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EFFECT OF THE MARTENSITE VOLUME FRACTION ON THE MACHINING OF A DUAL-PHASE STEEL USING A MILLING OPERATION

VPLIV VOLUMENSKEGA DELEŽA MARTENZITA NA OBDELAVO DVOFAZNEGA DUALNEGA JEKLA Z REZKANJEM

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Dual-phase steels are attractive because of their good combination of strength and ductility. However, an increase in the martensite content will decrease the steel's machinability significantly. Therefore, optimum cutting parameters in the machining of such materials should be determined. In this paper, the machinability of a low-alloy steel having various martensite volume fractions was investigated. The four groups of samples, three of which were intercritically annealed at three different temperatures and one of which was normalized, were used. Then, the machining experiments were carried out using a face-milling operation with two different tools. After that, the flank wear on the tools with respect to the chip-volume or flank-wear limit was determined for each case. Next, the surface roughness of the samples was measured. Finally, the wear behavior of the tools was examined with a scanning electron microscope (SEM). The experimental results indicated that the flank wear of the tools increased dramatically with the increasing martensite content of the dual-phase steels.

Keywords: dual phase steel; machinability; tool wear; milling.

Dvofazno dualno jeklo se odlikuje po dobri kombinaciji trdnosti in duktilnosti. Pri povečanju vsebnosti martenzita se obdelovalnost pomembno zmanjša, zato je treba za jeklo določiti optimalne pogoje rezanja. V tem delu je bila raziskana obdelovalnost malolegiranega jekla z različnim volumenskim deležem martenzita. Uporabljene so bile štiri skupine vzorcev, tri izmed njih so bile interkritično žarjene pri treh različnih temperaturah, ena pa je bila samo normalizirana. Obdelovalni preizkusi so bili izvršeni s čelnim rezkanjem z dvema različnima orodjema. Nato je bila za vsak primer določena čelna obraba orodij glede na prostornino ostružkov ali mejna vrednost čelne obrabe in tudi hrapavost površine obdelancev. Obrabno vedenje orodij je bilo raziskano z vrstičnim elektronskim mikroskopom (SEM). Poskusi so pokazali, da čelna obraba orodij dramatično raste z vsebnostjo martenzita v dualnem jeklu.

Ključne besede: dvofazno dualno jeklo, obdelovalnost, obraba orodij, rezkanje

1 INTRODUCTION

Making a dual-phase microstructure in a low-carbon and/or alloyed steel provides not only a high strength but also a good formability and yielding without serrations [1–7]. In this type of microstructure, soft ferrite and hard martensite phases are present and maintain the ductility and the strength of the steel. The improvement in the mechanical properties via forming a dual-phase microstructure in the steel supplies the benefit of reducing the weight of systems. The studies on dual-phase steels have been focused generally on the microstructural and mechanical characterizations after intercritical heat-treatment applications [1–17]. On the other hand, the machinability of these materials is also very important, particularly with respect to the martensite fraction. Optimum cutting parameters in machining should be determined for dual-phase steels with respect to the martensite fraction and the tool types. This knowledge would be very helpful for accelerating the machining process and extending the tool life. In the literature, the studies on the machinability of dual-phase steels are very scarce [18–20]. Therefore, the machinability of these materials still needs to be investigated in detail. El-Gizawy [18] carried out a study on the machining characteristics of a high-strength, low-alloy steel with 80 % martensite and 20 % ferrite using a face-milling operation in which high-speed steel tools were used. It was concluded that the steel with ferrite and martensite showed superior chip disposability compared to that with ferrite and pearlite [18]. In addition, Sueyoshi and Tanaka [19] examined the machinability of a tri-phase steel having the microstructure of ferrite, martensite and graphite and compared the results with a dual-phase steel containing ferrite and martensite phases. They found that the drillability of the tri-phase steel was better than the dual-phase one. In another study [20], tool wear and chip disposability in the machining of a tri-phase steel were investigated and the results compared with those of the dual-phase steel. It was stated that the tri-phase steel provided better chip-disposal behavior due to the fine graphite nodules. Furthermore, the flank wear for the tri-phase steel was found to be lower than that for the dual-phase steel at low cutting speeds with high-speed steel tool.

