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The Influence of Chip Breaker Geometry on Tool Stresses in Turning

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In this study, the influence of different chip breaker geometries on cutting forces and tool stresses developed during turning was investigated experimentally. For this purpose, turning tests in accordance with ISO 3685 were carried out on AISI 1050 steel using uncoated and coated cemented carbide cutting tools with different chip breaker geometries. The tests were carried out at different cutting parameters. The cutting forces were measured using a Kistler 9257B type dynamometer. The effect of cutting force variation on tool stresses was analysed using finite element analysis software (ANSYS). The analyses results showed that the coated tools were subjected to higher stresses than the uncoated ones. However, the stresses on the uncoated tools were found to be higher than those on the coated tools at the heavy cutting conditions. In addition, the chip breaker geometry was also found to result in variation in the stresses acting on the tools.

Keywords: metal cutting, chip breaker form, cutting forces, tool stresses, principal stresses, AISI 1050

0 INTRODUCTION

Parts manufactured by casting, forming and various shaping processes often require further processing or finishing operations to import specific characteristics, such as dimensional accuracy and surface finish, before the product is ready for use. These processes are generally classified as material-removal or cutting processes. Cutting processes remove material from the surface of the workpiece by producing chips [1]. Metal cutting is dynamic technology, involving several disciplines of science. It is continually changing in line with strategies and material developments through the manufacturing industry worldwide. On the other hand, it is also changing as a consequence of developments within the cutting tool industry. The relation between “machine tool – cutting tool – workpiece materials” should be well established. In addition, the variables called “cutting parameters (V, a, f)” should be well assessed [2].

Controlling of both the chip breaking and chip curling is the control of the chip form. Since the first use of carbide tools, many techniques have been developed to control the chip formation. The most widespread method is to employ chip breaker and chip curler. In order to determine the optimum cross-section which the cutting tool can withstand and the ideal angles (ideal tool geometry) which ease the cutting operation, many studies have been carried out. Although the cutting edges of the cutting tools used in machining metals and their alloys are quite sharp, they are forced significantly under the stresses developed during machining. Significantly high stress is required in order to break the chip. With the aid of this high stress, the chip breaker easily generates a bending torque [2] to [6].

Karahasan determined the characteristics of the optimum chip breaker form, which leads to acceptable chip geometry by examining the types of chip breakers and technological developments [7]. Mesquita and Barata Marques developed a method which predicts the cutting forces beforehand in their study on the influence of chip breaker geometry on cutting forces. In this developed model, they took into consideration the influences of chipping and penetration for the parallel groove type chip breaker. This technique is based on the formation of chip breaker geometry and calculation of effective side relief angle. Chipping effect, dynamic area effect and cutting forces were determined by experimental studies.

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The model which they proposed was applied to the machining of martensitic stainless steels by coated carbide tools. Finally, they compared the experimentally measured and theoretically predicted values [3]. Fang compared the chip breaking performance of an asymmetric grove type (AGT) to that of symmetric type (SGT). In this study, two mathematical models were developed using multiple linear regression model to predict chip breaking ability of the new type chip breakers. The experimental results showed that replacement of AGT by SGT is practical when the depth of cut, feed rate and chip breaking performances were taken into consideration. The theoretical predictions were obtained depending on the experimental results at the given cutting conditions [8].

