

# SURFACE INTEGRITY STUDY OF CREEP-FEED GRINDING

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Original scientific paper

<https://doi.org/10.18485/aeletters.2020.5.3.4>**Marin Gostimirovic<sup>1\*</sup>, Milenko Sekulic<sup>1</sup>, Dragan Rodic<sup>1</sup>**<sup>1</sup>University of Novi Sad, Faculty of Technical Sciences, Department of Production Engineering, Serbia**Abstract:**

This paper reports on the research results of surface integrity of the workpiece in creep-feed grinding on the high speed tool steel. The creep-feed grinding is an advanced abrasive process widely used in industry of complex and heavy engineering products. An experimental investigation of the fundamental characteristics of surface metallurgy and surface roughness is carried out. The metallurgical properties were determined by an optical microscope, and through: microstructure, microhardness, cracks and burns. The surface roughness was determined with multiple important roughness parameters through scanning the surface topography (roughness average, mean roughness depth, maximum roughness depth and profile bearing length ratio). The results show that the grinding surface integrity is acceptable with good material removal rate, so that the creep-feed grinding process is an excellent choice for efficient and quality material removal. However, creep-feed grinding is not suitable for the final machining because of the possible metallurgical alterations due to high thermal load.

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**1. INTRODUCTION**

Global manufacturing industry is facing a number of key challenges on a daily basis. Productivity, quality, reliability, flexibility, responsiveness, innovation and sustainability are the most important demands confronting the market oriented manufacturing systems. With the rapidly growing trends in deploying advanced components and products, only modern industrial systems shall be able to adjust their production process to all the complex challenges and demands.

Due to the aforementioned, along with the development of new product ranges, modern industrial concept implies permanent improvement of existing manufacturing technologies, as well as the introduction of new ones. In this context, there can be no doubt these technologies will remain important in the modern production, especially material removal processes. Basic advantages of the material removal processes are high quality and productivity with the ability to cope with difficult-to-machine

materials and complex geometrical shapes of engineering components [1].

Grinding is considered one of the most important material removal processes in the manufacturing industry today. The main advantages of grinding process include good dimensional accuracy and high surface finish [2-4].

In the recent period, in addition to conventional multi-pass grinding technology, there has been an introduction of high-performance grinding processes, Fig.1. These grinding methods use higher cutting speeds and larger depths of cut in order to increase the low productivity which has been considered the main drawback of the multi-pass grinding operations. However, the high-performance grinding conditions considerably change the kinematics of cutting process [5-8].

High-speed grinding is characterized by lower cross-section of chip and shorter time of contact between the workpiece and abrasive particles, but with a more intense friction in the cutting zone [9]. In creep-feed grinding there is very long wheel/workpiece contact which leads to especially

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intense friction [10]. This rapid increased contribution of the friction leads to a more intense development of thermal energy in the contact zone [11,12]. The unwanted thermal effect, primarily in the workpiece material surface layer, represents the

basic limitation for further development of high-performance grinding. For that reason, in the high-performance grinding a special attention is focused on surface integrity [13-15].

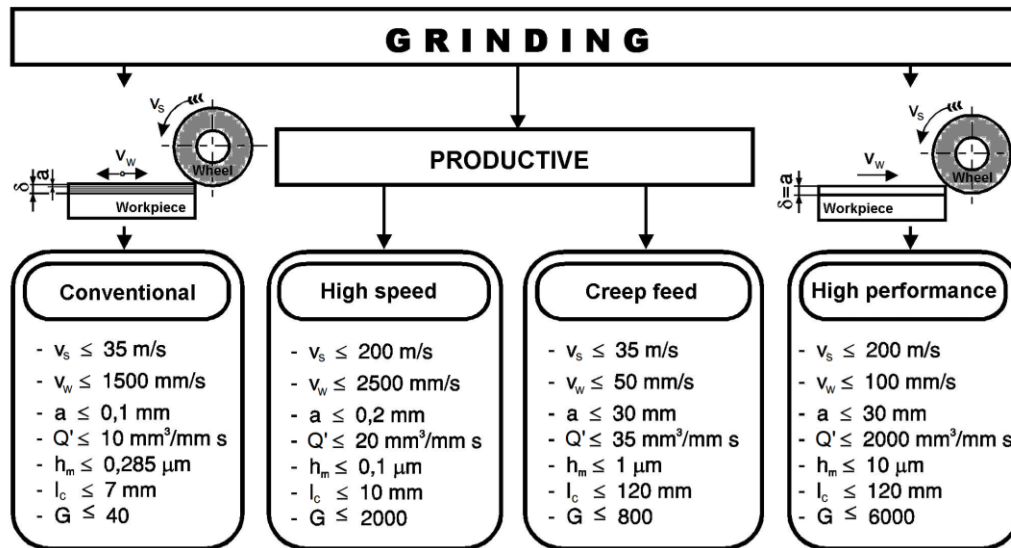


Fig. 1. Division and characteristics of grinding process

In the present work, the object of research is machining quality of the creep-feed grinding process. Since the main task of the creep-feed grinding is to achieve the required machining quality with as large productivity as possible, special attention is directed on the effect that machining conditions have on the change of the surface integrity. If the cutting conditions are poorly chosen, the overall effect can substantially diminish exploitation features of the grinding process. Therefore, in order to enable machining of the parts with a high surface quality, it is necessary to investigate the effect of the creep-feed grinding on the workpiece surface integrity.