In this paper, the machinability of a low-carbon, low-alloyed steel in a milling operation was presented. The main aim was to determine the effect of the martensite volume fraction and the cutting speed on the flank wear of coated and uncoated tools.

2 MATERIALS AND METHODS

The steel was supplied as a hot-rolled billet from a private steel company in Turkey. Its composition was 0.28 % C, 1.45 % Mn, 0.21 % Cr, 0.20 % Si, 0.13 % V, 0.01 % Nb and (bal) Fe in terms of mass fractions (%). The specimens were prepared as square shapes of size (100 × 100 × 10) mm. Next, the intercritical heat treatments at (737, 754 and 779) °C were applied to these steel specimens to obtain three different martensite volume fractions. These temperatures were utilized in our previous study [16] and corresponded to low, medium and high martensite volume fractions (approximately 30 %, 50 % and 80 %) in the steel. In addition, the normalizing treatment at 900 °C was also performed for one group of specimens to obtain a fine ferrite and pearlite microstructure to compare with the intercritically treated specimens. The details of the heat-treatment procedures of this steel can be found in Ref. [16]. In total, four different specimen groups, according to their microstructures, were formed. After finishing the thermal treatment procedures, the martensite volume fractions in the intercritically heat-treated samples were checked using an image-processing computer program. Furthermore, the macro-hardness of all the samples was measured by applying the Rockwell C test [21]. Finally, the face-milling experiments were carried out on a CNC vertical machining center (Johnford VMC-550 Fanuc Series O-M) in dry conditions (**Figure 1**). Two different types of tools, of which the properties are given in **Table 1**, were used in the face milling of the steel specimens. The tool geometry and the cutting conditions are also described in **Table 2**. The three different cutting speeds (100, 160 and 220) m/min were used in the operations while the feed was kept constant (0.2 mm per tooth). The milling operations were performed until a chip volume of 8000 mm^3 or a flank wear limit (V_B) of 0.3 mm was reached. Furthermore, the surface roughness of the machined samples was measured using a surface-roughness measurement device, i.e., a Perthometer M1 (Mahr). The microscopic observations on the tool inserts were made with the help of a scanning electron microscope (SEM) and an optical microscope to see their wear behavior clearly.

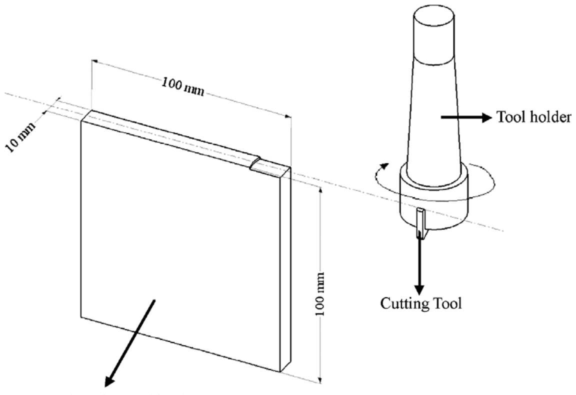

Figure 1: Schematic view of the face-milling operation. In one pass the tool moves from one end to the other end of sample at a certain cutting speed.

Slika 1: Shematičen pogled na proces čelnega rezkanja. V enem koraku se orodje pri določeni hitrosti rezanja premakne iz enega na drugi konec vzorca.