Kim and Kweun modelled the formation of chip flow using various cutting tools with different geometries. This study was centred on the chip breaker design and machining of medium carbon steels using cutting tool with chip breaker [9]. Kramar and Kopač investigated the application of high pressure cooling (HPC) assistance in the rough turning of two different hard-to-machine materials, namely hard-chromed and surface hardened C45E and Inconel 718 with coated carbide tools. The capabilities of different hard turning procedures were compared by means of chip breakability, cooling efficiency, temperatures in cutting zone, tool wear and cutting forces [10]. Mahashar and Murugan performed an experimental work which deals with the influence of two design parameters, width of chip breaker and angle of chip breaker of a clamped on chip breaker on effective chip breaking [11]. Karabulut and Gullu designed a chip breaker and experimental cutting of Inconel 718 was conducted with the designed chip breaker. Their experimental results showed that the designed chip breaker can break long chips at any cutting condition and acceptable surface finish can be achieved [12]. Arrazola et al. compared two AISI 4140 steels with different machinability ratings and three types of tools: (i) uncoated with 0° rake angle, (ii) coated with -6° rake angle and (iii) coated with chip breaker. A control volume approach was used to estimate the energy partition from thermal images and energy outflow was compared to direct measurement of the cutting power. This provided a new physical tool for examining machinability, tool wear and subsurface damage [13]. Kim et al. evaluated the performance of commercial chip breakers using a neural network that was trained through a back propagation algorithm. Important form elements (depth of cut, land, breadth, and radius) that directly influenced the chip formation were chosen among commercial chip breakers, and were used as input values of the neural network. As a result, they developed the performance evaluation method and applied it to commercial tools, which resulted in excellent performance [14].

Formation of chip breaker grooves on the rake faces of indexable insert type cutting tools is one of the effective methods for breaking chip. The influence of chip breaker geometry on the chip breaking performance was tackled by many researchers in the past [15] to [21]. This study concentrates on the influence of different chip breaker geometries on cutting forces and tool stresses developed during turning.

1 EXPERIMENTAL PROCEDURE

The cutting tools used were cemented carbide and were suitable for the experimental conditions defined in ISO 3685. They were in the form of SNMG120408R while the tool holder was in the form of PSBNR252512. This tool holder provided a 75° side cutting edge angle. The cutting tools were produced by Mitsubishi Carbide with MA, SA, MS, GH and standard (STD) types chip breaker forms. All these tools were coated. In addition, uncoated MS and STD types were also used. The tools had UC6010 and UT120T Mitsubishi Carbide designations equivalent to ISO P15 and P30. Fig. 1 gives the pictures of the cutting tools. The uncoated cutting tools in the experimental studies, was shown by letter “U”.

The tests were carried out on JOHNFORD T35 CNC turning centre. The workpiece material was AISI 1050 (DIN 1.1210) carbon steel widely used in manufacturing industry. The cutting forces developed during turning were measured using a Kistler 9257B type dynamometer. The dynamometer was connected to a computer and a total of 210 turning tests (30 tests for each cutting tool) were conducted without a coolant. The cutting parameters used in the experiments are shown in Table 1.

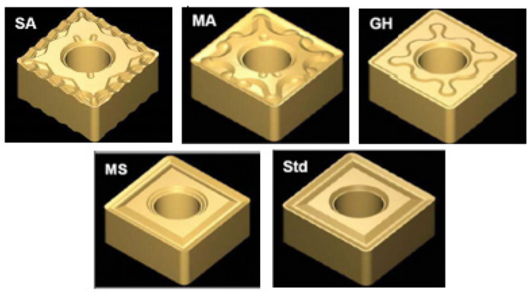


Fig.1. *The cutting tools used for the tests and their chip breaker forms*

Table 1. *Test parameters*

Cutting speed *V* [m/min]	150, 200, 250, 300, 350
Feed rate, *f* [mm/rev]	0.15, 0.25, 0.35
Depth of cut, *a* [mm]	1.6, 2.5

The tool holder and cemented carbide tools were modelled using CATIA V5R15 software for analysis purposes and recorded as CATIA model. The models were then opened in ANSYS with model extension. The material models for the insert and tool holder used in the analyses are shown in Table 2.

