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THE EFFECT OF CUTTING FORCES ON CUTTING TOOL DETERIORATION IN FACE MILLING OPERATIONS

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Abstract

Cutting tools are subjected to extremely unfavourable conditions during machining operations. High cutting temperatures, compressive and shear stresses, chemical interactions, mechanical loads are some adverse conditions that wear these tools. In addition to these factors, cutting force is an important phenomenon for the tool deterioration. In this study, the effects of cutting force on tool wear were evaluated in face milling operations according to cutting parameters. The experimental studies were carried out at the determined cutting parameters (the cutting speeds, the feed rates, the cutting depths and dry/wet coolant conditions). To measure the cutting forces a Kistler 9257B dynamometer and to inspect the tool deteriorations a scanning electron microscope (SEM) were used. The mostly seen deterioration on tool was found to be the mechanical fractures which increased with increasing cutting speed.

Key Words: Machining, face milling, cutting force, tool deterioration, cracks.

1. Introduction

As a basic machining process, milling is one of the most widely used metal removal processes in industry. Milled surfaces are largely used to mate with other parts in die, aerospace, automotive, and machinery design as well as in manufacturing industries [1].

The wear of tools is "the loss or dislocation of mass of a material caused by some kind of tribological phenomenon" [2]. In practice, different types of deterioration occur during the machining. Wear can be in a form of flank wear, face wear as crate or stair forms, chipping (breakage), cracks (as perpendicular to the edge, parallel to the edge and irregular directions), flaking, plastic deformation and catastrophic failure [3]. In cemented carbide cutting tools these forms of wear can flourish. Liu Z.Q. et. al. have studied the wear performance of PCBN, ceramic, coated carbide and fine grained carbide tools in high-speed face milling, when cast iron, 45# tempered carbon steel and 45# hardened carbon steel are machining. The tool wear pattern were examined thorough a toolmaker's microscope. They have reported different types of tool wears occur during the cutting processes depending on the materials and corresponding cutting tools. According to the their observation, the tool wear factors are high cutting temperature, rapid and high thermal shock as well as mechanical impact in high-speed milling operations [4].

Yan W. et. al. investigated to determine tool wear indices from the milling force signals referred as "An investigation of indices based on milling force for tool wear in milling". They read two orthogonal milling force signals F_x and F_y measured by a three-component (Kistler 9265A2) dynamometer (with a Kistler 5006 charge amplifier) and developed a mathematical model to predict tool wear with the help of cutting forces

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[5]. Diniz, Filho and Calderiani studied the influence of cutting conditions; cutting speed, feed velocity and feed per tooth, on tool life and surface finish of the workpiece in the face milling of flat surfaces [6]. The main conclusions of their work are that a) cutting speed has a strong influence on tool life, regardless of whether feed rate or feed per tooth varies and b) an increase in surface roughness of the workpiece is not closely related to an increase in wear of the primary cutting edge.

In this study, the effects of cutting forces obtained at various cutting conditions, on tool deterioration has been investigated experimentally. We specially focused on mechanical fatigue cracks that have an important effect on tool deterioration seen on the cutting edge of the tool.

2. Materials and methods

In this study, the effect of cutting forces on tool deterioration were investigated by varying the several cutting parameters such as the cutting speed, cut depth, feed rate and dry/wet conditions. Johnford VMC 850 CNC Machining Center was used in these experiments. Workpiece dimension, tool diameter and geometry selection were made by considering ISO 8688 tool life testing in milling Part 1 standards [2]. Cutting parameters and the properties of tools and workpieces used in these experiments are given in Table 1. Optimum milling parameters were selected according to catalogue values for tool supplier’s document.

Table 1. Experimental Conditions

Workpiece	SAE 1050 (AISI 1050)							
Chemical Composition [%]	C	Si	Mn	Cr	P	S	Mo	N
	0.49	0.19	0.65	0.03	0.01	0.005	0.01	0.08
Dimensions [mm]	75 x 375 x 20							
Tool Holder	AFR 75 0125 12 R06 4 0, Dia 125 mm, 6 teeth.							
Insert	Böhler SPKN 1203 SBF.							
Cutting Parameters								
Cut Depth [mm]	1.25 – 2							
Feed Rate [mm/teeth]	0.05 – 0.075 – 0.1							
Cutting Speed [m/min]	100 – 110 – 120 –130							
Coolant	Dry – Wet							
Coolant	Rocol Ultracut 390H, 20,6 ºC, Ph 10.10							

