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Investigation of the heat treatment effect in milling of K390 powder metallurgical steel

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Abstract

In this study, surface roughness, tool wear and cutting force have been investigated in milling of Böhler K390 cold work tool steel with coated carbide inserts. Test specimens were tempered at different three temperatures after quenching. Milling tests were performed at four different cutting speeds and feed rates. Surface roughness R_a and cutting forces were measured for further evaluation. Besides, images of cutting inserts were taken from electron microscope (SEM) for determining the wear types and mechanism. Analysis of variance (ANOVA) was used to determine the most influencing cutting parameters on the milling performance. According to the experimental results, they have been low cutting force, value of R_a (0.031 μm), and minimum tool wear in a specimen tempered at high temperature. Due to intermitted cutting, pressure and high temperature, there are more chipping and attrition on cutting insert. Surface qualities of milling surfaces were obtained by grinding operations. According to the analysis of variance feed rate levels, the most effective parameters are R_a and F_m.

K e y w o r d s: hard milling, cutting force, tool wear, surface roughness, powder metallurgical steel

1. Introduction

Powder metallurgy (PM) is the technology of producing pieces from metal powder that was first used by the Egyptians in 3000 BC. Due to the variety of the powder compositions using this method to their suitability for mass production, and to causing very little waste material, they are preferred in many industrial branches. Most of the PM pieces can bear large loads although they are very light [1, 2]. Studies based on laboratory and industrial experiences show the complexity of the machining processes in PM piece production. The effect of the process factors on machinability may be evaluated via the final properties of the sintered pieces. Chemical composition and the microstructure that are a result of the process, surface properties, pores, and remains, affect the machining properties of the work piece in different proportions. In order to prevent the cutting tip to break in intermittent cutting, hard tools are preferred. In cases where surface roughness is important, CBN tips are used [3]. Selecting appropriate factors plays an important role in achieving the desired surface roughness value. Jin et al. studied the effect of milling parameters under dry conditions on the surface quality of FGH95 super alloy based on PM nickel. Experimental results showed that surface quality of the milled FGH95 was more sensitive to the changes in cutting speed [4]. Also, Jin and Liu studied the chip formation as well as the surface quality when milling the same material. Experimental results showed that chip formation and surface quality were mostly under the influence of changes in cutting speed [5]. Aksoy [6] applied turning process at high cutting speeds with hard metal cutters having three different geometries to PMD23 powder metallurgy steel at a hardness of 260HB. He studied the tool wear, surface roughness and chip formation occurring at each cutting parameter. Ekinović et al. [7] studied the 90MnCrV8 steel to investigate the machinability behavior of the materials under differ-

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ent cutting conditions at high speeds. For the machinability assessment, the surface roughness obtained after milling process was taken as the basis. For the milling of hardened 90MnCrV8 steel, a good R_a value of 0.062 µm was obtained. Jawaid et al. [8] studied the cutting performance of Tungsten carbide quality tips with or without PVD TiN coating. Inconel investigated the effects of cutting speed and feed rate on the cutting tools performances in milling of 718 using cutting fluid. After the experiments, it was seen that flank wear was the most effective wear type and that coated tools exhibited better performance compared to uncoated tools. Kharis and Lin [9] studied the effect of the TiAlN coated carbide tips on the wear behavior using the PVD technique. Micro-wear mechanisms were evaluated with scanning electron microscope (SEM). Wear mechanisms like micro-abrasive, micro-fatigue, micro-chipping, and micro-wear were detected. Vakondios et al. [10] investigated the influence of milling strategy on the surface roughness in ball end milling of the aluminum alloy Al7075-T6. All possible milling strategies were considered, such as vertical, push, pull, oblique. All models were statistically validated and experimentally verified.