## 2. CREEP-FEED GRINDING PROCESS

Creep-feed grinding has been used for over fifty years. The creep-feed grinding is a highly productive and accurate process of machining complex shapes and forms in a wide variety of challenging materials. Compared to a conventional process, the creep-feed grinding allows lighter passes and shorter cycle time. At the same time, the creep-feed grinding is characterized by a lower wheel wear and good surface roughness [16]. However, a prolonged time of contact between the wheel/workpiece, results in the generation of more intense heat release on the workpiece material surface layer.

### 2.1 Mechanism of creep-feed grinding

The creep-feed grinding process differs from the conventional multi-pass grinding. In creep-feed grinding, very low (creep) feed rate and extremely large depth of cut is used, generally with a profiled wheel [17]. In this context, the cutting process in creep-feed grinding is achieved through a large number of abrasive particles that catch a very thick layer of the material that is inserted in the space between the abrasive and in the pores of the grinding wheel. When the abrasive particles come out of the workpiece material, chips leave the pores under the influence of centrifugal force and the agent for cooling, lubrication and flushing.

The creep-feed grinding process itself is defined by the kinematic and geometric parameters, Fig.2. Kinematic parameters are: wheel cutting speed  $v_s$  and workpiece feed rate  $v_w$ . The geometrical parameters are: wheel diameter  $D_s$ , depth of cut  $a$ , length of contact  $l_c$  and average chip thickness  $h_m$ .

The length of contact of surface grinding is distance that grain actively exceeds from the moment of contact with the workpiece until exit from a contact:

$$l_c = \sqrt{a \cdot D_s} \quad (1)$$

The average chip thickness is the approximate thickness cut with abrasive grains, and determined by:

$$h_m = \frac{a \cdot v_w}{v_s} = \frac{Q'}{v_s} \quad (2)$$

In the previous equation (2) it is observed that specific material removal rate:

$$Q' = a \cdot v_w \quad (3)$$

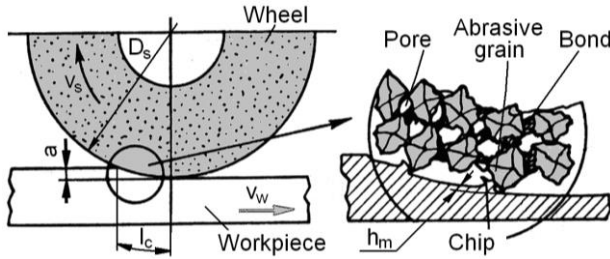


Fig. 2. Mechanism of creep-feed grinding

## 2.2 Surface integrity of creep-feed grinding

Surface integrity is presented with all of the parameters that define aspects existing on the surface and below the surface of the machined material. The surface integrity includes two important categories: surface topography (surface texture) and surface metallurgy (surface layer modification). The surface topography includes the physical geometry of the surface, respectively form, waviness and surface roughness. The surface metallurgy includes the properties of the material layer, respectively study of the nature of the local plastic

deformation, microstructure, microhardness, residual stress, crack, burn, etc [18].

Surface topography describes surface roughness and other features associated with the geometry of the surface. The degree of surface roughness is the most important characteristic. The surface roughness is represented by a large number of irregularities on the surface incurred during material remove [19]. The most common surface roughness parameter is the roughness average, also known as arithmetic average of the surface. In grinding process, surface roughness is dependent of the workpiece material, size and orientation of the abrasive particles, machining conditions, etc.

Surface metallurgy is concerned primarily with the host of effects a machining process has on the subsurface altered material zone. The subsurface characteristics can be caused by mechanical, thermal or chemical energy, and affect the metallurgical and physical properties of the material. In grinding process, heat affected zone is the most important characteristic. The heat affected zone is an area of the base metal that has had property changes [20-22]. Fig.3 shows the creep-feed grinding process with the performance characteristics and the surface integrity.

