bonded milling cutter. As illustrated in the figure, the cutter has overall all length of 136.55 mm (5–3/8″) by 25.4 mm (1″) diameter. Furthermore, the two triangle cutting inserts (TPG321) are mounted with 90° setting angle (see Fig. 2) this enable to mill straight right angle cutting edge including facing operation.

3. Finite-element model development and assigned boundary conditions

Finite-element (FE) mesh considered in the current study is developed using GID pre-processing program (GID, 2001) after importing the solid model developed by CATIA software (CATIA). The finite-element (FE) computational was carried out using Tochnog FE program (Tochnog, 2001). Finally, post-processing the FE results was carried using GID program (GID, 2001).

The GID program is widely used for generating data files and results visualization in a number of linear and non-linear problems in thermal and structure engineering mechanics, using finite-element method. Tochnog (Tochnog, 2001) is explicit-implicit FE program that can be used in the analysis of structure, thermal, elastic or elastic-plastic engineering problems. Tochnog FE program and GID program are both run under Linux operating system.

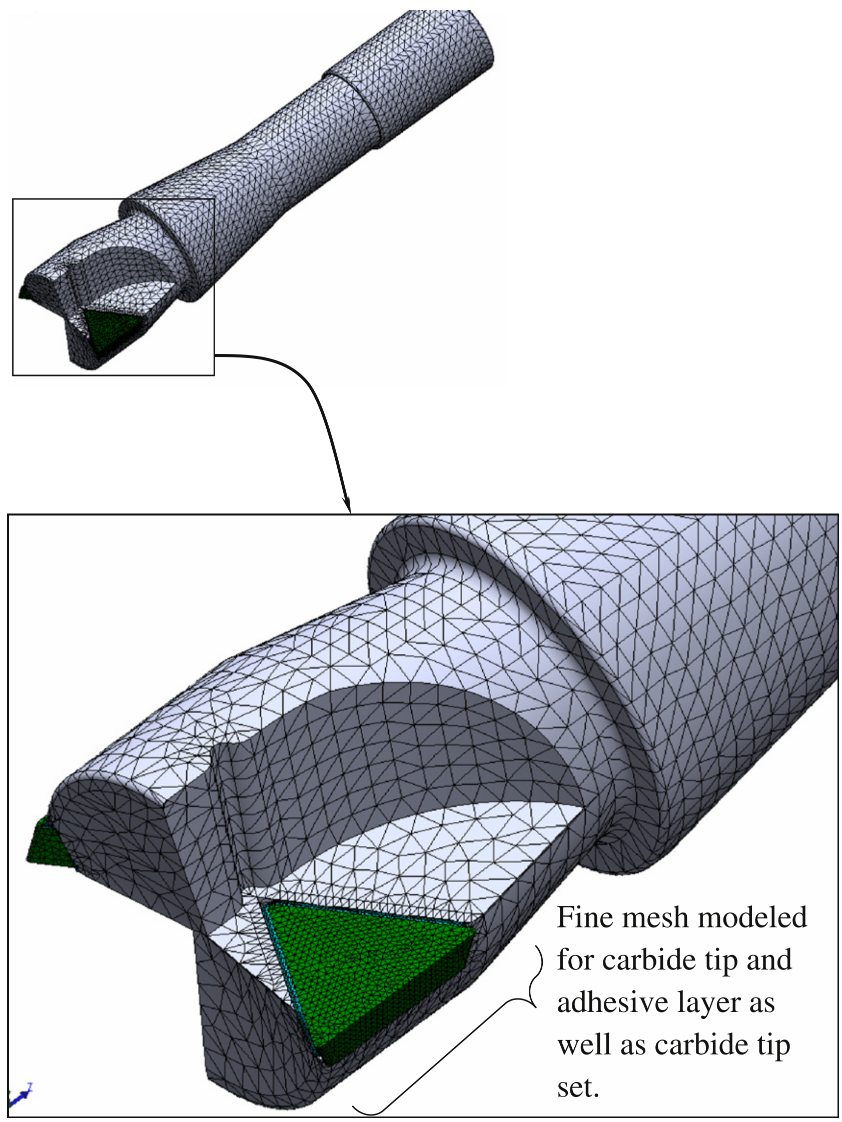

Figure 4 Finite-element mesh generation for the FE model of the bonded carbide tip face milling cutter.