Table 2. *Material properties of the cutting tools*

Cutting tools	Modulus of elasticity *E* [GPa]	Poisson's ratio υ	Ref.
P15	530	0.23	[22]
P30	558.6	0.22	[23]
Tool holder	210.7	0.28	[24]

SOLID92, three-dimensional (3-D) 10-node tetrahedral structural solid with a quadratic displacement behaviour well suited for modelling irregular meshes (such as those produced from various CAD/CAM systems) was used as the element type for the cutting tools in the FEM model. The mesh density was selected very densely (smartsize = 3) in the tool-chip contact areas. However, it was selected sparsely (smartsize = 5) in other parts of the cutting tool. The contact pairs were also applied between the cutting tool and the seating surface of the tool holder in parallel to the literature [25] (3-D eight-node surface-to-surface contact element CONTA174 for the insert and 3-D target segment TARGE170 for the tool holder). The behaviour of the contact surface between the cutting tool base and cutting tool base plate was bonded in all directions. When forming the contact pair between two edges of the cutting tool in contact with the tool holder, the behaviour of the contact surfaces was applied as "standard". The friction coefficient between the contact surfaces was selected as "0.1" and the starting penetration was selected as "0" since there was no penetration between the contact surfaces. The target was selected as the cutting tool while the contact was selected as the tool holder. In the analysis, "P" method was used to fix the cutting tool to the tool holder in accordance with ISO 1832 (the tool holder was in PSBNR form). In this method, a pin is used to fix the cutting tool. In "P" method, the squeezing force was found to be around 1040 N from the previous studies [25] to [27]. This force was applied as surface pressure to the squeezing area and then transferred to the elements.

In parallel to the literature [26], the cutting forces were applied to the nodes in the tool–chip contact areas as follows: the primary cutting force was applied as triangular surface load throughout the tool–chip contact length. The feed and the passive forces were applied to the nodes in the contact areas in the feed direction of the cutting tool and the workpiece as the nodal force. In order to reduce the calculation time in the analysis, some assumptions were performed as follows: the weight of the tool holder and the insert were neglected. The inserts used in the analysis were new and unused (sharp). The vibrations and temperatures occurred in the metal cutting were also neglected in the analysis. The static analysis solution method was used. As a boundary condition for constraint, the degree of freedom of the nodes (nodal displacements) in the area to mount the tool holder to the dynamometer, on the tool holder mounting length, was selected as zero in all directions (nodal displacements = 0).

Maximum principal stress (S_1) and minimum principal stress (S_3) were used to investigate the stresses on the cutting tool according to the cutting parameter variations.

2 EXPERIMENTAL RESULTS AND DISCUSSIONS

When the graphs in Fig. 2 are examined, it is seen that main cutting force (F_C) increases with increasing depth of cut and feed rate and decreases with increasing cutting speed for all the chip breaker types.

This situation is in agreement with the literature [22] and [28]. Decreasing cutting forces can be explained by increasing energy spent with increasing cutting speed and almost all of this energy is transformed into temperature. This temperature, in turn, eases the chip formation during machining. According to Kienzle's "$F_C = A \times k_s$" equation, cutting forces increase depending on increasing chip cross-section (A) which is the product of feed rate and depth of cut [2]. When both uncoated and coated tools having the same type of chip breaker are compared, no significant difference in the cutting forces was observed at low cutting speeds. However, when cutting speed was increased to 300 and 350 m/min, the uncoated tool with the STD type chip breaker resulted in higher F_C forces than the coated one with the same type of chip breaker (Fig. 2). A similar finding was also observed for MS type breaker. The main cutting forces (F_C) obtained with the uncoated MS chip breaker type were higher than those obtained with the coated MS chip breaker type especially at 350 m/min. This situation can be attributed to faster wear of