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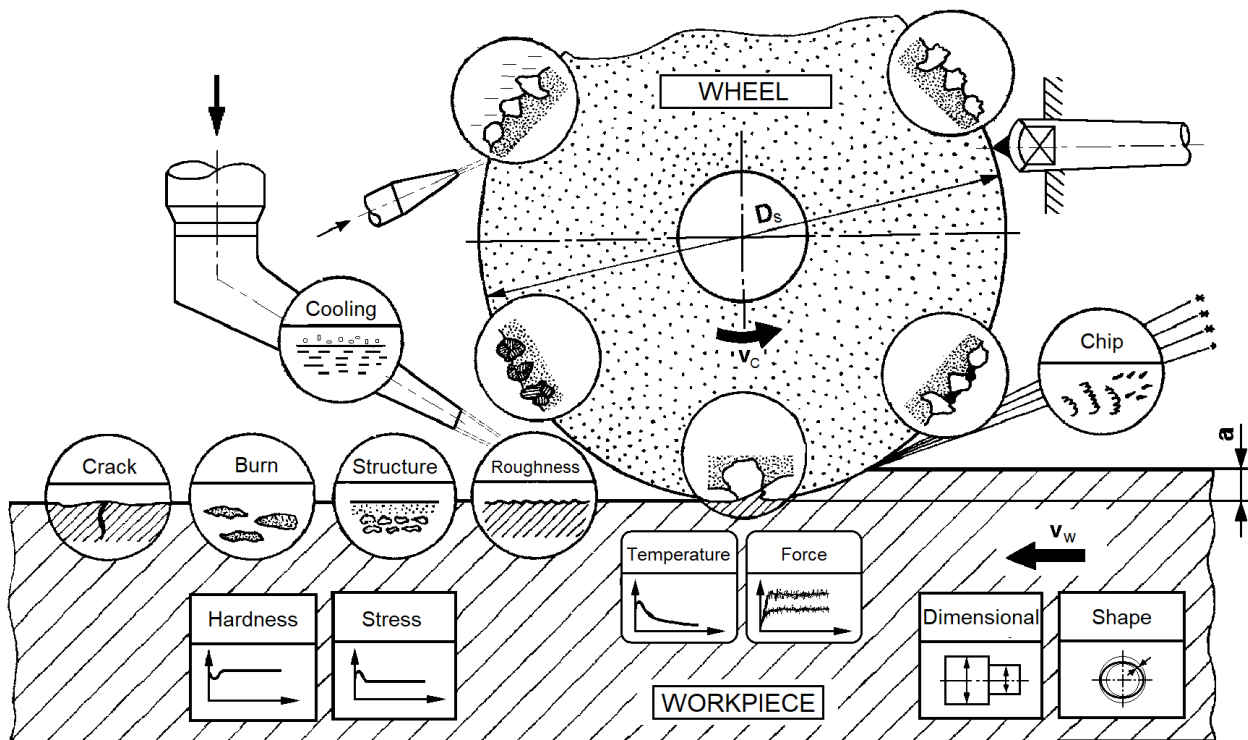


Fig. 3. Performance and surface integrity of creep-feed grinding process

### 3. EXPERIMENTAL PROCEDURES

The experimental investigations were conducted on the 3-axis creep-feed grinding machine type CF 412 CNC by a manufacturer Majevica from Republic of Serbia, Fig.4. Main technical data of the grinding machine are as follows: table area 400x1200 mm, workpiece height max. 500 mm, power 50 KW, wheel spindle speed 3000 rev/min, table speed 20-20000 mm/min, coolant flow 425 l/min. Water-based coolant (emulsion 6 %) was used during the creep-feed grinding test with a flow rate of 175 l/min.

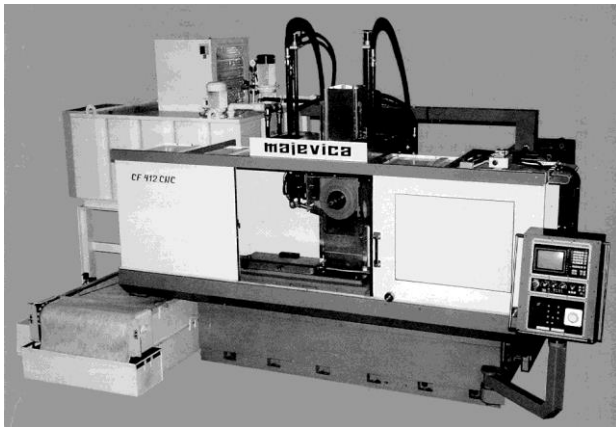


Fig. 4. CF 412 CNC creep-feed grinding machine

Based on the chosen material of the workpiece and the conditions of processing, the high porosity grinding wheels with the uniform characteristics were selected: Norton grinding wheel type 32A54 FV BEP, dimensions 400x80x127 mm, respectively Winterthur grinding wheel type 53A80 F15V PMF, dimensions 400x50x127 mm. The wheels are with high quality aluminium oxide abrasive grain, medium grain size, wheel hardness soft, open structure wheel, and made of ceramic binder. All of the experiments were conducted with sharp abrasive grains, and dressing is done with a diamond tool with a depth of dressing cut 0.01 mm and dressing feed rate 0.1 mm/rev.