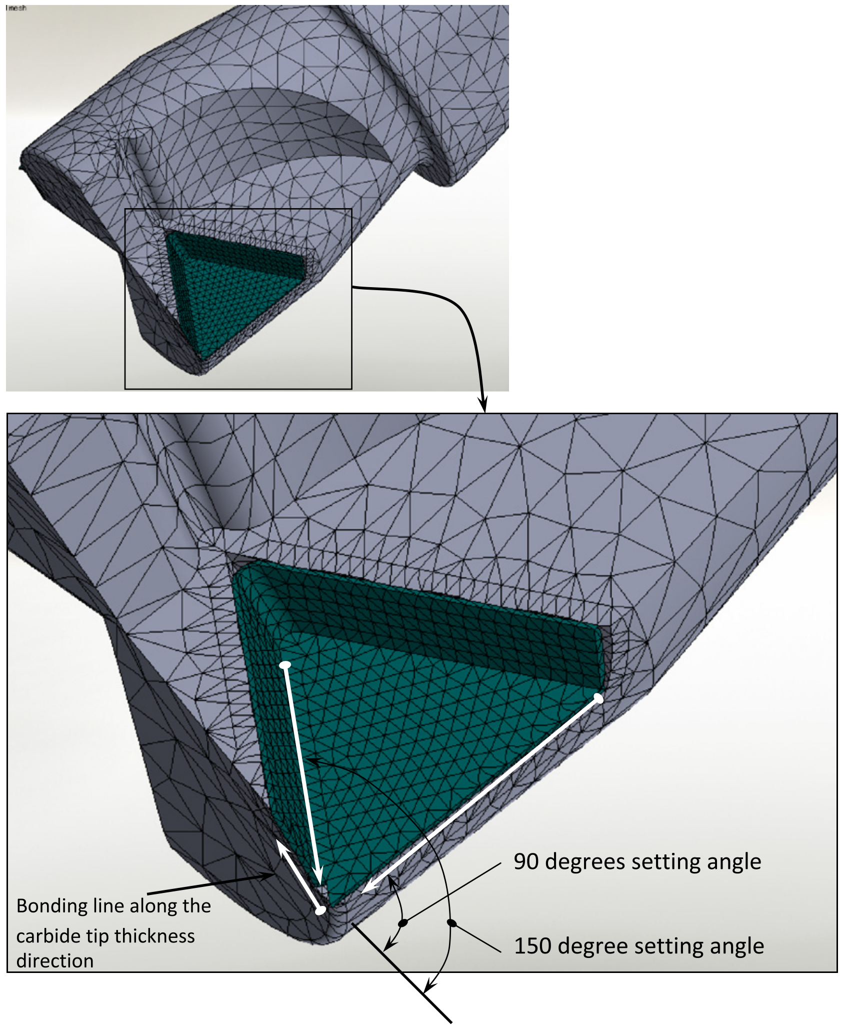

Figure 5 FE results monitored along adhesive mid-layer and through the two bonded lines having carbide edge setting angles of 90 and 150 degrees, and along bonding line through carbide thickness direction.