For the force measurements Kistler 9257B 3-Component Dynamometer and Kistler 5070A Amplifier were used as shown in Figure 1. In this setup, a fixture is designed to support the workpieces to dynamometer using M8 at 8 point. The directions of cutting forces are shown in Figure 2. Based on these configuration, the resultant force and normal force will be given as F= $\sqrt{F_n^2 + F_x^2}$ and $F_n = \sqrt{F_y^2 + F_z^2}$, respectively

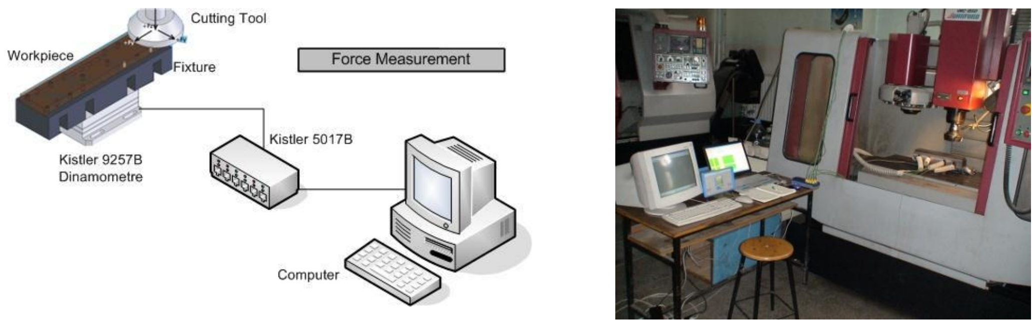

Figure1**.** Experimental setup used for force measurements

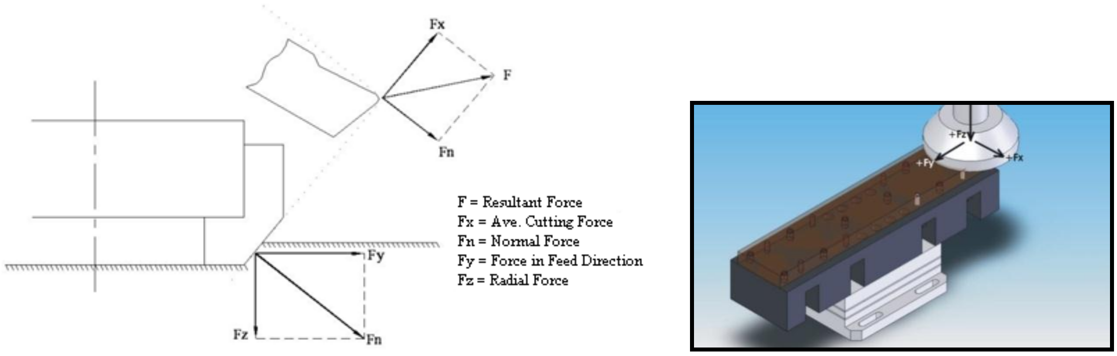

Figure 2**.** Schematic representation of the force directions

The experiments were carried out for 48 samples in total that correspond to different cutting parameters. It has been reported that the relative positions of tool and workpiece have an important effect on the output of the face milling operations [7]. Since the tool wear is more crucial than the tool chipping and breakage for tool life the relative positions of tools and workpieces are applied symmetrically in our experiment.

SEM (Scanning Electron Microscope) images were taken to examine the tool inserts used in experiments with Carl Zeiss – Evo40. The specifications of the SEM are given in Table 2.

Table 2. Technical specifications of the SEM used in this work.

CARL ZEISS EVO 40		
Resolution	3.0 nm 30 kV (SE) 4.5 nm 30 kV (BSD)	
Voltage	0.2 - 30 kV	
Magnification	7 - 1,000,000 x	
Display	3072 x 2304 piksel .TIFF, .JPEG	

3. Experimental Results

The machining has been applied to as three pass along the 375 mm long samples for all cutting conditions given in Table 1. The total chip removal volume was realized as 35156 mm^3 for 1.25 mm cut depth and 56250 mm^3 for 2 mm cut depth. The tool wears were then inspected. Due to the limitation of the machine tool such as power, the main deterioration type was found to be mechanical cracks in the tests. Since other types of deterioration occurred during experiments are not as significant as mechanical cracks, we have excluded their analysis in this work.