Workpiece material used in the experimental setup was the high speed tool steel (HSS). Designation of the selected steel is DIN S 2-10-1-8 (W. Nr. 1.3247). This steel belongs to a group of highly-alloyed steel with a microstructure consisting of martensite and fine mixtures of primary and secondary carbides, Fig.5. The chemical composition of the test material was as follows: 1.08 % C; 0.22 % Si; 0.23 % Mn; 0.014 % P; 0.019 % S; 4.1 % Cr; 1.5 % W; 9 % Mo; 1.1 % V and 8 % Co. The surface hardness on all samples was

the range  $66 \pm 1$  HRC. Experimental specimens consisted of tiles whose dimensions were 40x20x16 mm.

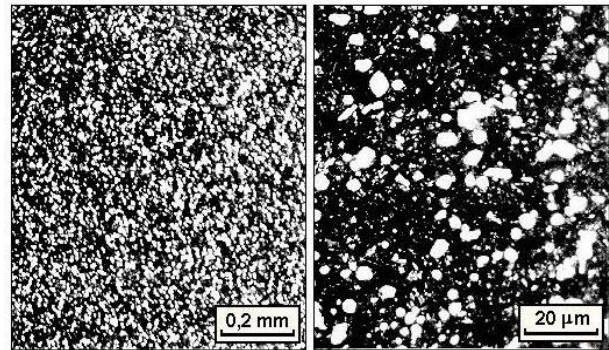


Fig. 5. Microstructure of workpiece material - HSS DIN 1.3247

The machining conditions are mean values of the depth of cut and the workpiece feed rate at a constant specific material removal rate  $Q' = 2.5 \text{ mm}^3/\text{mm s}$ . The range of the depth of cut was  $a = 0.05$  to 1 mm, while the workpiece feed rate was chosen from the interval  $v_w = 2.5$  to 50 mm/s. The grinding wheel cutting speed was constant at  $v_s = 30 \text{ m/s}$ .

Surface metallurgy of the machined specimens was assessed by investigation of surface layer properties of the high speed tool steel in the creep-feed grinding. In this testing were conducted: metallographic examination of the microstructure, measuring the microhardness, and exploring cracks and burns. The surface metallurgy identification of the workpiece material surface layer after grinding was performed with an optical microscope with 200x magnification by a manufacturer Leitz Aristomet from Germany, Fig. 6. Examinations were performed in a transverse section of the prepared samples.

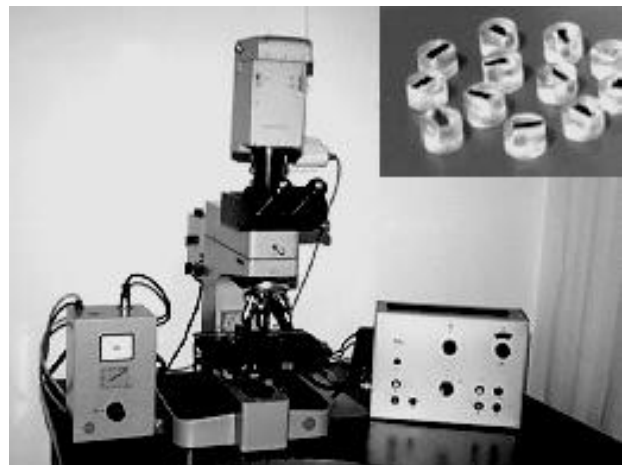


Fig. 6. Aristomet optical microscope with samples



Surface roughness of the workpiece in the creep-feed grinding process was estimated by measuring a set of surface parameters. The measured parameters were: arithmetic mean deviation of the assessed profile (Roughness Average  $R_a$ ), mean height value of five local maxima and five local minima (Mean Roughness Depth  $R_z$ ), maximum height of the profile (Maximum Roughness Depth  $R_{max}$ ) and description of the material portion in the roughness (Profile Bearing Length Ratio  $t_p$ ). These parameters are the most widely used in surface topography and defined in the specification standard ISO 4287/1. The surface roughness measurements were conducted using the profilometer Form Talysurf made by Taylor Hobson Ltd from UK, Fig.7.

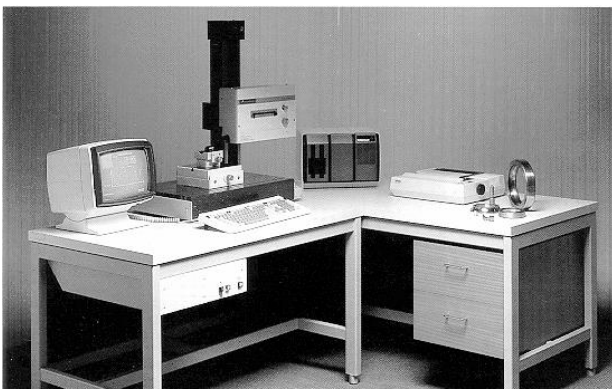


Fig. 7. Form Talysurf profilometer

#### 4. RESULTS AND ANALYSIS

It is evident that due to intensive friction between the grinding particles and the workpiece material, an enormous quantity of thermal energy develops in the creep-feed grinding. The increased

contribution of the direct-contact thermal energy significantly increases the temperature in the cutting zone. This high cutting temperature has a pronounced negative effect on the grinding wheel, workpiece surface and machine tool. If the temperature thus formed is high enough to cause structural and phase transformations of the workpiece material, the machined surface shall suffer from a number of disadvantages. Should, in addition, low surface roughness appear as well, the overall creep-feed grinding effect can substantially diminish the exploitation properties of the finished product.