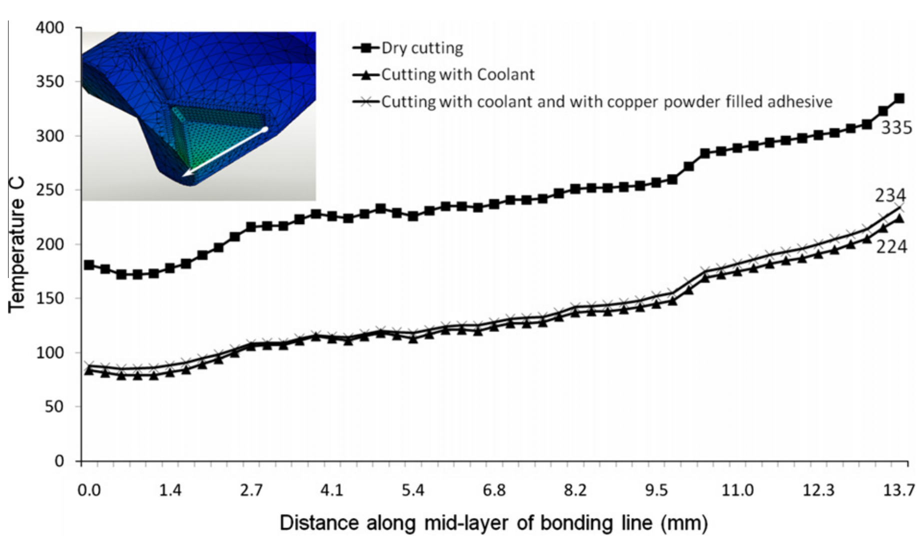

Figure 6 Temperature distribution along the bonding line have 90 degrees carbide tip setting angle (for dry cutting, cutting with coolant and cutting with coolant and copper powder fill adhesive).

In the beginning, solid model is imported from CATIA and then a data file of the FE model is generated by the GID program and next completed using a text editor. Followed, Tochnog FE module is called and executed using the generated data file. Finally visualization of the FE results performed using the GID program through the output files obtained by the Tochnog FE program.

The following assumptions and boundary conditions were considered throughout the developed FE model:

- The problem is three-dimensions FE model.
- The adhesive layer is isotropic, i.e. stresses on the micro-scale, such as those caused by flaws is the adhesive, were neglected (in case of incorporation of adhesive layer) (Darwish and Davies, 1989b).
- The far end of the tool shank is assumed to be at room temperature.
- Elastic–plastic FE analysis considered in current study.

During the data file development, GID program demand material properties for the composite bonded face milling cutter constituents. Table 1, shows the material constituents and properties of the bonded carbide tip face milling cutter assigned to FE model. This cover tool holder and shank, cutting inserts, plain adhesive and a copper powder fill adhesive (30%) (Davies and Darwish, 1991).

The tool-chip temperature was taken to be 313 °C based on actual measurements by the author (Darwish and Alsamha, 2004) when face milling mild steel block of ($80 \times 40 \times 25$ mm) on vertical milling machine. Where temperature measurement is conducted using infra-red camera instruments (Omega mod-

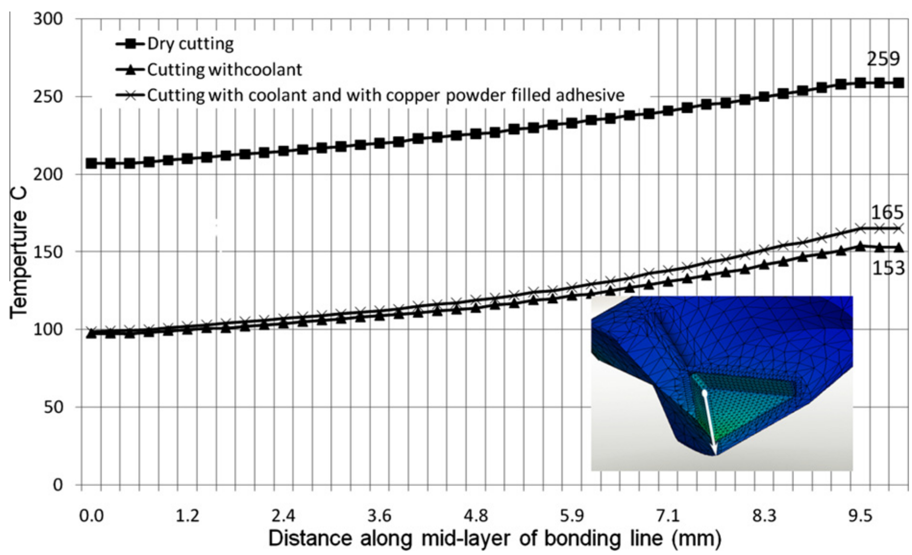

Figure 7 Temperature distribution along the bonding line have 150 degrees carbide tip setting angle for dry cutting, cutting with coolant and cutting with coolant and with copper powder fill adhesive.