In the recent years, machining of the steel in manufacturing industry after having been hardened has been a focus of interest in industry and science circles. Also, improved cutting tool industry offers new solutions for machining of steels. Machining on hardened steels was limited to grinding at first. Today, it is possible to perform turning, milling, and perforation operations using suitable cutters and cutting parameters. Turning and/or milling of steels after having been hardened is a more economical, efficient, and environment-friendly manufacturing method compared to grinding operation. The most significant advantage of this operation over grinding operation is that both shape and a better surface quality are achieved in a single operation [11, 12]. Gear, axle, rolling bearing, cam and rotation, volume, and production of sheet steel mold pieces may be given internal systems examples of machining steels after having been hardened in the industry [13]. Machining of steel after having been hardened has been rapidly spread in the molding and machine tools industry. Consequently, steel developing strategies have gained significance for the milling of hardened steels. Especially in the milling of hardened steels, the microstructure of the material has a strong effect [14]. Changes in the conditions of thermal processes, such as hardening and tempering, cause changes in the tool steels such as HSS, etc. [15]. In their study of the milling of hardened tool steels, Iqbal et al. stated that the main mechanisms leading to toll wear were the mechanisms of notch, adhesion, and chipping wear [16]. Axtinte and Dewes obtained an R_a value between 0.5–2.5 µm for the milling of hardened H13 steel with spherical carbide tip at a cutting speed of 350 m min^{-1} [17]. In another study [18], an R_a value between 0.2–0.4 µm was measured for the milling of hardened AISI D3 steel with CNB cutting tips. Aslan [19] studied the tool performance and wear behavior under different cutting conditions for the milling of X210Cr12 cold work tool steel with the hardness of 62 HRC. TiCN and TiCN + TiAlN coated tungsten carbide, mixed ceramic with Al_2O_3 + TiCN content, and CBN cutting tools were used. When the results were examined, CBN cutting tool exhibited the best performance with regards to roughness, flank wear, and the volume of machining. In the field of milling of hardened steels, in contrast to others, Zhang and Guo [20] studied the relations between the chip morphology, phase transformation, and oxidation and milling of final finishing milling of these. Also, in different studies carried out on both the same material and powder metallurgy steels, it is observed that now the tension and surface conditions are being studied [6, 7, 21, 22]. Cui et al. [23] studied the tool wear occurring during the milling of hardened AISI H13 steel with CBN tips, cutting forces, and chip formation. It was seen that increasing cutting speed, together with increasing temperature, accelerated the thermal cracks, oxidation, and adhesion formations. Niu et al. [24] studied the tool performance of carbide tools coated with TiN/TiAlN via PVD method and of carbide tools coated with TiN/Al_2O_3/TiCN via the CVD method in milling of TC6 alloy and stated that carbide cutters coated with TiN/TiAlN via PVD exhibited better performance.

In this study, differing from the above mentioned studies, K390 cold work tool steel manufactured by Böhler via powder metallurgy technique was tempered at three different temperatures and milled with TiAlN coated carbide inserts. The results were evaluated with regards to surface roughness R_a, cutting force, and tool wear. The experimental material was used for applications such as volume/manufacture of cutting molds, etc., due to its superior properties. However, its purchase value is high. The results to be obtained from these experiments may provide great contribution to increasing the milling performance of K390 steel.

2. Material and method

Milling tests of PM K390 cold work tool steel tempered at different temperatures were performed with coated carbide inserts in dry condition. Surface roughness, tool wear and cutting force were taken into account for the evaluation of machining performance.

Dimensions of the work piece and milling method are given in Fig. 1. The chemical composition of PM K390 steel used in milling tests is given in Table 1.

Highly alloyed cold work tool steel was produced by the most modern PM method with excellent wear res-

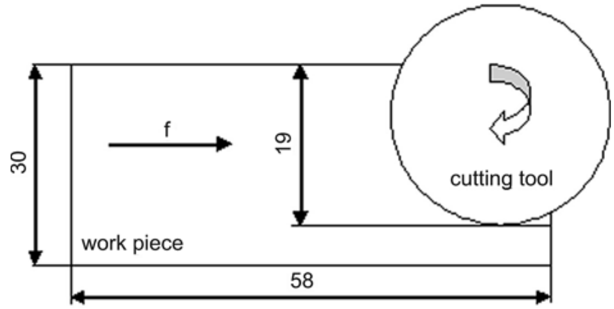

Fig. 1. Work piece and milling method.

Table 1. Chemical composition of K390 (wt.%) [25]

C	Si	Cr	Mo	V	W	Co
2.45	0.55	4.15	3.75	9.00	1.00	2.00

istance, high compressive strength, very good hardening behavior, good ductility and toughness properties. In addition, manufacturing using third generation PM-production technology at Böhler leads to excellent purity, good fatigue properties and very good machinability (e.g., good grindability) [25]. Before milling tests, work pieces were quenched and tempered at three different temperatures. Heat treatments of work pieces have been conducted by ISTAŞ-Bursa heat treatment. Heat treatment conditions determined by suggestion of work piece manufacturer and obtained values of hardness are given in Table 2.

Milling test was conducted in Johnford VMC 550 CNC vertical machining center with 7.5 kW and maximum 6000 rev min^{-1} at the University of Gazi, Faculty of Technology, Department of Manufacturing Engineering. Produced by SAFETY for the milling of hardened steel, TiAlN coated cutting inserts with PVD method and coded RT 100308-R81 kodlu 2003 (ISO H10) were used. Cutting insert was fixed on SAFETY RT10/025-03-QCC20-110 tool holder with diameter of 25 mm. The cutting insert and tool holder used in the experiments are presented in Fig. 2.