Cracks are fracture of cutting tool material which does not immediately cause loss of tool material. Cracks can be categorized as follow according to ISO 8688 [2];

a) Thermal Cracks; cracks which appear on both the tool face and tool flank are oriented approximately perpendicular to the major cutting edge as shown schematically in Fig.3.
b) Mechanical (Parallel) Cracks; cracks which appear on the tool face on the tool flank are oriented approximately parallel to the major cutting edge (see Fig. 3).
c) Irregular Cracks; cracks which sometimes appear on the tool face and on the tool flank are irregularly oriented (see Fig. 3).

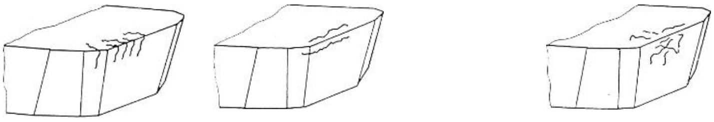

Figure 3. Schematically representations of the crack types [2].

The cutting parameters used in experiments for which the samples participate some mechanical cracks along with the measured resultant forces are given in Table 3.

Table 3. The parameters of the tests in which the mechanical cracks are observed.

Fig.No	Test Order No	Cut Depth (mm)	Coolant Condition	Feed Rate fz (mm/teeth)	Feed Rate F (mm/min)	Cutting Speed (m/min)	Num. of Revolution n (rev/min)	Resultant Force F (N)
Fig.4	2	1.25	Dry	0.075	115	100	255	996
Fig.5	3	1.25	Dry	0.100	153	100	255	1287
Fig.6	26	1.25	Wet	0.075	115	100	255	983
Fig.7	16	2.00	Dry	0.050	84	110	280	1537
Fig.8	17	2.00	Dry	0.075	126	110	280	2000
Fig.9	29	1.25	Wet	0.075	126	110	280	1107
Fig.10	30	1.25	Wet	0.100	168	110	280	1244
Fig.11	42	2.00	Wet	0.100	168	110	280	1834
Fig.12	7	1.25	Dry	0.050	92	120	306	808
Fig.13	9	1.25	Dry	0.100	183	120	306	1130
Fig.14	33	1.25	Wet	0.100	183	120	306	1154
Fig.15	45	2.00	Wet	0.100	183	120	306	1967

The formation of mechanical cracks is determined from the SEM images. Figures 4-6 show the SEM images for the experiments numbered as test order of 2, 3 and 26 (Table 3). In these particular set of experiments, the cutting speeds of 100 m/min and cut depth of 1.25 mm were fixed. The feed rate and coolant conditions were chosen as free parameters. Only small mechanical cracks which are nearly independent of the feed rate and coolant condition are observed in the SEM images.

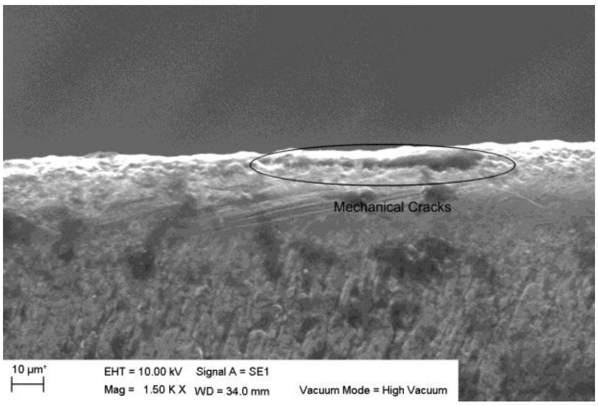

Figure 4. The SEM Image of insert in experiment #2.

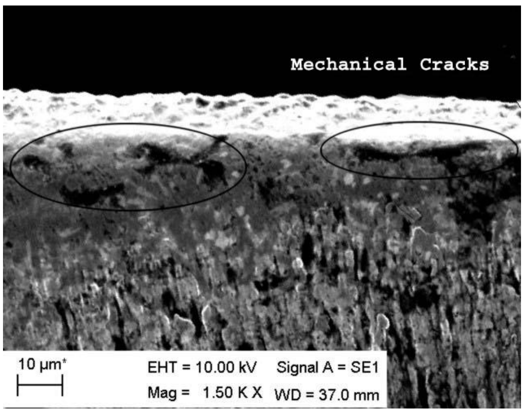

Figure 5. The SEM Image of insert in experiment #3.