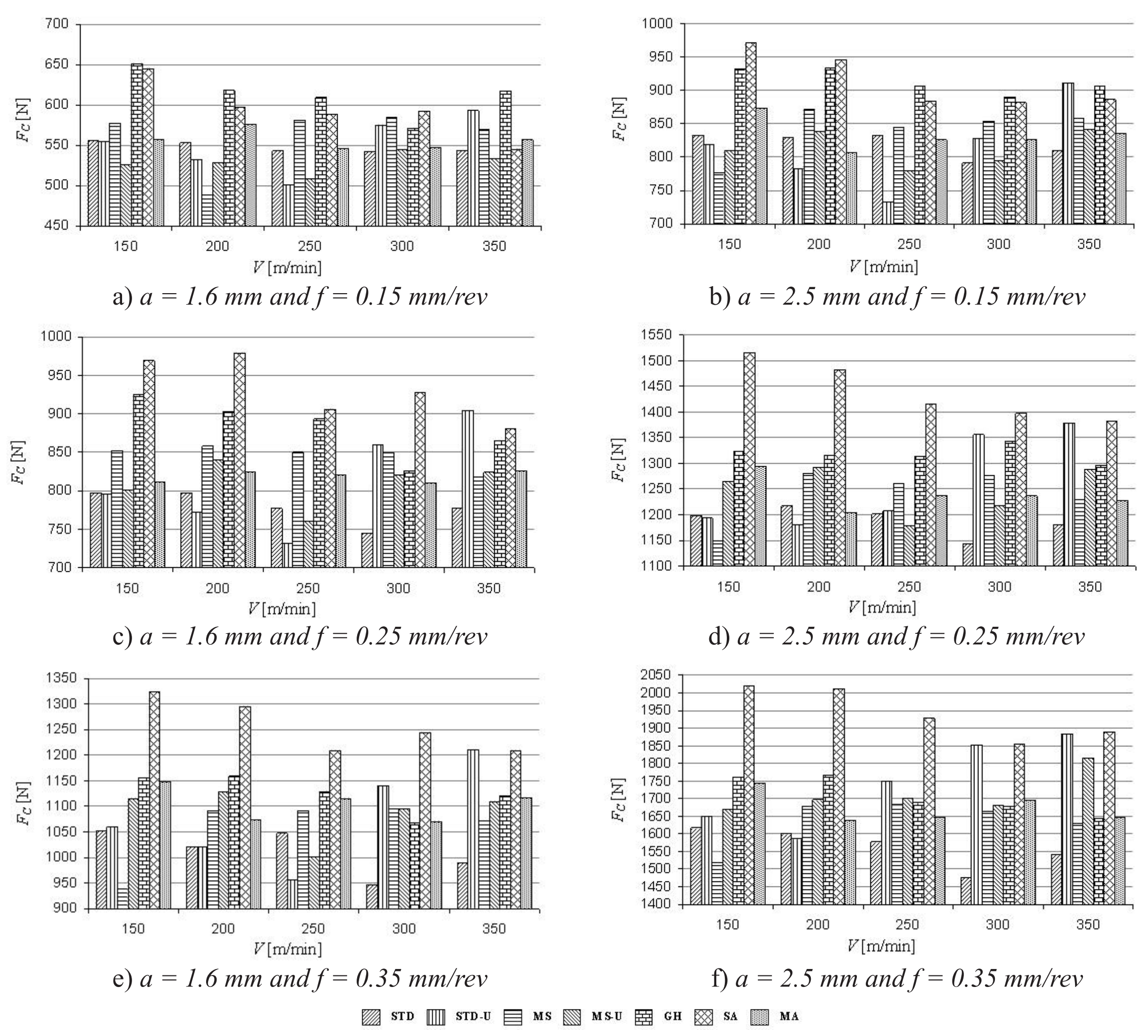
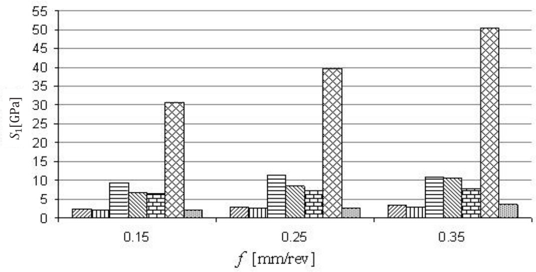
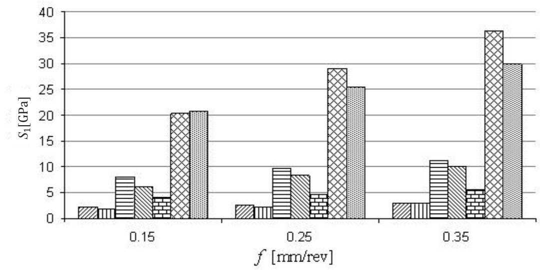