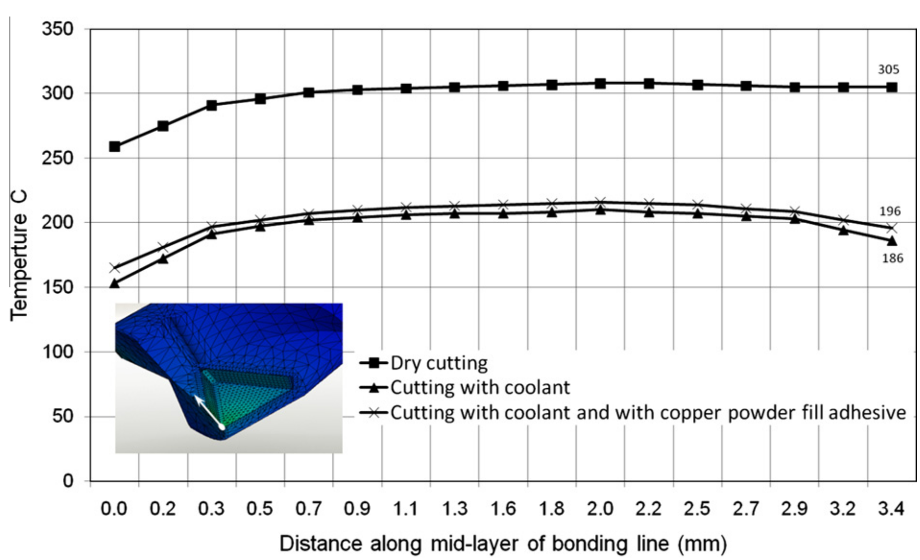

Figure 8 Temperature distribution along the bonding line through insert thickness direction (for dry cutting, cutting with coolant using plain and copper powder filled adhesives).

el) mounted on milling bed. The cutting conditions associated with the measured temperature were as follows: a cutting speed of 1.32 m/s, feed rate of 1.66 mm/s and depth of cut 2 mm. Also, cutting forces was reported during the experiment work and it was found 1200 N was the cutting force. Fig. 2 shows the block diagram of the utilized experimental set-up. For more accurate FE results, it is decided to consider actual temperature of 500 °C in FE model development.

Because there is a significant dependence of the physical properties of water (taken as a coolant in this work) on temperature, the bonded milling cutter was considered to be three different surfaces and the heat transfer coefficients was calculated separately (force convection model) for each surface as a function of its mean temperature (Davies and Darwish, 1991). For example, a solid temperature of 500 °C was assigned on the insert tip of area 1.66 mm (feed) by 2 mm (depth), see Fig. 3. Fig. 3 shows also the assigned thermal and constrain boundary conditions on the FE model of the bonded insert face milling cutter.

A tetrahedral element type is used in the FE mesh generation where 144355 nodes and 100283 elements were used. Fig. 4 shows the developed FE mesh for the face milling cutter model. As illustrated in the figure, fine elements were assigned in the adhesive layers and in the carbide tip set.

4. Finite-element results and discussion

4.1. Finite-element results for the thermal FE model

It was decided to monitor the FE results along the three edges of the carbide tip located toward the cutting insert nose, fur-