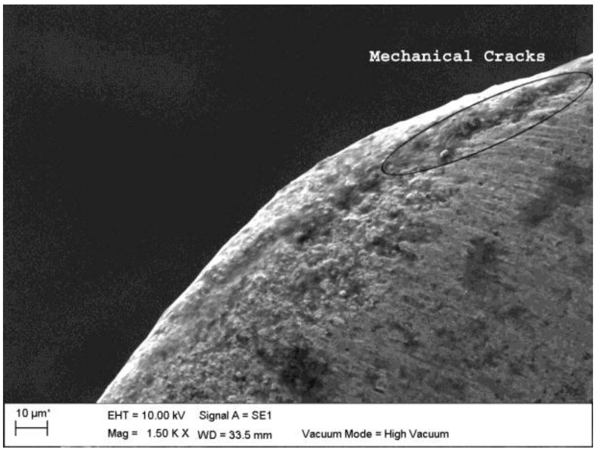

Figure 6. The SEM Image of insert in experiment #26.

Figures 7-11 represent the SEM images of the experiments #16, 17, 29, 30 and 42. In this set of experiments the cutting speeds were fixed to 110 m/min, and cut depth, coolant conditions and feed rates were varied. As seen from the figures the formation of the mechanical cracks become more significant compared to the first set of experiments with 100 m/min. For the experiment #29 and 42 flaking and plastic deformation, respectively, is also observed.

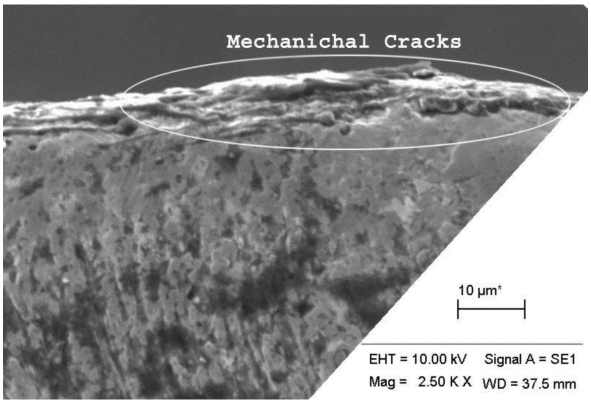

Figure 7. The SEM Image of insert in experiment #16.

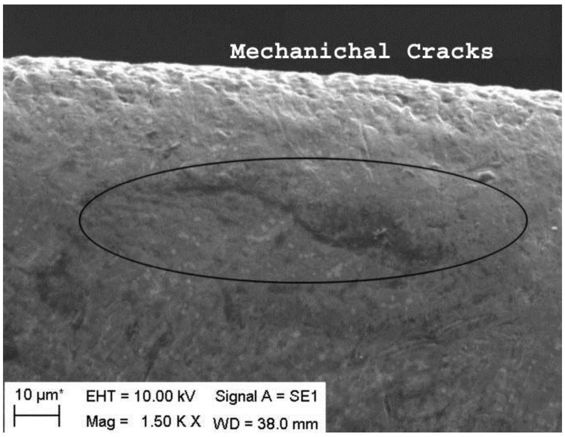

Figure 8. The SEM Image of insert in experiment #17.

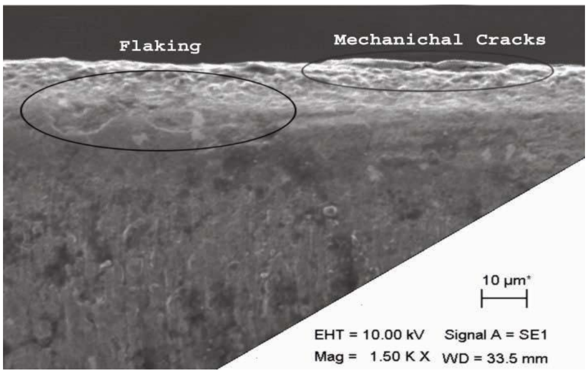

Figure 9. The SEM Image of insert in experiment #29.