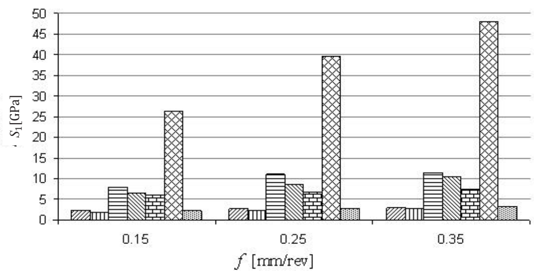
Fig. 2. *Variation of main cutting forces (F_C) depending on chip breaker form*



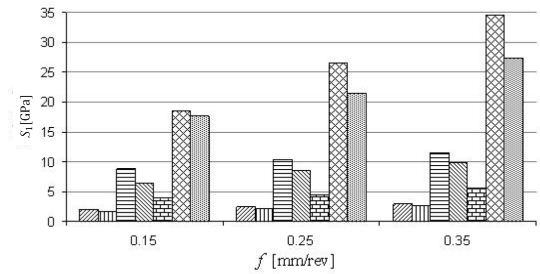
a) *a = 1.6 mm and V = 150 m/min*



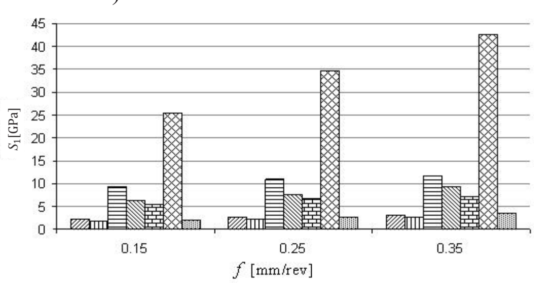
b) *a = 2.5 mm and V = 150 m/min*



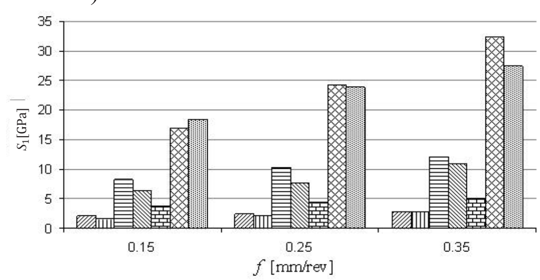
c) *a = 1.6 mm and V = 200 m/min*



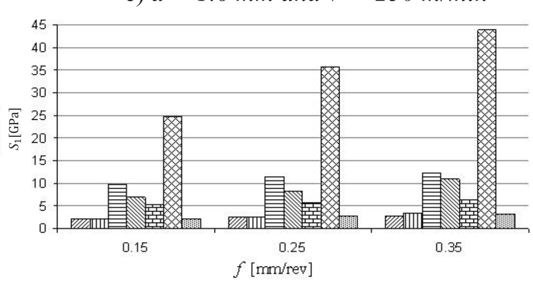
d) *a = 2.5 mm and V = 200 m/min*



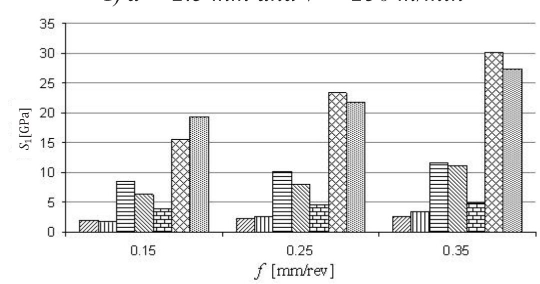
e) *a = 1.6 mm and V = 250 m/min*



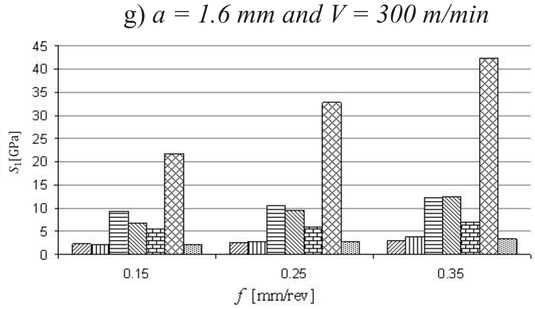
f) *a = 2.5 mm and V = 250 m/min*



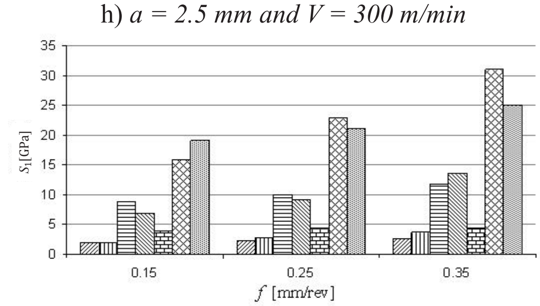
g) *a = 1.6 mm and V = 300 m/min*



h) *a = 2.5 mm and V = 300 m/min*



i) *a = 1.6 mm and V = 350 m/min*



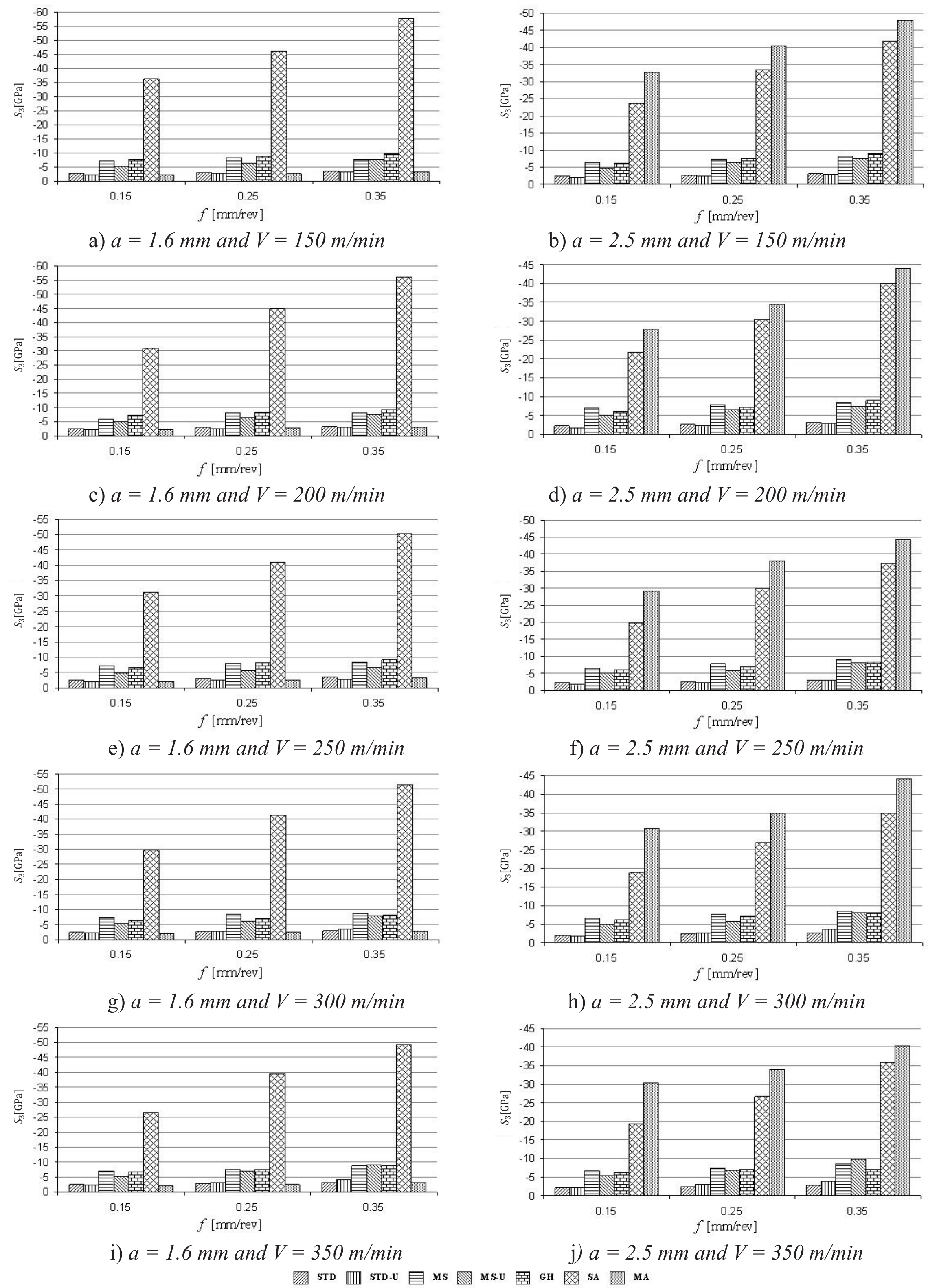
j) *a = 2.5 mm and V = 350 m/min*

Fig. 3. *Variation of maximum principal stress (S_1) depending on chip breaker form*

the uncoated tools than the coated ones at high cutting speeds. For all the chip breaker types, increasing cutting speed generally decreases the cutting forces. However, a slight increase is observed when the cutting speed is raised to 350 m/min. This increase can be explained by the higher cutting speed which is above the range suggested by the manufacturer for this cutting tool. Generally, the