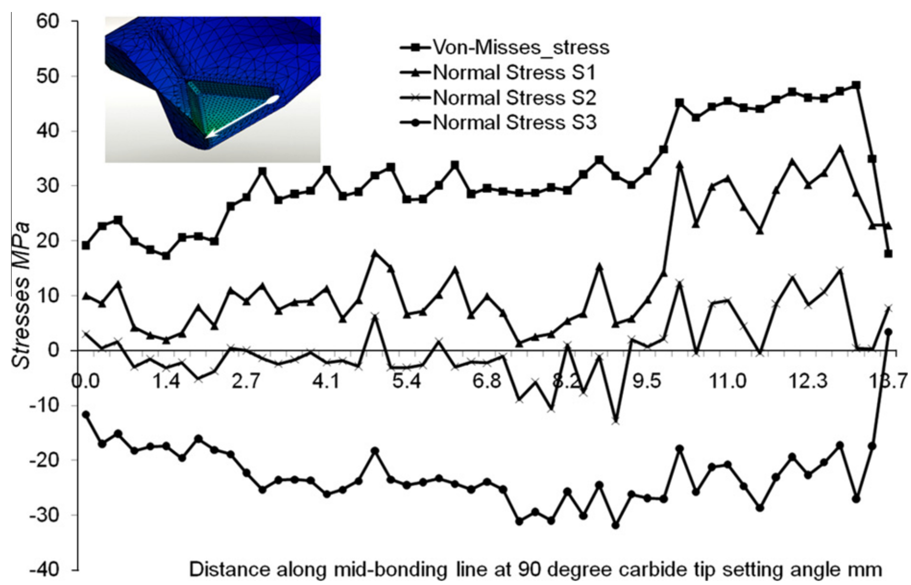

Figure 9 Von-Misses and normal stress distributions along mil-bonding line for 90 degree carbide tip setting angle for dry-cutting operation.

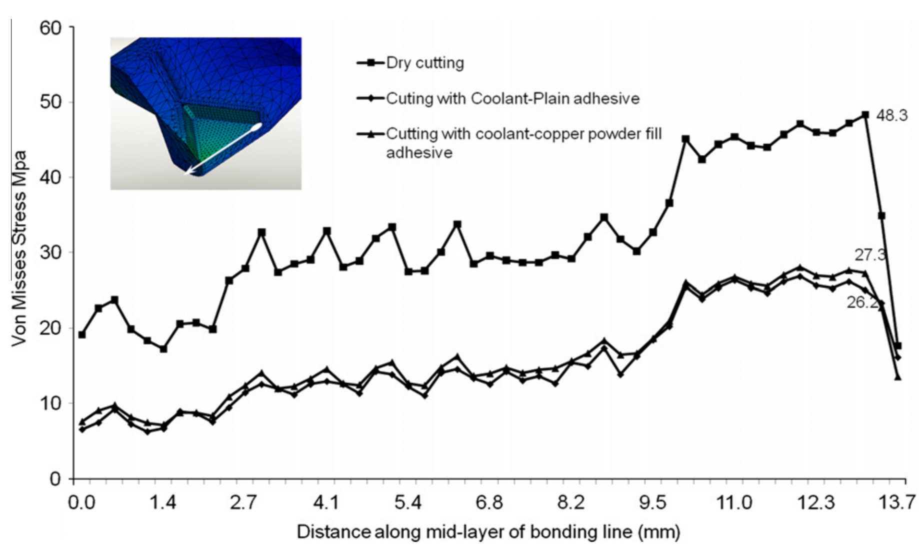

Figure 10 Thermal stress distributions along bonding line have 90 degrees carbide tip setting angle for dry cutting, cutting with coolant and cutting with coolant and copper powder fill adhesive.

thermore, the monitored FE results are considered along the mid-layer of the bonded lines. These three edges are shown in Fig. 5, the first edge has 90 degree setting angle that provides side milling cut, while the second edge has 150 degree setting angle that produce face milling cut. Finally, the third edge along insert thickness direction.

Figs. 6–8 show the predicted temperature distributions along mid-layer of adhesive for 90 degrees setting angle, 150 degree setting angle and through insert thickness direction. Furthermore, these FE results were reported for both cases, dry cut and cutting with coolant operations (plain and copper powered filled adhesives).

From Figs. 6–8, it is clearly observed that cutting with coolant decreases the predicted temperature by 33–40%. Furthermore, little variation in temperate reduction were reported for copper power fill adhesive compare to the plain adhesive.