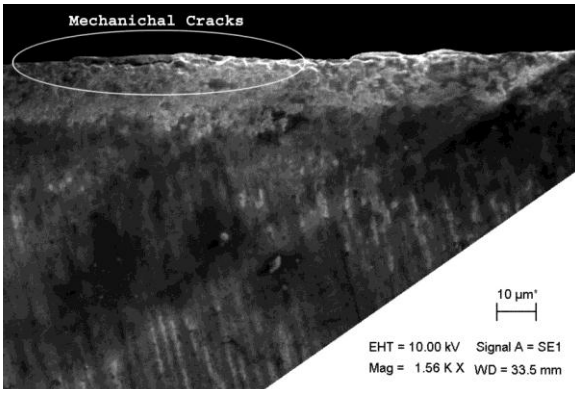

Figure 10.The SEM Image of insert in experiment #30.

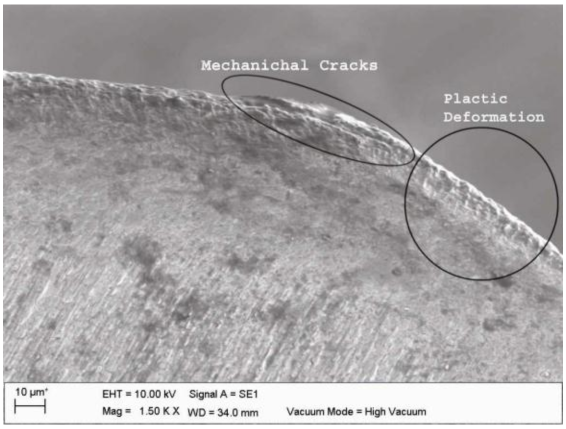

Figure 11. The SEM Image of insert in experiment #42.

Figures 12-15 represent the SEM images of the experiments #7, 9, 33 and 45, where the cutting speeds were fixed to 120 m/min. The cut depth, coolant conditions and feed rates were chosen as free variables. As seen from the figures the formation of the mechanical cracks are found to be significant as in the case of the second set of experiments. Moreover, a combination of mechanical and thermal crack is observed in the SEM image of the sample # 9 (see Fig. 13). This experiment was performed at the same conditions with experiment #7 except that the feed rate of 0.100 mm/teeth was used instead of 0.050 mm/teeth as seen in Table 3. When the coolant condition was changed from dry to wet the cracks associated with thermal type disappeared for the experiments #33 and 45

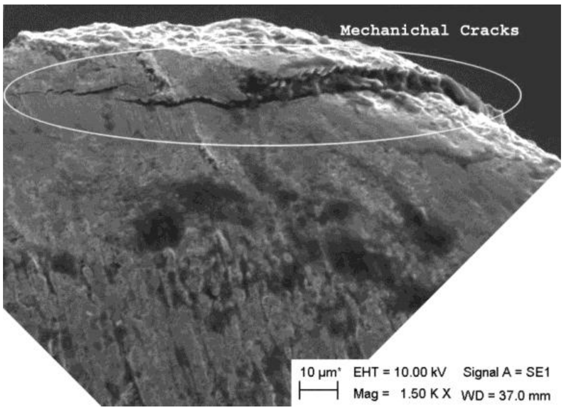

Figure 12. The SEM Image of insert in experiment #7.

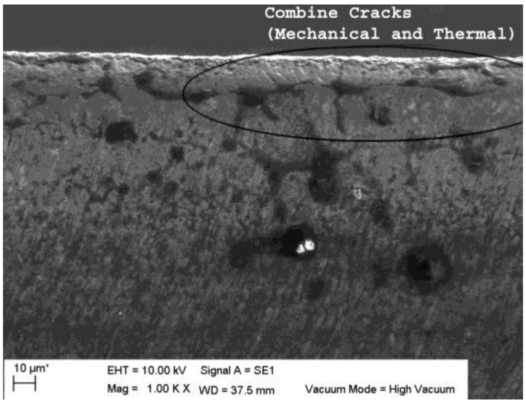

Figure 13. The SEM Image of insert in experiment #9.