highest main cutting forces were obtained for the tools with the most complex chip breaker type while the lowest main cutting forces were obtained for the tools having the least complex chip breaker type.

It is seen from the graphs in Fig. 3 that the principal stresses obtained are in the following order from the highest to the lowest: coated SA/MS type chip breaker, uncoated MS type chip breaker, coated GH/STD type chip breaker, uncoated STD type chip breaker and coated MA type chip breaker at 1.6 mm depth of cut. On the other hand, at 2.5 mm depth of cut, the principle stresses (S_1) from the highest to the lowest are obtained in the following order: coated SA – MA – MS, uncoated MS, coated GH – STD and uncoated STD type chip breakers. At 1.6 and 2.5 mm depth of cut values, the reason for this order can be explained depending on the cutting force (F_C) values obtained by the chip breaker forms. As the forces increase, S_1 stresses are considered to increase. The highest stresses were observed for the most complex chip breaker forms while the lowest stresses were observed for the least complex chip breaker forms. When the maximum principal stress (S_1) graphs are examined, S_1 stress is seen to be very high when the depth of cut is increased from 1.6 mm to 2.5 mm for MA type chip breaker at all the feed rates and cutting speeds. This can be explained by the depth of cut and cutting speed values which are outside ranges suggested by the cutting tool manufacturer for MA type chip breaker. Generally, increasing feed rate increases the maximum principal stresses S_1 for all the cutting tools while increasing cutting speed and depth of cut decreases S_1 stresses. It is considered that increasing feed rate and depth of cut increased the tool-chip contact area and chip cross-section and increasing cutting speed decreased the cutting forces and these, in turn, reduced S_1 stresses. When the maximum principal stress S_1 graphs are examined, it is seen that the coated (MS, STD) chip breaker forms result in higher stresses than the uncoated (MS, STD) chip breaker forms. However, the uncoated (MS, STD) chip breaker forms result in lower stresses than the coated (MS, STD) chip breaker forms at 350 m/min cutting speed and 0.25 to 0.35 mm/rev feed rates. The reason for this can be explained depending on the cutting force (F_C) values obtained with these chip breaker forms at these cutting conditions. As the uncoated chip breaker forms result in higher forces than the coated chip breaker forms, increasing forces is considered to increase S_1 stresses.