##### 4.1 Surface metallurgy of HSS

In this study, the surface metallurgy, respectively the heat affected zone of the steel DIN S 2-10-1-8 was assessed by investigation of surface layer properties of the workpiece in the creep-feed grinding, with two grinding wheels.

It was first implemented the metallographic examination of the microstructure. Fig.8 and 9 show typical photomicrographs of surface layer of the investigated high speed tool steel by the grinding wheel type 32A54 FV BEP and 53A80 F15V PMF, respectively.

The metallographic examinations of the microstructure showed presence of the heat affected zone and recast layer in the creep-feed grinding. The recast layer of a surface machined was presented through uniform representation of the microstructure transformations compared to the bulk material.

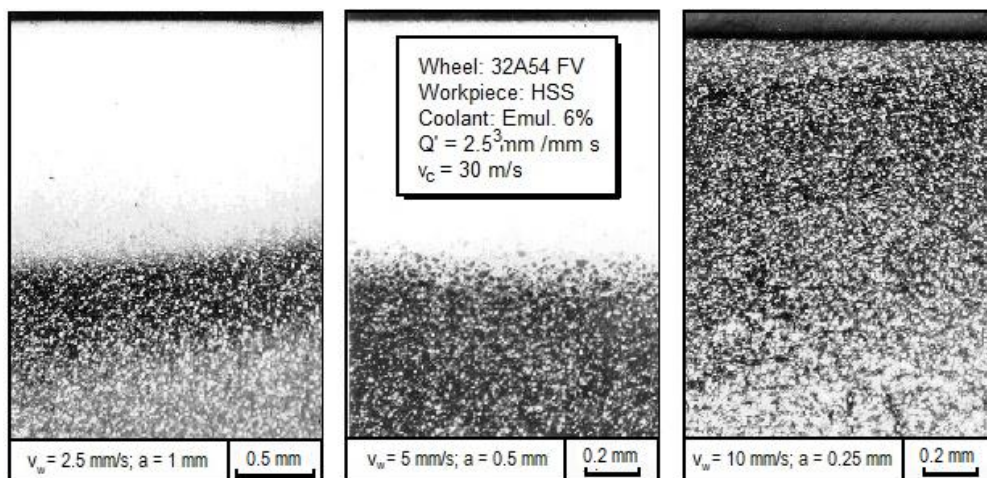


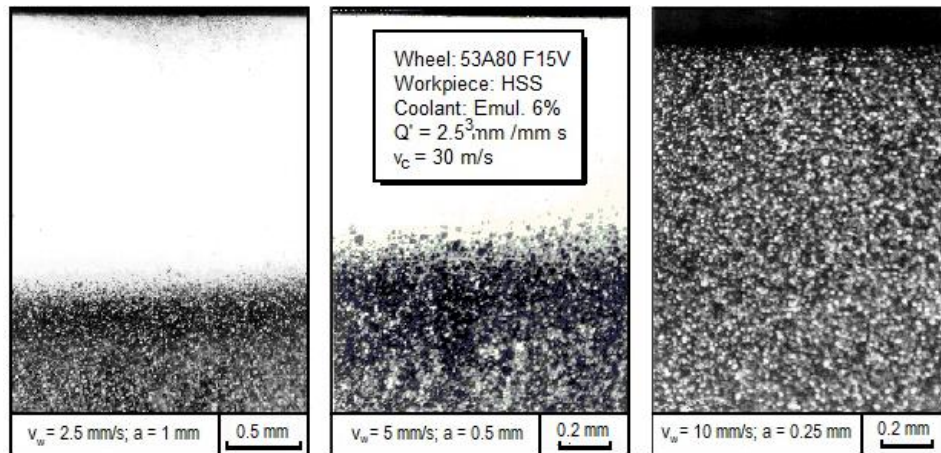
Fig. 8. Typical photomicrographs of surface layer of HSS steel machined with the wheel type 32A54 FV BEP

The analysis of the photomicrographs revealed four characteristic layers: surface hardened layer, interlayer, tempered layer and bulk material,