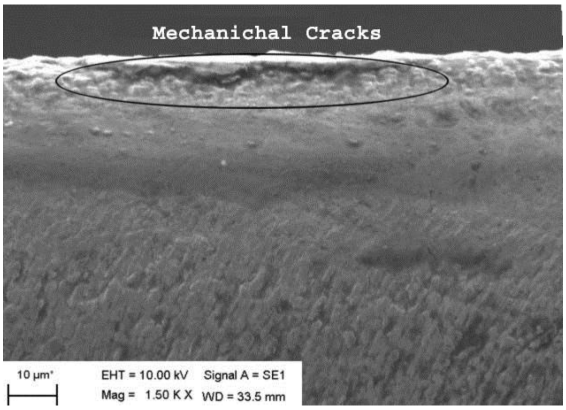

Figure 14. The SEM Image of insert in experiment #33.

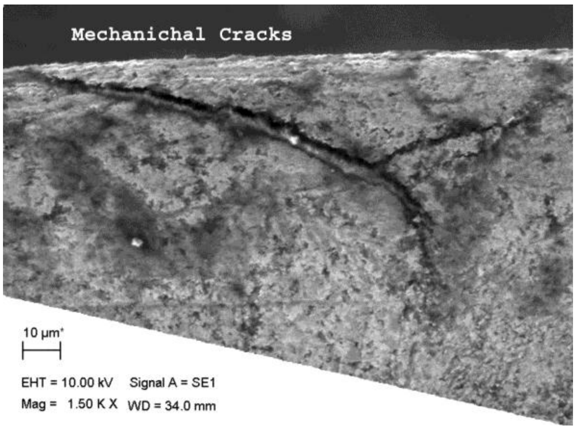

Figure 15.The SEM Image of insert in experiment #45.

Figure 16 and 17 shows typical SEM images for the experiments performed under cutting speed of 130 m/min, cut depth 1.25 mm and dry coolant conditions.

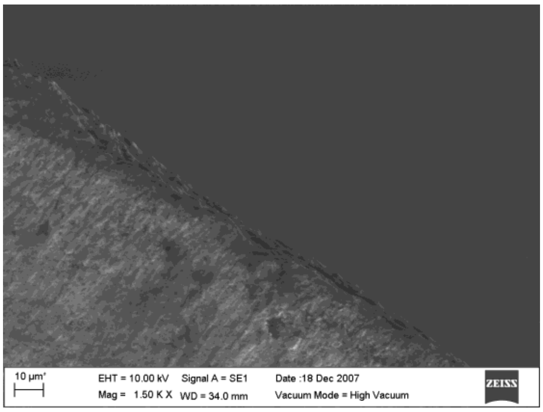

Figure 16.The SEM Image of insert in experiment #10.

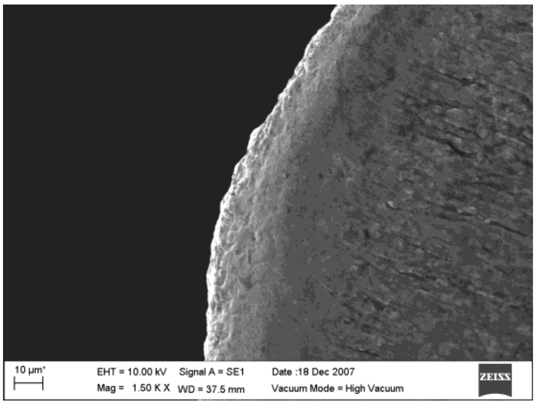

Figure 17.The SEM Image of insert in experiment #12.

Here, we will discuss the effect of the cutting parameters on the resultant force that can be related with the observed mechanical cracks. Table 4 summarizes the resultant forces for the experiments performed at various cutting speeds and feed rates by fixing the cut depth of 1.25 mm and milling condition at dry. As is seen, the resultant force increases monotonically as the feed rate increases for all cutting speeds. On the other hand, it does not depend on cutting speeds explicitly and only very small irregular variation is realized. Neither, there is any clear relation found between the resultant force and mechanical cracks. As a result, the cutting speeds of 110 and 130 m/min can be suggested for the crack free products when these experimental conditions are used.

Table 4. The resultant forces at 1.25 mm cut depth and dry milling conditions for the experiments carried out at different cutting speeds and feed rates.

	Cutting Speed (m/min)							
	100		110		120		130	
Feed Rate (mm/teeth)	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**
0.050	1	890	4	882	7	808*	10	786
0.075	2	996*	5	1037	8	937	11	945
0.100	3	1287*	6	1293	9	1130*	12	1159

* Experiments in which the mechanical cracks are observed.