Table 1: Cutting-tool type and characteristics used in the experiment

Tabela 1: Tip rezalnega orodja, ki je bilo uporabljeno pri poskusih

Tool name	Cutting tool designation	Substrate and coating	Coating technique	Depth of cut (DOC) h/mm
Tool A	TPMN160308	K20 (no coating)	Uncoated	1.0
Tool B	TPMN160308	F620 + TiN coating	CVD	1.0

Table 2: Tool geometry and cutting conditions

Tabela 2: Geometrija orodja in pogoji rezanja

Cutting conditions	Parameters
Clamping type of tool holder	Collet
Tool holder diameter [mm]	32
Rake angle	0°
Relief angle	11°
Insert angle	60°
Cutting length, l/mm	100
Number of tooth	Single
Approach angle	90°
Nose radius, r/mm	0.8
Cutting speed, v/(m/min)	100, 160, 220
Feed per tooth [mm per tooth]	0.2
Axial depth of cut, h_a/mm	1
Radius depth of cut, h_r/mm	10

3 RESULTS AND DISCUSSION

Figure 2 shows typical microstructures of the samples with different thermal treatment histories. The martensite volume fractions of samples, treated intercritically at (737, 754 and 779) °C, were approximately (30, 50 and 80) %, respectively. The hardness was recorded to be (30, 35 and 40) HRC for the same samples, successively. The lowest hardness value belonged to the normalized specimen, which was 20 HRC. **Figure 3** depicts the change in the flank wear of both types of tools at the cutting speed of 100/min in the milling of four group specimens. It can be seen from this figure that an increase in the hardness of the dual-phase samples accelerated the wear of both types of tools. Although the performances of both tools were similar for the milling of the high martensitic samples (40 HRC), the uncoated tool had the lower flank-wear values for the milling of the low and medium martensitic samples. On

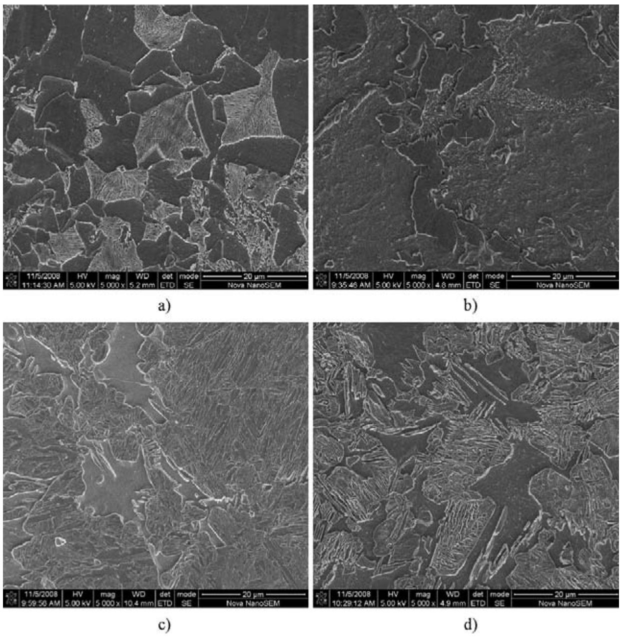

Figure 2: Typical microstructures of the steel samples a) normalized, b) intercritically annealed at 737 °C, c) intercritically annealed at 754 °C, d) intercritically annealed at 779 °C

Slika 2: Tipične mikrostrukture vzorcev jekla: a) normalizirano, b) interkritično žarjeno pri 737 °C, c) interkritično žarjeno pri 754 °C, d) interkritično žarjeno pri 779 °C

the other hand, the normalized and the low martensitic dual-phase samples led to a similar flank wear on Tool A (uncoated). In addition, the Tool B (coated) failed at the beginning of the milling of the normalized specimen (20 HRC) due to the excessive formation of a built-up edge (BUE).

The variation in the flank wear for the tools with respect to the chip volume at the cutting speed of 160 m/min is illustrated in **Figure 4**. When the high martensitic sample was machined, the flank wear increased very rapidly on both tools. It exceeded the limit when the chip volume of 3000 mm^3 was removed from the samples. It is interesting to note that in the machining of the low and medium martensitic samples, the Tool A had lower flank-wear values than the Tool B. Tool B (coated) was fractured at the beginning of the milling process of the normalized sample again so the data was missed for this case. Furthermore, it also failed in the milling of the dual-phase sample with 35 HRC after a chip volume of 7000 mm^3 was removed.