Milling experiments were performed in the light of the values given in Table 3. For each milling test, one cutting insert was fixed on tool holder. Thus, clear evaluation of cutting force and tool wear was provided. A KISTLER 9257B piezoelectric dynamometer and multi-channel 5070A amplifier were used to measure three components of cutting force. Measurement ranges were ± 5 kN for F_x, F_y and –5 to 20 kN for F_z. Sensitivities were ≈ –7.9 pC N^{-1} for F_x, F_y and ≈ –3.6 pC N^{-1} for F_z. The measurements obtained from dynamometer and amplifier were processed with KISTLER-Dynoware software. The machining force F_{m} was determined by using the following equation [26]:

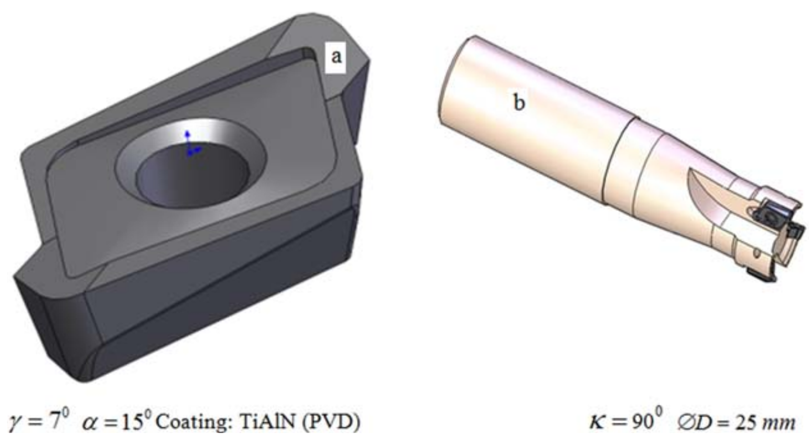

Fig. 2. Form and dimensions of the cutting insert used in the experiments (a), tool holder (b).

Table 2. Heat treatment properties and hardness of experimental work piece materials

Material	Austenitising temperature (℃)	Tempering temperature (℃)	Hardness HRC
M1	1040	550	62
M2	1040	575	59
M3	1040	600	56

*vacuum hardening

Table 3. Experimental parameters

Parameters	Levels			
Cutting speed, V_c (m min^{-1})	60	80	100	120
Feed rate, f_z (mm/tooth)	0.02	0.05	0.1	0.15
Depth of cut, a_p (mm)	0.25			

$$F_m = \sqrt{F_x^2 + F_y^2 + F_z^2}. \quad (1)$$

Average surface roughness (R_a) measurements were performed by using a Mahr Perthometer M1 with a cut-off length of 0.8 mm. Average surface roughness value was calculated using the value of surface roughness measured in three different points on milling surface. Also, electron microscope (SEM) images of the cutting inserts were taken and examined to evaluate more effectively the development of wear mechanism and defect type on tool deformation. The photos which were taken during performing of experiment in machine and measuring of surface roughness are given in Fig. 3. Analysis of variance (ANOVA) was used for determining that the most influencing machining parameters on milling performance of K390 steel in terms of the statistics were: heat treatment, cutting speed and feed rate.

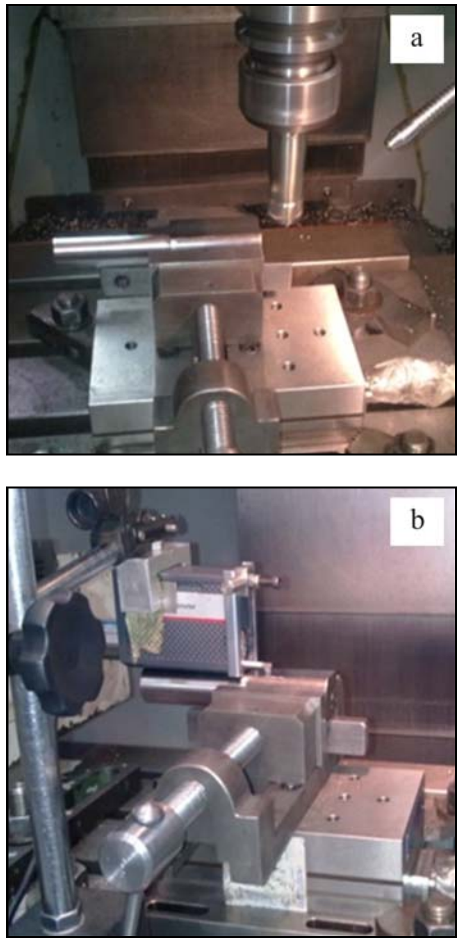

Fig. 3. Performing of experiment in machine (a), measuring of surface roughness (b).

3. Results and discussion

The graphs showing the relation of the mean roughness (R_a) values measured as a result of the cutting experiments, the cutting force values and the cutting parameters were formed. In Fig. 4, the graphs showing the change of R_a with the feed rate are given.