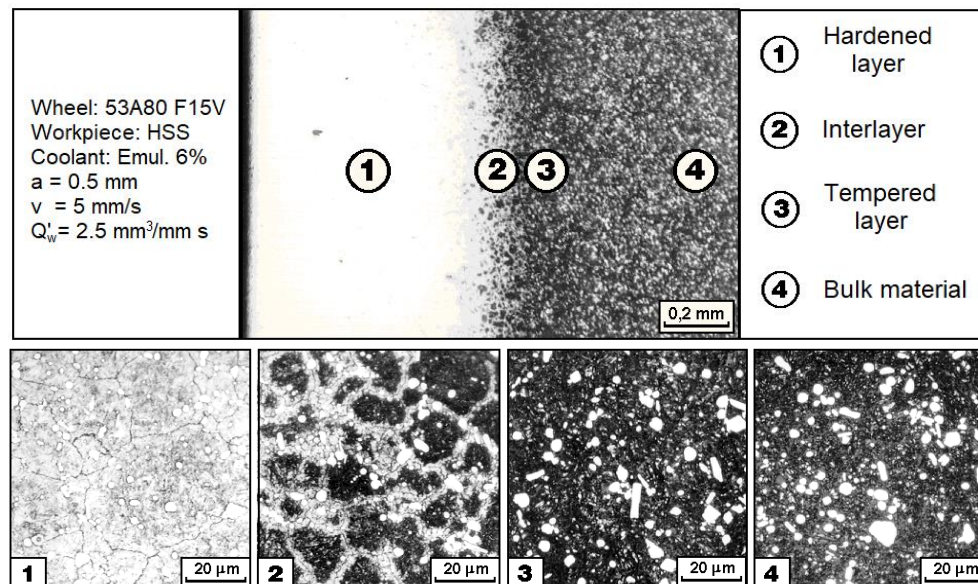
Fig.10. The secondary hardened layer consists of hardened martensite, residual austenite and carbides. The interlayer consists of martensitic-

austenitic structure and carbides, where the ratio of the austenite reduces in the direction to the tempered layer. The tempered layer is tempered

martensite and carbides, which gradually phase into bulk material consisting of martensite with fine carbides.



**Fig. 9.** Typical photomicrographs of surface layer of HSS steel machined with the wheel type 53A80 F15V PMF



**Fig. 10.** Microstructure of characteristic surface layer of high speed tool steel in creep-feed grinding

Table 1 shows thickness of the recast layer of the experimental specimens. The metallographic examination showed that thickness of the recast layer appeared in case when the temperature of the cutting zone was higher than the tempered temperature, which is 550 °C for the high speed tool steel. At the same time, if the cutting temperature does not exceed the transformation temperature which is 723 °C for the steel that was used in this test, only the tempered layer can be registered. In the opposite case, if the temperature goes beyond 723 °C, multiple layers are registered. In this context, on the basis of metallographic examinations it can be clearly concluded that in

creep-feed grinding extremely high cutting temperatures are developed.

Shown in Fig.11 is obtained dependence of the thickness of the recast layer (depth of heat affected zone) on machining conditions of high speed tool steel in creep-feed grinding, for a constant specific material removal rate. It can be seen that the value of the thickness of the recast layer is much higher when the depth of cut is the bigger, and the workpiece feed rate is the lower.

The microhardness measurement on the thickness of the recast layer was performed on a single specimen. Fig.12 shows the photomicrograph of the method of microhardness measurement of high speed tool steel in creep-feed grinding.

**Table 1.** Thickness of the recast layer of high speed tool steel in creep-feed grinding

Machining conditions			Specific material removal rate $Q'$ (mm <sup>3</sup> /mm s)	Thickness of the recast layer			
Depth of cut $a$ (mm)	Feed rate $v_w$ (mm/s)	Wheel speed $v_s$ (m/s)		Hardened layer (mm)	Interlayer (mm)	Tempered layer (mm)	Recast layer (mm)
Norton grinding wheel type 32A54 FV BEP							
0.05	50	30	2.5	Without a recast layer			
0.1	25			Without a recast layer			
0.25	10			-	-	0.2	0.2
0.5	5			0.7	0.15	0.3	1.15
1	2.5			1.2	0.6	0.8	2.6
Winterthur grinding wheel type 53A80 F15V PMF							
0.25	10	30	2.5	0.4	0.15	-	0.55
0.5	5			0.75	0.2	0.5	1.45
1	2.5			1.4	0.4	1	2.8