4.2. Predicted thermal stresses in the carbide tip bonded face cutter FE model

Fig. 9 shows the predicted Von-Miss and normal stress distributions for dry-cut and along the mid-layer of adhesive at the carbide edge having 90-degree setting angle. It is clearly observed that normal stresses are lower when compared with

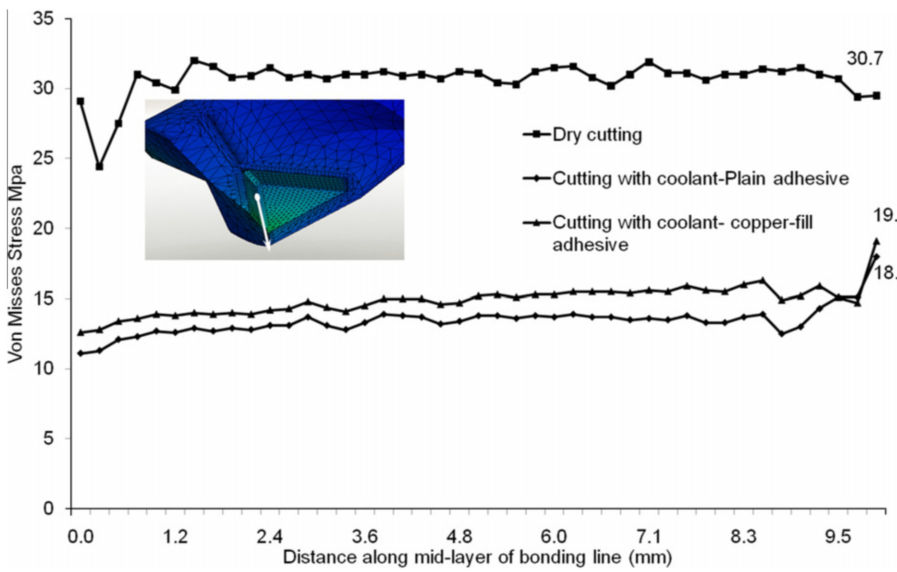

Figure 11 Thermal stress distributions along bonding line have 150 degrees carbide tip setting angle for dry cutting, cutting with coolant and cutting with coolant with copper powder fill adhesive.

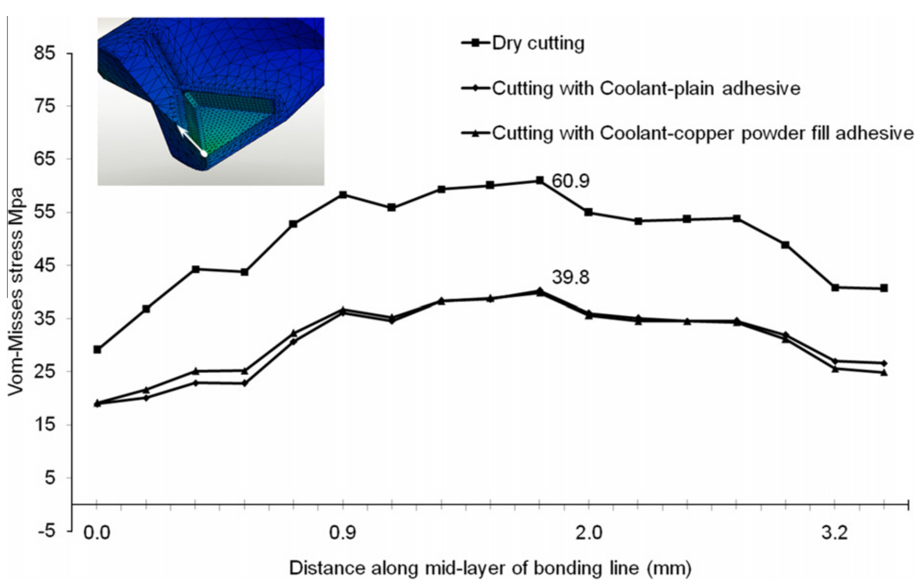

Figure 12 Thermal stress distributions along bonding line for dry cutting, cutting with coolant and cutting with coolant with copper powder fill adhesive and along carbide tip thickness direction.