In the graphs, the R_a value increased with the increasing feed rate value for all the samples at each one of the four cutting speeds. For the M3 sample, the changes in feed rate did not greatly affect the R_a value. An increase in the cutting speed decreased the R_a values of only the M1 sample (especially at the value of $f = 0.15$ mm/tooth). It did not exhibit a significant change in M2 and M3 samples. For the M1 sample, the R_a value exhibited a rapid increase after a feed rate of 0.1 mm/tooth. The lowest R_a value was measured as 0.031 μm for the M3 sample at a cutting speed of 80 m min^{-1} cutting speed and with a feed rate value of 0.02 mm/tooth. The highest roughness value was measured as 0.763 μm for the M1 sample at a cutting speed of 60 m min^{-1} cutting speed and with a feed rate value of 0.15 mm/tooth. In Fig. 5, the graphs showing the change of F_m value, calculated using Eq. (1), with the feed rate value are given. When viewed in general, an increase in the feed rate value increased the F_m value. Since the chip cross-section increased depending on an increase in the feed rate value, the cutting forces also tended to increase [26]. When the curves of the M1 samples were examined, it was observed that, as the feed rate value of 0.05 mm/tooth increased to the feed rate value of 0.15 mm/tooth, an increase in the F_m value was greater compared to the other feed rate values. The combination of the fact that the hardness of the work piece was high (62 HRC) with the increasing chip cross-section increased significantly the energy required to deform the chips, therefore the cutting forces increased. The highest F_m value was measured as 309.3 N for the milling of the M1 sample with a hardness of 62 HRC at a cutting speed of 80 m min^{-1} and with a feed rate value of 0.15 mm/tooth. The lowest F_m value was 51.27 N for the milling of the M3 sample with a hardness of 56 HRC at a cutting speed of 100 m min^{-1} and with a feed rate value of 0.02 mm/tooth. When the graphs were examined with regards to cutting speeds, a significant decrease occurred in the F_m value at high cutting speeds. This may be associated with the fact

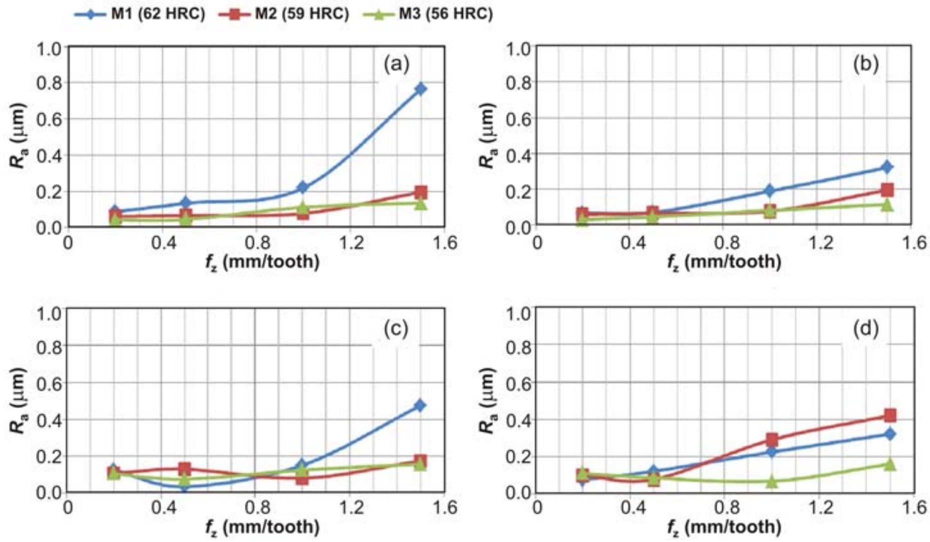

Fig. 4. Changing of R_a according to the feed rate at four different cutting speeds: 60 m min^{-1} (a), 80 m min^{-1} (b), 100 m min^{-1} (c), 120 m min^{-1} (d).