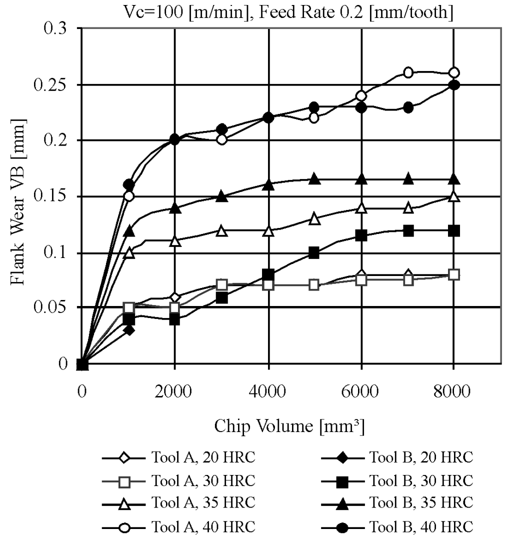

Figure 3: Flank wear on the tools at the cutting speed of 100 m/min in the milling of the investigated samples

Slika 3: Čelna obraba orodij pri hitrosti rezanja 100 m/min pri rezkanju preiskanih vzorcev

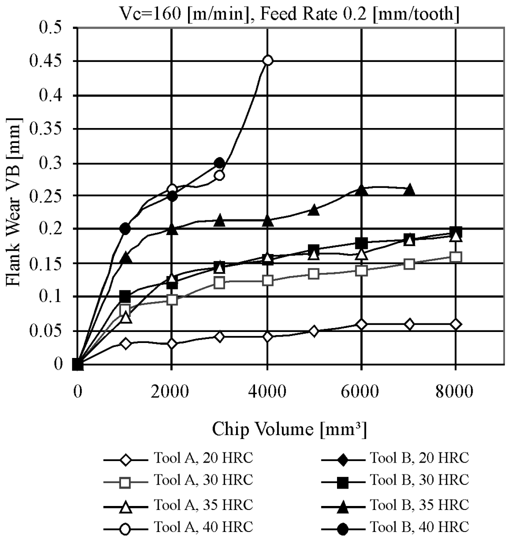

Figure 4: Flank wear on the tools at the cutting speed of 160 m/min in the milling of the investigated samples.

Slika 4: Čelna obraba orodij pri hitrosti rezanja 160 m/min pri rezkanju preiskanih vzorcev

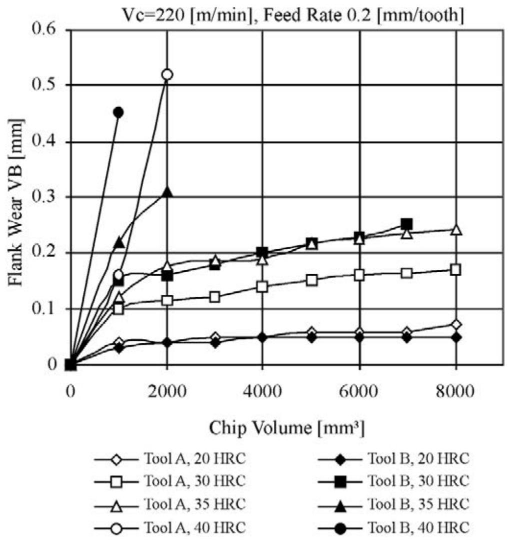

Figure 5: Flank wear on the tools at the cutting speed of 220 m/min in the milling of the investigated samples.