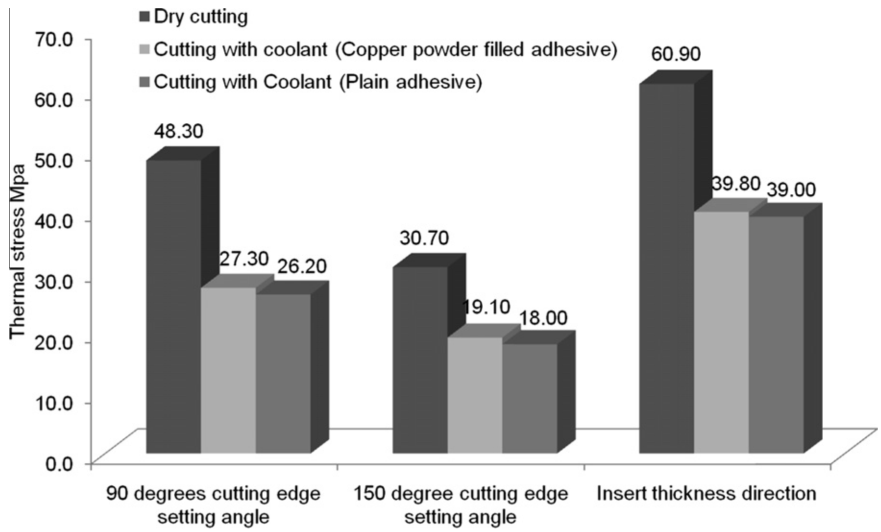

Figure 13 Predicted peak thermal stresses through the 90 and 150 degree setting angle edges, and through the insert thickness direction (for dry cutting, cutting with coolant with and without copper powder filled adhesives).

Von-Misses stress. For this reason, it is decided rely on the Von-Misses stress as thermal stress for our further study.

Figs. 10–12, show the predicted thermal stress distributions along the mid-layer of adhesive of carbide edge having 90, 150 degrees insert setting angles and along insert edge-thickness, respectively. These three figures, are shown for dry cutting and cutting with coolant (plain and copper filled adhesives). From three figures, it is clearly observed the thermal stresses are concentrated near the cutting edges and in the area of tool-chip interface. Fig. 13, shows the plot of peak thermal stresses developed at the mid-layer of adhesive through 90, 150 degree carbide edge setting angles and through the carbide thickness edge direction, see Fig. 5. From Fig. 13, it is observed the peak thermal stress is more higher along insert thickness direction compare to former cases. This can be attributed to the location that it is more closer to the tool-chip interface area. Also, it is observed the thermal stress is tremendously decreases when applying coolant. For example, the peak thermal stress decreases from 60.9 MPA to 39 MPa (35%) when coolant was applied, see Fig. 13.

The effect of adding copper powder as a filler on the adhesive material also shown in Figs. 10–13. From these figures It is can be observed, for both plain adhesive and copper powder filled adhesive, a decrease in thermal stresses is reported compare to dry cutting cooperation. However, a little variation on thermal stress is reported with the case of copper powder filled adhesives. This results also confirmed with the results obtained by Davies and Darwish (1991).

5. Conclusions

- Thermal stresses are concentrated near the chip-tool interface area for the case of bonded tools.
- The thermal stresses developed in bonded carbide tip face milling cutter decrease tremendously with applying cutting coolant.
- The thermal stresses developed in bonded carbide tip face milling cutter are effected by cutting conditions e.g. dry cutting and cutting with coolant.
- Cutting fluid is important factor in dissipating the developed heat during cutting in case of bonding tools.
- Adding copper powder fill in adhesive layer has a lower effect factor in dissipating the developed heat during bonded tool cutting compared to plain adhesive.
- In current case, the predicted thermal stresses in adhesive material are within elastic range. The stress may becomes residual when adding cutting force to the FE model.

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