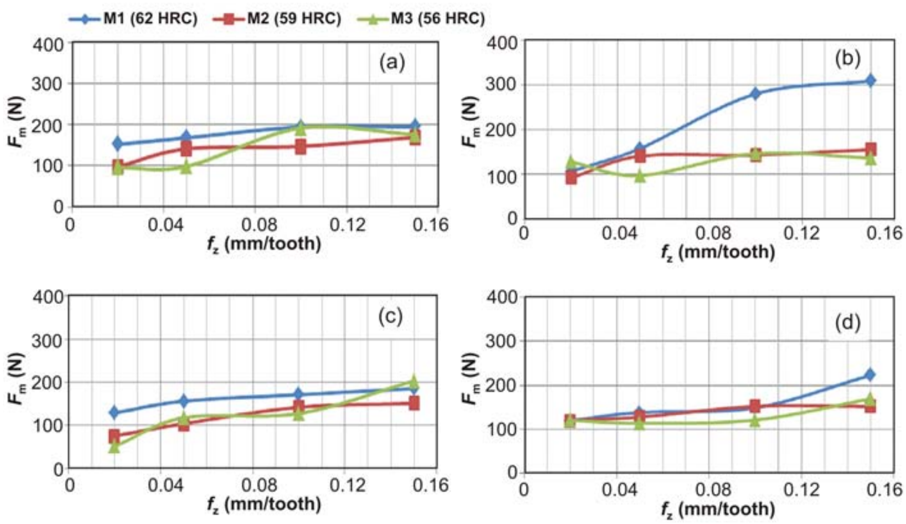

Fig. 5. Changing of F_m according to the feed rate at four different cutting speeds: 60 m min^{-1} (a), 80 m min^{-1} (b), 100 m min^{-1} (c), 120 m min^{-1} (d).

that the increase in the cutting speed facilitates the chip formation with the increasing heat at the cutting area, and that it improves the removal capacity.

The images of the cutting inserts were taken with the scanning electron microscope at first with a zoom rate of 100×. Later, the zoom rate was increased for determining other regions, providing a closer investigation. In the photograph groups given in Figs. 6–8, first the photograph taken at a zoom of 100× is given, and the images taken based on this are shown with frames and arrows. Also, since there are similar conditions in all three photographs, these areas are marked with "X". In the photographs, small material adhesions are seen scattered at the surfaces with "X". According to Cui et al. [23], some of the chips formed in the milling of hard materials acceptance melted because of the high temperature and flew down depending on the cutting environment. These flowing melted particles spread on the tool surface, adhering and accumulating. In Fig. 6, the SEM images of the cutting tools were given after the milling of the M1 sample under cutting conditions of $V_c = 120$ m min^{-1}, $f_z = 0.02$ mm/tooth. When Fig. 6 was examined, it was seen that the coating was laminated. Although TiAlN coating is highly resistant to high temperatures and oxidation [27], in the temperature, which rises extremely at the cutting area depending on the milling of the hardened material, it may weaken the material and reduce the hardness [8]. When the frame numbered 1 was observed closely, there was material

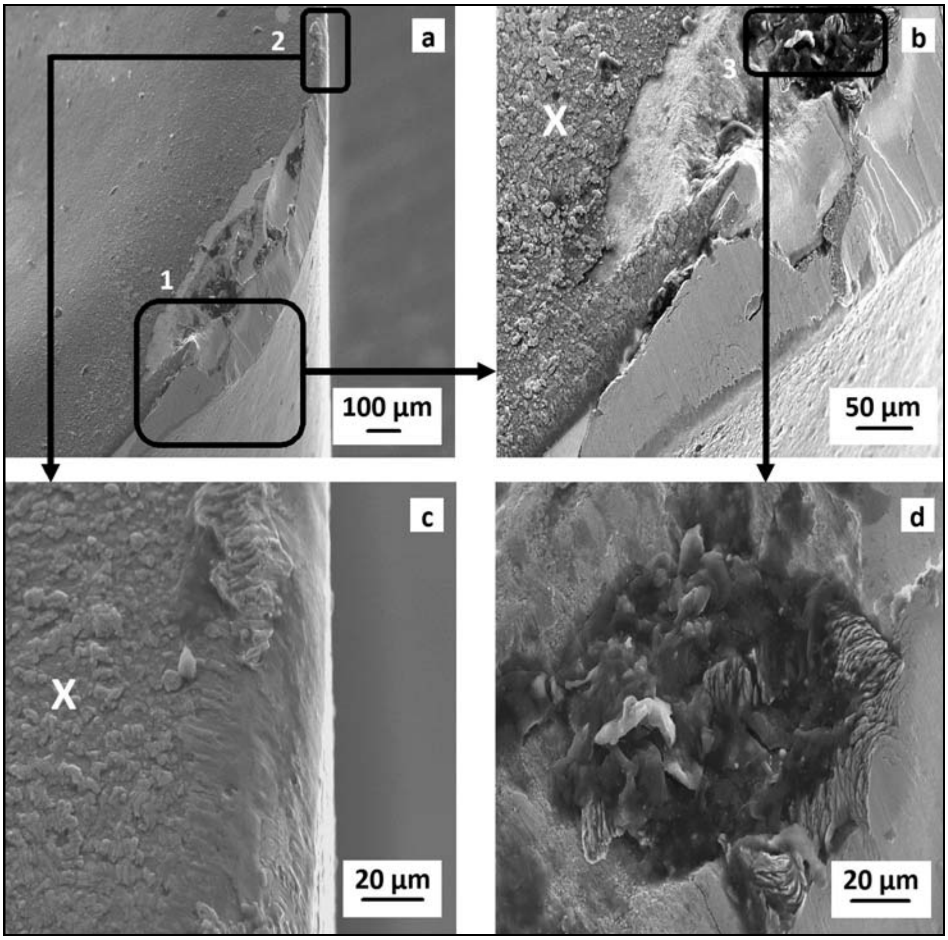

Fig. 6. The SEM images of cutting insert after milling of specimen M1 with parameters of $V_c = 120\ \mathrm{m\,min^{-1}}$, $f_z =$ 0.02 mm/tooth.

