

## SURFACE LAYER PROPERTIES OF LOW-ALLOY HIGH-SPEED STEEL AFTER GRINDING

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**Abstract:** Investigations of the surface layer characteristics of selected kinds of low-alloy high-speed steel after grinding were carried out. They were carried out on the flat-surface grinder with a 95A24K grinding wheel without cooling. The influence of grinding parameters was defined especially for: the quantity of secondary austenite, surface roughness, microhardness and grinding efficiency with a large range of grinding parameters: grinding depth 0.005–0.035 mm, lengthwise feed 2–6 m/min, without a cross-feed on the whole width of the sample. It was found that improvement of grinding properties of low-alloy high-speed steels is possible by efficient selection of their chemical composition. The value of the grinding efficiency is conditioned by grinding forces, whose value has an impact on the grinding temperature. To ensure high quality of the tool surface layer (i.e. a smaller amount of secondary austenite, lack of wheel burn and micro-cracks) in the case of sharpening of tools made of low-alloy high-speed steel, the grinding temperature should be as low as possible.

**Key words:** Grinding, High-Speed Steel, Microhardness, Secondary Austenite, Surface Roughness

### 1. INTRODUCTION

Grinding and sharpening are the final operations in the manufacturing of cutting tools. Under the influence of these operations, in the tool surface layer occur e.g. structural changes, surface stresses, plastic deformations and others (Jóźwik and Pietras, 2013). These phenomena determine the quality of the tools to a great extent, which mainly depends on the state of the surface layer (Jaworski and Trzepieciński, 2016b; Li and Axinte, 2016; Uhlmann et al., 2016). Grinding is an integral process composed of several simultaneous sub-processes, and chemical additives can affect these sub-processes. The past reports on the effect of physico-chemical parameters of the environment on mechanical properties and grindability of materials were reviewed by El-Shall (1984). The degree of the effect of grinding on the properties of high-speed steel depends on such factors as the abrasive, the workpiece, the type and parameters of grinding, coolant, etc. (Ding et al., 2015). For example, increasing the speed of grinding or lengthwise feed leads to grinding burns on the surface layer of the workpiece or tool made of steel with low grindability. The mathematical model relating the heat transfer between the grinding wheel, fluid, and the workpiece is presented by Gu et al. (2004). Coolant fluids have been used in grinding processes to reduce workpiece temperature and decrease the risk of thermal damage (Tawakoli et al., 2011). In addition, thanks to their lubricant properties fluids serve to enhance process performances (Torrance, 1978).

Many studies have shown that the formation of grinding burns denotes the formation of a clear layer having an austenitic-martensitic microstructure on the hardened steel surface, due to secondary hardening (El-Rakayby and Mills, 2013; Romano et al., 2006; Zhou et al., 2016). This shows that the temperature in the grinding zone exceeds the transition temperature  $Fe_{\alpha} - Fe_{\gamma}$ .

In grinding, the literature generally distinguishes two transient temperatures: a background temperature rise and a local temperature rise (Lefebvre et al., 2012). The background temperature results from the cumulative effect of all local heat sources on the ground surface. The background temperature damages the workpiece subsurface, whilst the temperature flashes and heat generated at the grain/workpiece interface increase the wear rate (Lefebvre et al., 2008; 2012). The grain–workpiece interactions at the local level and the wheel–workpiece interactions at the global level are studied by Hou and Komanduri (2004). The first attempt to correlate actual grinding temperatures with structural metallurgical changes in the workpiece was reported by Littman and Wulf (1955). The heat is primarily carried away to the machined part, because the cross-section and volume of the chip are very small, and the grinding wheel hardly conducts heat. Stresses are formed in the surface layer under the influence of heating and phase transformations. The magnitude of stresses may even exceed the allowable stress of the workpiece, which can lead to the formation of micro-cracks on the surface of the workpiece. Thermal damage is one of the main factors which affects workpiece quality, so it is especially important to understand the underlying factors which affect the grinding temperatures. The use of superabrasive grinding wheels is known to reduce the risk of thermal damage of the workpiece (Rowe et al., 1995). A comprehensive overview of thermal analyses for grinding processes and the effect of grinding temperatures on thermal damage is provided by Malkin and Guo (2007). The changes in the microstructure of the steel as a result of grinding depend on its chemical composition and parameters of the grinding (Abidi et al., 2013; Jaworski and Trzepieciński, 2016b). These changes can be divided into two categories:

- changes related to the establishment of microstructure of secondary hardening with tempering; and

– changes related to the establishment of microstructure with different degrees of tempering.

On the whole, in the surface layer, one changed zone of secondary hardening or secondary tempering, or several zones can be created i.e. secondary hardening, transient and secondary tempering (Bonek, 2014; Moravcik et al., 2012). During the secondary hardening, a clear outer surface layer consisting of a large amount of austenite, usually ~10–70%, is normally formed. Austenite is formed at high intense heat, is very stable, and hardly decomposes upon cooling. However, the decomposition of high-speed steels occurs from 400–450°C during the heating. Walton et al. (2006) found that the effect of the heating rate due to the grinding conditions have a significant influence on the A3 austenitic transition temperature. A review of early works concerned on hardening of alloy steel surfaces by grinding was done by Torrance (1978).