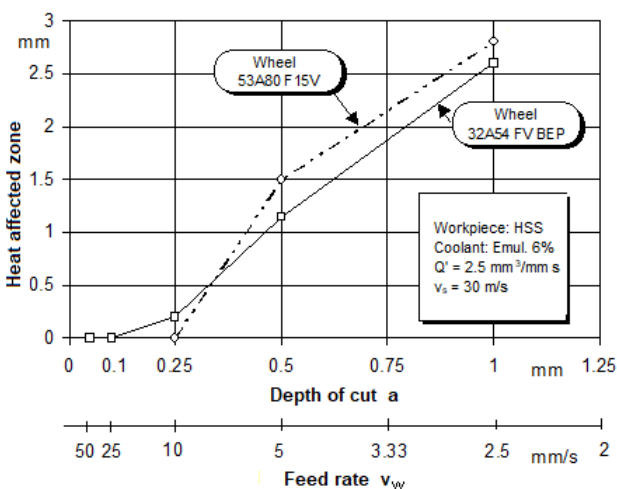
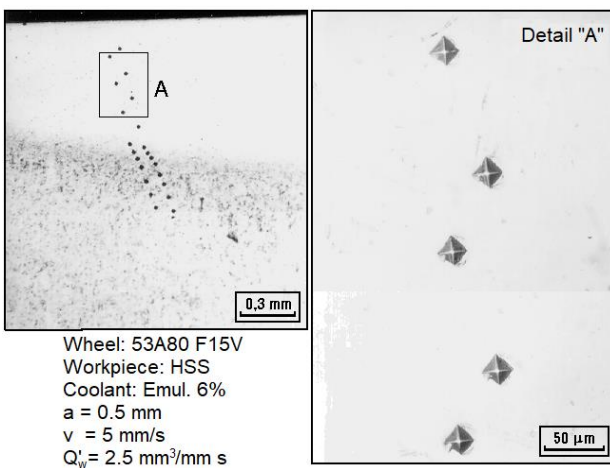
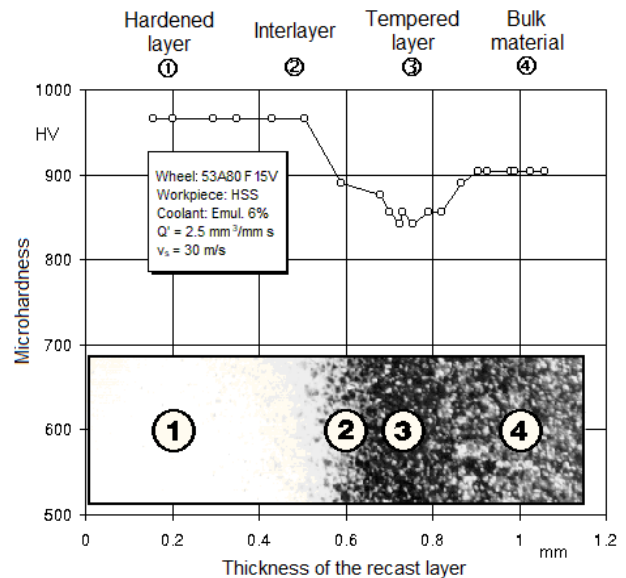
**Fig. 11.** Dependence of heat affected zone on the machining conditions of HSS steel in creep-feed grinding**Fig. 12.** Photomicrograph of microhardness measurement

Fig.13 shows the diagram of change of microhardness on thickness of the surface layer in creep-feed grinding.

The measured microhardness indicates that the hardness of the hardened layer (965.4 HV) is somewhat higher than the hardness of the bulk material (904.5 HV). The smallest measured value of the hardness is found in the tempered layer (842.3 HV) of the steel DIN S 2-10-1-8.

The higher hardness of the hardened layer was the result of the fine-grained austenitic-martensitic structure, while the lower hardness of the tempered layer occurred in the martensitic-austenitic phase transformation of high speed tool steel.

**Fig. 13.** Dependence of microhardness on depth of the surface layer in creep-feed grinding

During the further inspection of the workpiece material surface layer condition, not one specimen was found with cracks.

On the other hand, burns were noticed in all specimens where is present the heat affected zone and recast layer. Fig.14 and 15 show images of the



workpiece surface of the investigated high speed tool steel after the creep-feed grinding by wheel

type 32A54 FV BEP and 53A80 F15V PMF, respectively.

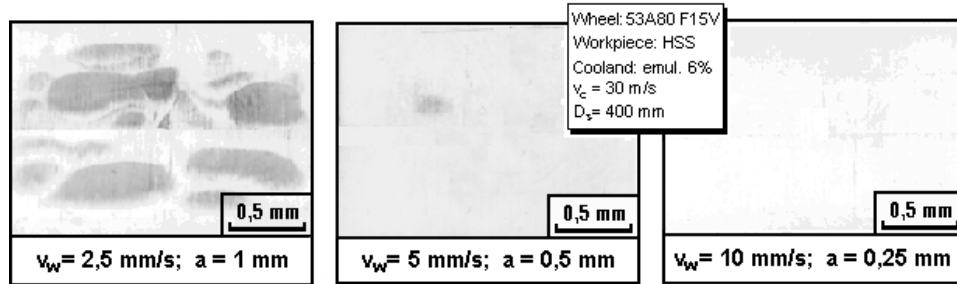


Fig. 14. Images of the workpiece surface of HSS steel machined with the wheel type 32A54 FV BEP