adhesion at the cutting edge. It attracted attention that the adhered parts broke during the continuing cutting process and also ripped pieces from the tool material off. Serious breaks occurred especially in the tip part of the tool. When the frame no. 2 was examined closely, it was seen that chip adhesions occurred on the cutting edge at the direction of the chip flow. These surfaces located between the tool and the chip were shaped with the effect that the chips sliding over these surfaces during cutting were formed. When the frame no. 3 was examined in detail, a rapid deterioration started on the tool material after the coating had been laminated. Here, especially the effects of chipping and diffusion wear mechanism can be observed. During milling processes, thermal and mechanical effects causing micro-cracks, chipping, and serious breaks are the most significant factors deforming the cutter [7]. Chipping developed in the form of fatigue cracks, which were created on the cutting edge in intermittent operations such as milling, crisping and breaking the tool [23, 28] by changing thermal and mechanical loads.

In the study [29] carried out, similar formations were encountered in the machining of spheroidized Ç52100 bearing steel with coated carbide. Also, it was possible to see the formation of micro-cracks at the cutting edge and the dark-colored area. At the dark-colored part, work piece materials adhering could also be seen. These adhering parts rip particles from the surface they are on, making the already worn surface rougher and causing the subsequent chips to attach and adhere more easily. Consequently, the wear is accelerated [30, 31].

In Fig. 7, the SEM images of cutting tips after the milling of the M2 sample ($V_c = 120\ \mathrm{m\,min^{-1}}$, $f_z =$ 0.02 mm/tooth) are presented. In general, failure of the coating, adhesion, flank wear, and chipping are seen. When the frame no. 1 was observed closely, it was seen the work piece material adhered intensely as a BUE (built-up edge) on the tip part of the cutting insert. The break of this stable BUE should also damage the cutting tool material seriously. Taking into account that the milling operation is an intermittent cutting operation, it is inevitable that this piling breaks in a short time. Again at the tip part of the cutting insert, there were layered BUE adhesions shaped as