Slika 5: Čelna obraba orodij pri hitrosti rezanja 220 m/min pri rezkanju preiskanih vzorcev

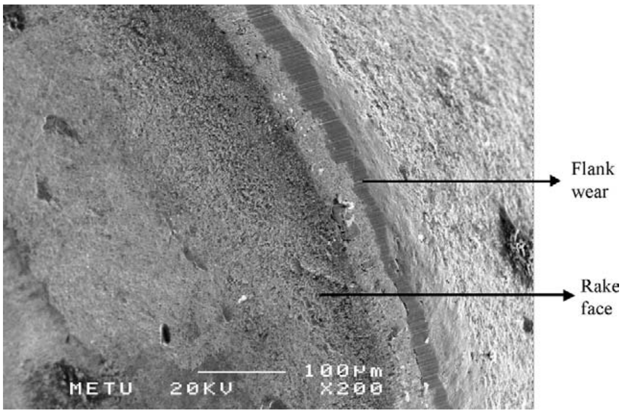

Figure 6: Typical SEM view of the flank wear on Tool A after machining of the normalized specimen at the cutting speed of 160 m/min.

Slika 6: Tipična SEM-slika čelne obrabe orodja A po obdelavi normaliziranega vzorca pri hitrosti rezanja 160 m/min

Figure 5 presents the tool-wear behavior versus chip volume during the milling of the investigated samples at a cutting speed of 220 m/min. The effect of the sample hardness on the flank wear of the tools was clearly seen. Increasing the cutting speed of the tool caused faster tool wear in all cases. Tool B exceeded the flank-wear limit for the dual-phase samples with 35 HRC and 40 HRC before removing the chip volume of 2000 mm^3. Furthermore, Tool B fractured after having seven passes over the dual-phase sample having 30 HRC. At the cutting speed of 220 m/min, the normalized specimen was machined by both tools without causing any fracture. **Figures 6 and 7** show a typical SEM view of the flank wear observed on the tools after machining. An increase in the cutting speed of the process increases the temperature of the cutting zone significantly. This leads to a softening of the chip and the formation of a BUE. For this reason, the removal of the BUE from the cutting tool becomes much easier. On the other hand, in the intercritically annealed samples, the hardness values are much higher than the normalized one. So that BUE formation is not so severe in these samples.

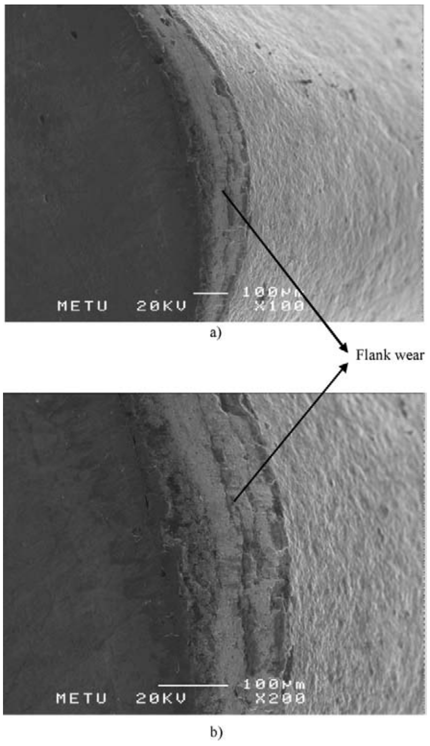

Figure 7: View of Tool B after machining of the low martensitic dual-phase steel a) X100, b) X200

Slika 7: Videz orodja B po obdelavi jekla z malo martenzita; a) povečava 100-kratna, b) 200-kratna