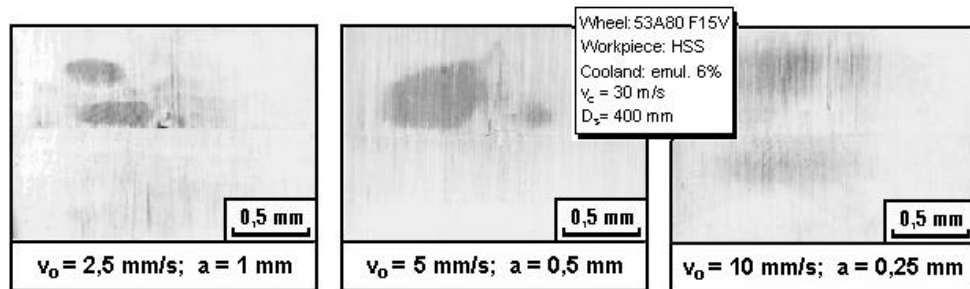


Fig. 15. Images of the workpiece surface of HSS steel machined with the wheel type 53A80 F15V PMF

#### 4.2 Surface roughness of HSS

The purpose of this study was to identify the influence of creep-feed grinding process on surface roughness. For that purpose, a set of surface roughness parameters under various machining conditions were determined for high speed tool steel by the grinding wheel type 32A54 FV BEP and 53A80 F15V PMF. The surface roughness was measured in multiple places on the machined surface of a workpiece.

In Fig.16 is shown experimentally obtained dependence of the surface roughness parameters (roughness average  $R_a$ , mean roughness depth  $R_z$ , maximum roughness depth  $R_{max}$  and profile bearing length ratio  $t_p$ ) on the depth of cut and feed rate for a constant specific material removal rate.

The increase of the surface roughness with increasing the depth of cut is present because of increased chip thickness and higher friction in the workpiece cutting zone. On the other hand, when the workpiece feed rate is increasing, due to the decrease of the contact time, the surface roughness is decreasing. The diagrams show that there exists an optimal specific material removal rate which results in minimum possible surface roughness. By all means, it is evident that creep-feed grinding process gives an excellent surface roughness.

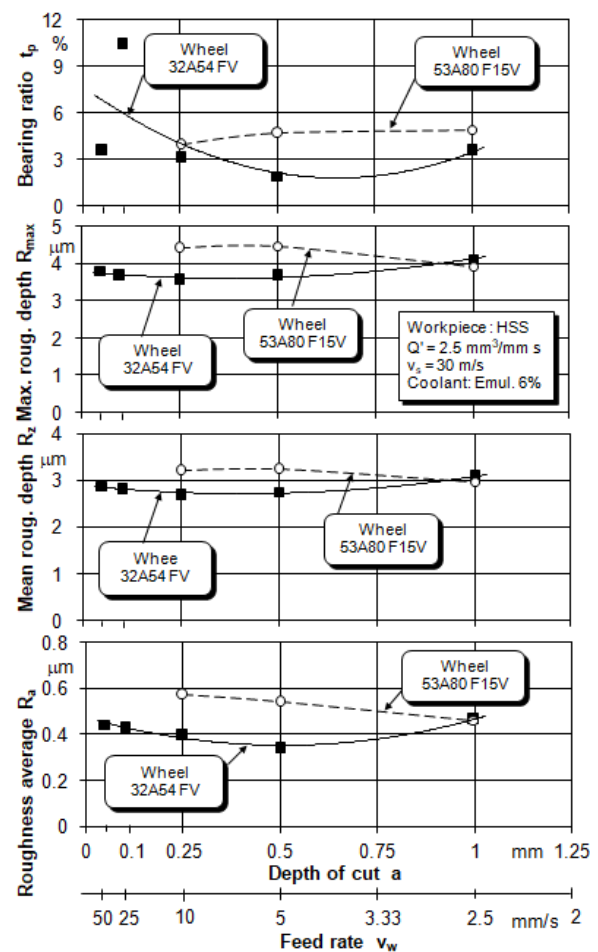


Fig. 16. Dependence of surface roughness parameters on machining conditions of HSS steel in creep-feed grinding for a constant specific material removal rate



## 5. CONCLUSIONS

With the rapidly growing trends in terms of productivity and surface quality, the high-performance grinding process is becoming an important segment of the manufacturing industry. The creep-feed grinding is an advanced abrasive process widely used in machining complex engineering products made from difficult-to-machine materials. However, the creep-feed grinding leads to a more intense development of thermal energy in the cutting zone, which is why special attention is focused on surface integrity.

The unwanted heat affected zone and recast layer in the workpiece material was detected in almost all cases the creep-feed grinding. Metallurgical changes were detected in all cases when the cutting temperature was higher than tempering temperature. Thickness of the recast layer is in direct proportion with the machining conditions. It can be seen that the recast layer is higher when the depth of cut is bigger, i.e. when the workpiece feed rate is lower. Compared to the microhardness of the bulk material, hardness of the hardened layer was slightly higher, while the hardness of the tempered layer was lower. As regards, the burns appeared in all cases when the heat affected zone is present. On the other hand, the cracks were not noticed.

Related to experimental study of the surface roughness, it follows that in the creep-feed grinding exists an optimal machining condition which results in very good surface. Increasing the depth of cut leads to a slight increase of surface roughness, while with decreasing the workpiece feed rate the surface roughness is increasing. Generally, the creep-feed grinding process impress that workpiece has a glossy surface topography.

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