When the cut depth is increased to 2.0 mm the resultant force and associated crack status is given in Table 5. At these experimental conditions, mechanical cracks are observed in only three experiments. The dependence of resultant force on feed rates at various cutting speeds is similar to that of experiments discussed above. It monotonically increases as the feed rate increases and no systematic dependence on cutting speeds is seen. Neither, there is any clear relation found between the resultant force and mechanical cracks. However, we can speculate that the mechanical cracks occur for the experiments where the highest resultant forces present at the same feet rate (experiments #16, 17 and 20). When these experimental conditions are satisfied the cutting speeds of 100 and 130 m/min could be suggested to be used for the crack free samples.

Table 5**.** The resultant forces at 2.0 mm cut depth and dry milling conditions for the experiments carried out at different cutting speeds and feed rates.

	Cutting Speed (m/min)							
	100		110		120		130	
Feed Rate (mm/teeth)	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**
0.050	13	1396	16	1537*	19	1446	22	1418
0.075	14	1564	17	2000*	20	1734*	23	1662
0.100	15	1850	18	2110	21	2009	24	1900

* Experiments in which the mechanical cracks are observed.

When the coolant condition is changed from dry to wet for a fixed cut depth of 1.25 mm the resultant force and associated crack status is given in Table 6. At these experimental conditions, mechanical cracks are mainly observed in the experiments where the cutting speed set to 120 m/min. In this set of experiments, there is any clear relation found between the resultant force and mechanical cracks. However, we can speculate that the mechanical cracks usually occur for the experiments where the highest resultant forces present at the same feet rate (experiments #29, 30 and 33). At the same cutting speed increasing feed rate causes mechanical cracks. When we compare these results with Table 4, we can conclude that the coolant condition does not effect on the resultant force, and hence the formation of mechanical cracks. The cutting speeds of 100 and 130 m/min could also be suggested to be used for the crack free samples as in the case of 1.25 mm cut depth and dry coolant condition.

Table 6. The resultant forces at 1.25 mm cut depth and wet milling conditions for the experiments carried out at different cutting speeds and feed rates.

	Cutting Speed (m/min)							
	100		110		120		130	
Feed Rate (mm/teeth)	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**
0.050	25	814	28	948	31	791	34	828
0.075	26	983*	29	1107*	32	1016	35	872
0.100	27	1177	30	1244*	33	1154*	36	1186

* Experiments in which the mechanical cracks are observed.

If the cut depth is increased to 2.0 mm the resultant force and associated crack status is given in Table 5. At these experimental conditions, mechanical cracks are rarely observed (only two experiments # 42 and 45). As will be noticed the mechanical cracks occur in the experiments where the resultant forces are highest at fixed cutting speeds. When these experimental conditions are satisfied the cutting speeds of 100 and 130 m/min could be suggested to be used for the crack free samples.

Table 7. The resultant forces at 2.0 mm cut depth and wet milling conditions for the experiments carried out at different cutting speeds and feed rates.

	Cutting Speed (m/min)							
	100		110		120		130	
Feed Rate (mm/teeth)	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**	**Test No**	**F (N)**
0.050	37	1861	40	1562	43	1534	46	1446
0.075	38	2037	41	1738	44	1696	47	1581
0.100	39	2170	42	1834*	45	1967*	48	1806

* Experiments in which the mechanical cracks are observed.

4. Conclusion

In this study, following conclusions can be drawn according to milling tests;

- Mechanical cracks are the most frequent deterioration types to be exposed.
  - ✓ For the cutting speed of 100 m/min, the mechanical cracks are relatively small.
  - ✓ For the cutting speed 110 and 120 m/min, crack formations are critical and mostly depend on other cutting parameters.
  - ✓ For the cutting speed 130 m/min, the crack formation is not observed.
- Although there is no clear dependence is observed between the formation of mechanical crack and the resultant force one can propose that the probability of the formation of mechanical cracks increases as the resultant force become high.

- Mechanical crack formation does not occur at low feed rates (0.05 mm/teeth) nearly independent of other cutting parameters.
- The effect of cut depth and coolant condition on mechanical cracks is not realized probably due to particular experimental conditions used in this study. As far as the resultant force is concerned, it strongly dependent on the cut depth and the feed rate by which it increases. However, the coolant condition does not have any considerable effect on the resultant force.

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