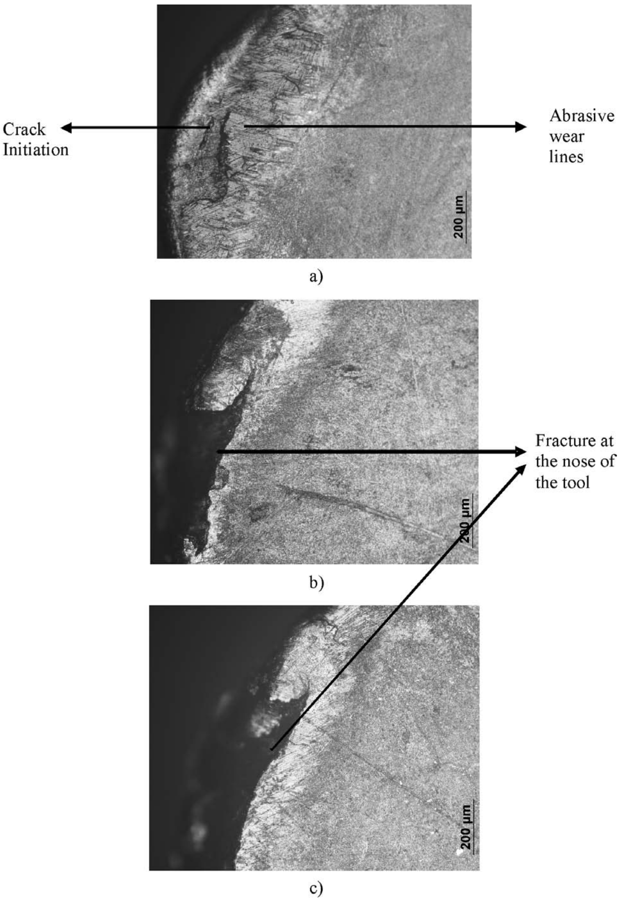

Figure 8: A typical failure of the coated tool after milling: a) the normalized specimen, b) the dual-phase specimen with 30 HRC, c) the dual-phase specimen with 40 HRC (100-times)

Slika 8: Značilna oblika poškodb prekritega orodja po rezkanju: a) normalizirani vzorec, b) dualno jeklo s trdoto 30 HRC, c) dualno jeklo s trdoto 40 HRC (pov. 100-kratna)

Even though the performances of both tools are close to each other at all cutting speeds in the machining of high martensitic dual-phase steel, Tool A exhibited a better performance than Tool B in the machining of other types of samples. The adhesion of the chips to the coated tool was found to a much greater extent, especially for the cutting speeds of 100 m/min and 160 m/min. Furthermore, the coating material of TiN was easily removed from the tool by an abrasive wear mechanism for the harder samples. Therefore, its protection ability was