When all the graphs in Fig. 4 are examined, it is seen that S_3 stresses increase with increasing feed rate for all the chip breaker forms and decrease with increasing cutting speed and depth of cut. It is considered that increasing feed rate and depth of cut increased the tool-chip contact area and chip cross-section and increasing cutting speed decreased the cutting forces and these, in turn, reduced S_3 stresses. When the least principal stress (S_3) graphs are examined, the highest stresses are seen for the coated SA type chip breaker while the minimum principal stresses (S_3) are seen for the uncoated STD type chip breaker generally at 1.6 mm depth of cut. These sorts of stress results can be explained by the number of node at the tool-chip area for the chip breaker forms. According to this, increasing the node number increases the stresses while decreasing the node number decreases the stresses. At 1.6 mm depth of cut, the highest S_3 stresses are caused by the coated SA type chip breaker while the coated MA type breaker results in the highest stresses when the depth of cut is increased to 2.5 mm. It is considered that the stresses increased due to the chip breaker geometry for this cutting tool form and that such high stresses were due to the used depth of cut which was outside the range suggested for MA type chip breaker by the manufacturer. When the coated (MS, STD) and uncoated (MS, STD) chip breaker forms are compared, it is seen that the coated chip breaker forms generally result in higher S_3 stresses than the uncoated ones. On the other hand, the uncoated chip breaker forms result in higher stresses than the coated ones only at 350 m/min cutting speed and 0.25 to 0.35 mm/rev feed rates. The reason for this can be explained depending on the cutting force (F_C)



a) *a = 1.6 mm and V = 150 m/min* b) *a = 2.5 mm and V = 150 m/min*

c) *a = 1.6 mm and V = 200 m/min* d) *a = 2.5 mm and V = 200 m/min*

e) *a = 1.6 mm and V = 250 m/min* f) *a = 2.5 mm and V = 250 m/min*

g) *a = 1.6 mm and V = 300 m/min* h) *a = 2.5 mm and V = 300 m/min*

i) *a = 1.6 mm and V = 350 m/min* j) *a = 2.5 mm and V = 350 m/min*

Fig. 4. *Variation of minimum principal stress (S_3) depending on chip breaker form*

values obtained with these chip breaker forms and it is considered that increasing forces increase the stresses.

3 CONCLUSIONS

Increasing cutting speed was generally found to decrease the main cutting force (F_C) for all the chip breaker forms up to 300 m/min cutting speed beyond which it increased. At all the cutting conditions, increases in feed rate and depth of cut increased the main cutting force (F_C) for all the chip breaker forms. The highest F_C cutting forces were generally obtained for SA type chip breaker and the complex chip breaker geometry was determined to result in these higher cutting forces. Generally, increasing feed rate was found to result in increases in the maximum principal stresses (S_1) and minimum principal stresses (S_3) while S_1, S_3 stresses decreased depending on the cutting speed and depth of cut for all the cutting tool forms. The analysis results showed that the highest values of maximum principal stresses (S_1) and minimum principal stresses (S_3) were generally obtained for the most complex coated SA and MA type chip breaker forms. On the other hand, the lowest values for these stresses were obtained for the uncoated STD type chip breaker form. When (S_1, S_3) graphs are examined, it is seen that the stresses produced by MA type chip breaker were raised significantly at all the feed rates and cutting speeds when the depth of cut was increased to 2.5 mm from 1.6 mm. This can be explained by the depth of cut and cutting speed values which are outside the ranges suggested by the cutting tool manufacturer for MA type chip breaker.

4 ACKNOWLEDGEMENTS

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