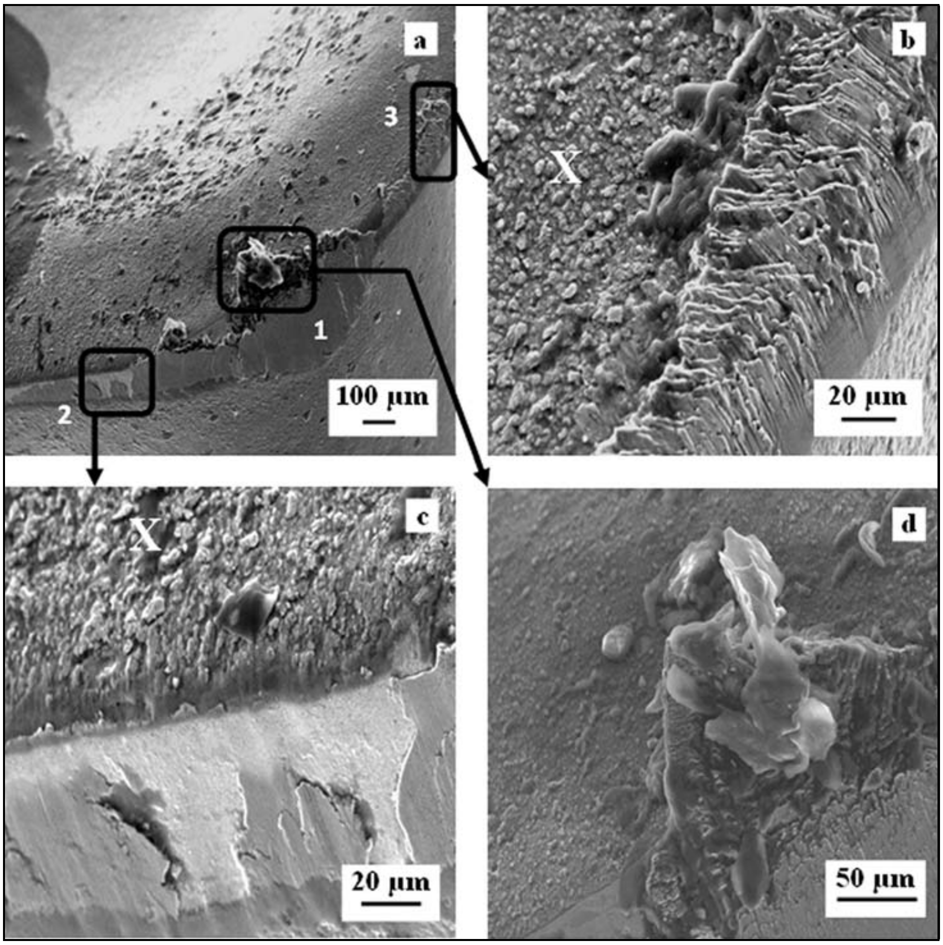

Fig. 7. The SEM images of cutting insert after milling of specimen M2 with parameters of $V_c = 120\ \mathrm{m\ min^{-1}}$, $f_z = 0.02\ \mathrm{mm/tooth}$.

chamfers by the effect of high pressure at the cutting area. When the detail of the frame no. 2 was studied, it was seen that the coating was laminated and the work piece material adhered to this area. The adhering layers were chipping. The two main factors affecting chipping are vibration and sudden loads [32]. It was also seen that the surfaces adhering on the sedge were shaped with the effect of pressure. In the detail no. 3, chip pieces that shaped BUE as mountain ranges were observed gradually. High temperature and intermittent cutting may be the factors in the shaping of the BUE [23, 32]. Traces in the direction of the flow were observed on the BUE due to the chip flow.

In Fig. 8, the SEM images of the cutting tip taken after the milling of the M3 sample ($V_c = 120\ \mathrm{m\ min^{-1}}$, $f_z = 0.02\ \mathrm{mm/tooth}$) are given. Failure of the coating, adhesion, flank wear, and chipping were the striking wears. When the frame no. 1 was examined in detail, it was seen that the work piece material adhered the edge with the laminated coating. Also, excessive heat and mechanical-thermal loads caused micro-chipping at this area depending on the hardness of the milled piece (detail of the frame no. 2). The effect of diffusion wear mechanism was also observed in this area. Also, it was seen that abrasive wear grooves (also called as grinding marks) occurred on the surface with the adhesion. When the detail of the frame no. 3 was examined, there were work piece materials adhering on each other in different manner. The lower layers had quite smooth surfaces due to the pressure during cutting.

The effect of the cutting parameters on R_a and F_m was evaluated using variance analysis with 95 % confidence level ($P < 0.05$). ANOVA is a method most widely used and aims at determining significant parameters on experimental results and measuring their effects. The F-tests and P-value provided a decision at some confidence level that is the realized significance level, for each source of variation [33, 34]. The results of the ANOVA are given in Table 4. As can be understood from the Table 4, it is seen that, with regards to P-values, material and feed rate have a significant effect on both R_a and F_m due to the values of $P < 0.05$. Besides, according to the P-value of R_a ($P = 0.395$) and F_m ($P = 0.187$), effect of cutting speed is insignificant. With the value of F, it was seen