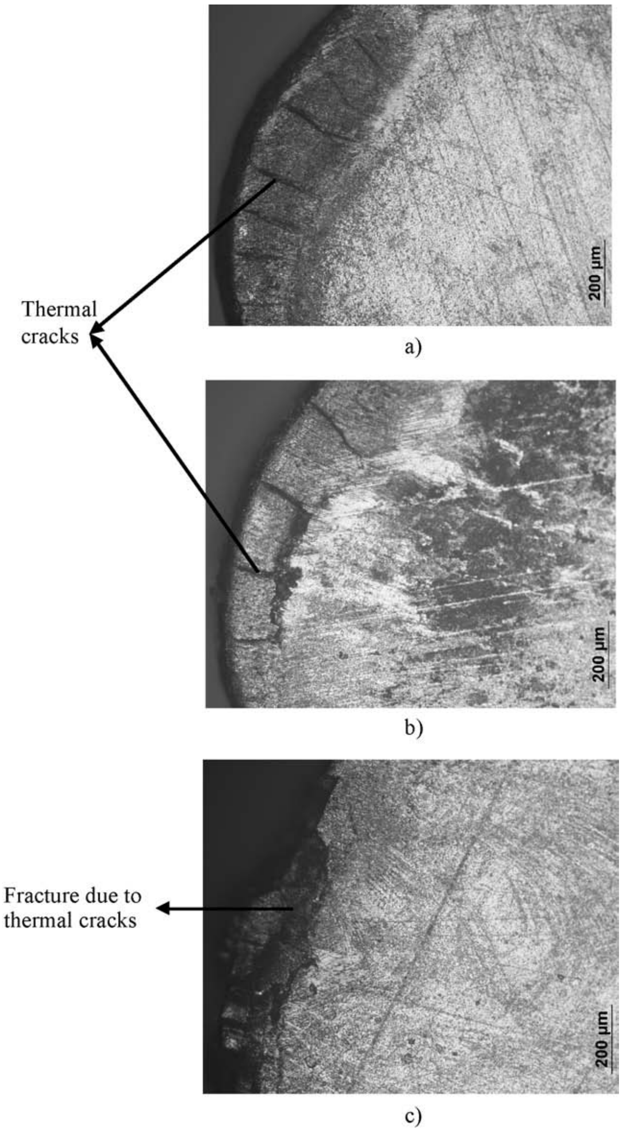

Figure 9: A typical view of the cracks on the uncoated tool after milling the dual-phase sample with: a) 30 HRC, b) 35 HRC, c) 40 HRC (100-times)
Slika 9: Značilen videz razpok na nepokritem orodju po rezkanju dualnih vzorcev s: a) 30 HRC, b) 35 HRC, c) 40 HRC (pov. 100-kratna)

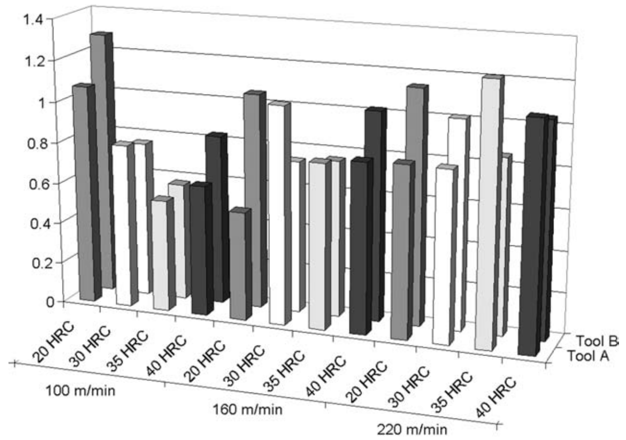

Figure 10: Surface roughness of the machined samples
Slika 10: Hrapavost površine obdelanih vzorcev

largely destroyed by the hard martensite phase in the dual-phase steels. It is generally expected that the coating material reduces the friction between the tool and the workpiece and causes lower temperatures and longer tool lifetimes. However, lower temperatures prevent the softening and effective removal of the BUE from the cutting zone. As mentioned before, higher the BUE accumulation takes place in the cutting zone, the higher the mechanical stresses form on the tool. **Figure 8** illustrates the obtained wear of Tool B after the milling of various samples. It is clear that the mechanical cracks dominate the failure mechanism for this tool. The abrasive wear caused by the chip on the rake face can be seen. On the other hand, thermal cracks were widely observed in Tool A, especially at the cutting speeds of 160 m/min and 220 m/min (**Figure 9**). The crater wear accelerated the fracture of Tool A significantly.

The surface roughness for the machined samples with Tools A and B is presented in **Figure 10**. It changed between 0.5 µm and 1.3 µm, depending on the cutting speed and the type of workpiece material. When the coated tool was used, the highest surface-roughness values were recorded for the normalized samples. In addition to that, there seemed to be a low tendency to increase the surface roughness of the dual-phase samples with increasing the cutting speed for the milling with either Tool A or B. The surface roughness was mainly influenced by the BUE formation.

4 CONCLUSIONS

The results of the machinability experiments for dual-phase steel using a milling operation led to the following conclusions:

- The machinability of the dual-phase steel decreased substantially with an increase in the martensite content.
- An increase in the cutting speed led to faster tool-flank wear on both the uncoated and coated tools.
- The highest BUE formation was observed on the coated tool (Tool B) in the milling of the normalized samples.
- Thermal cracks dominated the failure mechanism of the uncoated tool, whereas the mechanical cracks governed that of the coated tool.
- The surface roughness of the dual-phase samples had a tendency to slowly increase with an increasing cutting speed.

For future studies, the effect of the feed and the depth of the cut on the tool wear can be investigated to understand the machinability of the dual-phase microstructure in details.

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