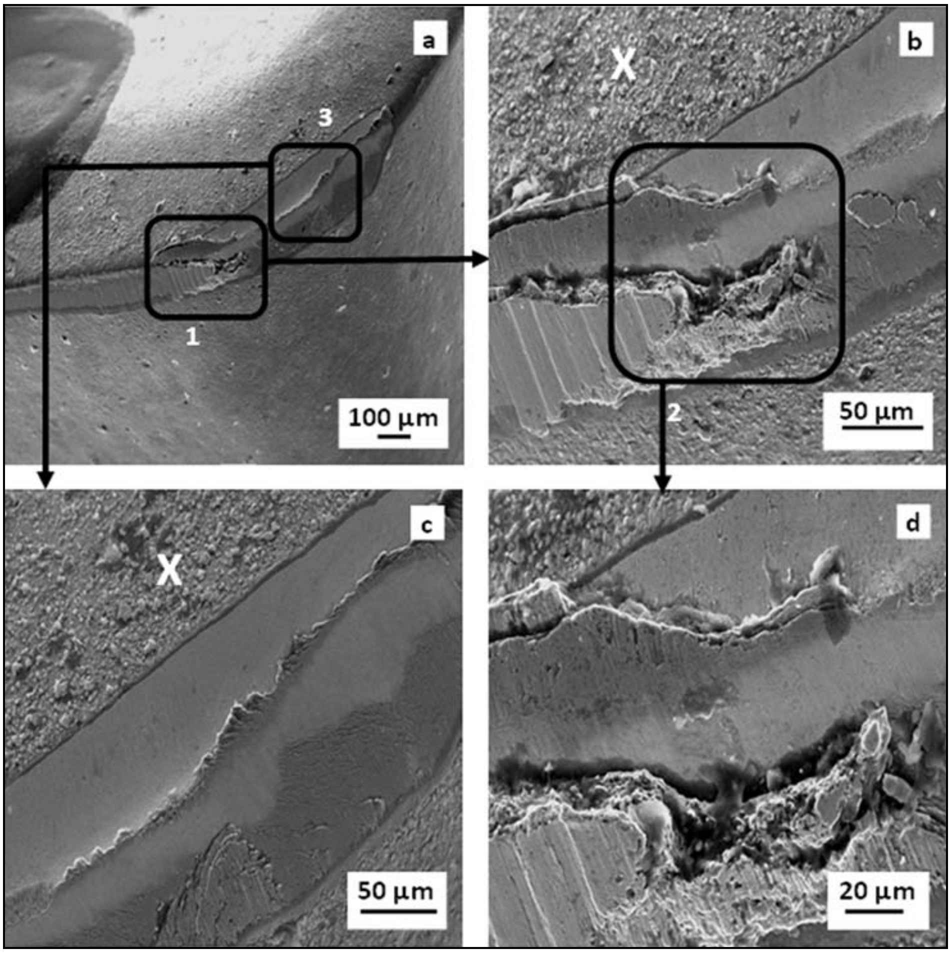

Fig. 8. The SEM images of cutting insert after milling of specimen M3 with parameters of $V_c = 120\ \mathrm{m\ min^{-1}}$, $f_z = 0.02$ mm/tooth.

Table 4. ANOVA results for R_a and F_m

Source	DoF	SS	MS	F	P
R_a					
Material	2	0.114186	0.057093	6.48	0.004
Cutting speed	3	0.026961	0.008987	1.02	0.395
Feed rate	3	0.328269	0.109423	12.41	0.000
Residual error	39	0.343832	0.008816		
Total	47	0.813247			
F_m					
Material	2	22338.1	11169.1	13.75	0.000
Cutting speed	3	4088.4	1362.8	1.68	0.187
Feed rate	3	43767.6	14589.2	17.96	0.000
Residual error	39	31672.3	812.1		
Total	47	101866.5			

that the change in the feed rate levels was the most effective parameter on R_a and F_m.

Looking at all the findings obtained in general, the highest values with regards to both R_a and F_m values were measured on the M1 sample. The fact that the M1 sample was the hardest sample with 62 HRC had a significant impact on this result. Also, when the tool wears were compared, a more intense deformation was observed on the cutting tip used for the milling of the M1 sample. The abnormal rise of 0.15 mm/tooth in the R_a value may be associated with the deformation of the tool geometry due to wear. Increasing caused serious damages on the cutting tool, and this was reflected on both F_m and R_a. After the milling of heat treated PM K390 steel, it was seen that the expectations of lower cutting forces, lower R_a value, and little tool wear were met to a great extent. Taking into account that the milling experiments were also carried out under dry conditions, the hazardous environmental impacts of the cutting fluid would be eliminated. Generally, the carbide cutting inserts that are not recommended for materials with high hardness are preferred with priority in intermittent cutting operations such as milling due to their satisfactory toughness. Developing cutting tool technology also supports this fact. In this study, very good results were obtained on the sample with a hardness of 56 HRC.

4. Conclusions

The results obtained as a result of dry milling of quenched and tempered Böhler K390 steel are listed as follows:

– It was seen that feed rate had a significant effect on R_a. Tempering temperatures did not create a significant difference on R_a except the value of the M1 sample at a feed rate of 0.15 mm/tooth. It was revealed that the change in cutting speed did not create a significant change on R_a. The lowest R_a value was measured as 0.031 μm for the M3 sample at a cutting speed of 80 m min^{-1} and with a feed rate value of 0.02 mm/tooth. This value is a good value for milling operations.

– The lowest F_m value was 51.27 N for the milling of the M3 sample at a cutting speed of 100 m min^{-1} and with a feed rate value of 0.02 mm/tooth.

– In the view of the analysis of the SEM images, the diffusion wear mechanism and abrasive wear mechanism were more effective in the milling of thermally-treated PM 390 steel with carbide cutting inserts. Because of high temperature, intermittent cutting, and pressure, mechanical-thermal fatigue cracks were formed. As a result of this, chipping and attrition occurred.

– After the milling of heat treated PM K390 steel, it was seen that the expectations of lower cutting forces, lower R_a value, and little tool wear were met to a great extent.

– Material and feed rate have a significant effect on both R_a and F_m in terms of statistics according to the ANOVA. The change in the feed rate levels is the most effective parameter on R_a and F_m.

– In the milling of the PM K390 steel giving perfect results in the cutting, perforating, plastic injection casts, and cold shaping applications in the industry after heat treatment, surface qualities that were close to the ones obtained from grinding processes were achieved. Thus, it will be possible to eliminate the high cost of the grinding operation and the hazardous environmental impacts related to the cutting fluid.

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