Because all of the mentioned changes in the surface layer when sharpening of tools directly affect the durability of the tools, they can be used to assess the grindability of high-speed steel. Steel grindability can be interpreted as a comprehensive parameter that allows one to characterise the ability of steel to provide the required properties of the surface layer under certain conditions (Urbaniak, 2006). For grindability assessment, a knowledge of the efficiency of the grinding process of a particular grade of steel is also important. The grindability strongly depends on the tendency of grinding wheels to blunt. Therefore, to determine the grindability, first we must examine all the physical processes that occur during the grinding. The characteristics of ground surface layer depend on the depth of microhardness variation, depth of occurrence of structural modifications in the surface layer, micro-cracks forming and surface roughness (Foeckerer et al., 2013; Jaworski and Trzepieciński, 2016a; Oliveira et al., 2009; Weiss et al., 2015; Zhang et al., 2015). The grindability of high speed steel in terms of specific grinding energy versus undeformed chip thickness and maximum temperature rise versus specific material removal rate is presented by Krajnik et al. (2011).

Wear and tear of cutting and grinding tools is one of the most important characteristics that define the accuracy of technological system of parts machining (Arsecularatne et al., 2006; Jaworski et al., 2014; Jaworski et al., 2016). Recognition of the machining properties and defining the tool operational reliability as one of the elements of that system is realised through the help of experimental data about wear and tear of a knife-edge, depending on machining time or path (Kulesza et al., 2012).

Here, the measurements of parameters of the surface layer and grinding efficiency of selected kinds of low-alloy high-speed steel were carried out. The aim of the investigations is to find the effect of grinding depth and lengthwise feed on such grinding parameters as the quantity of secondary austenite, surface roughness, microhardness, and grinding efficiency.

## 2. MATERIALS AND METHOD

The cubicoid samples have dimensions of 6 x 6 x 65 mm. The heat treatment was carried out according to the recommendation of suitable standards. The selected physical-mechanical properties of the tested steels are shown in Tab. 1.

The investigations were carried out on the flat-surface grinder with a disk-type grinding wheel 95A24K without cooling. The influence of the grinding parameters was defined especially for: quantity of secondary austenite, roughness of surface, microhard-

ness and coefficient of grinding with a large range of grinding parameters:  $v_c = 20$  m/s,  $a_p = 0.005$ – $0.035$  mm,  $v_f = 2$ – $6$  m/min, without cross-feed on the whole width of sample. After each study, the disk-type grinding wheel was dressed by diamond dresser. The temperature was measured using a half-artificial thermocouple according to methodology, which is known. The force was measured using a dynamometer, whereas the roughness of the surface was measured using Surtronic 3+ profilograph and the microhardness using the Brivisor KL2 microhardness tester on oblique cuts. The surface roughness is calculated by choosing cut-off length of 0.8 mm, according to the recommendation of ISO 3274:1998 and ISO 4288:1998 standards. The amount of secondary austenite both on the surface and in depth was determined using a Philips device.

## 3. RESULTS AND DISCUSSION

### 3.1. Microhardness

To increase the efficiency of sharpening by means of increasing its parameters, it is better to increase lengthwise feed than the grinding depth. The microhardness of the surface layer in relation to the grinding depth was measured on the skew-polished sections. The microhardness of HS3-1-1 steel has undergone considerable modification together with an increase of grinding depth (Fig. 1). The decrease of microhardness can be observed at  $a_p = 0.015$  mm and increase of microhardness at  $a_p = 0.025$ – $0.035$  mm. The decrease of hardness for HS6-5-2 steel is not observed at all cutting depths and decrease of hardness at  $a_p = 0.035$  mm is less substantial (Fig. 2). Results confirm higher propensity to structural modifications for HS3-1-1 steel during grinding. At the distance from the surface layer  $d_s = 0.02$  mm for both steels the change of microhardness value is not observed.

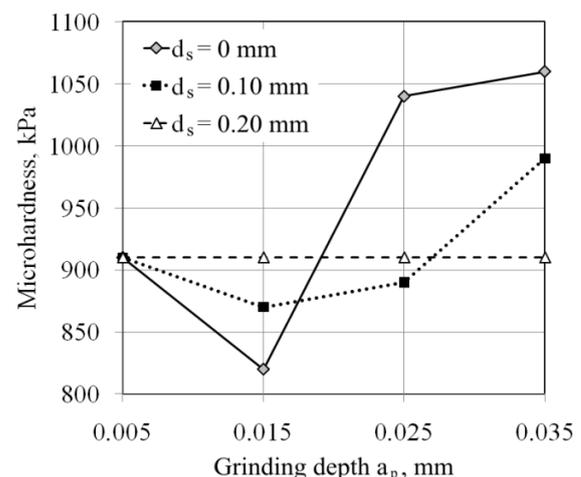


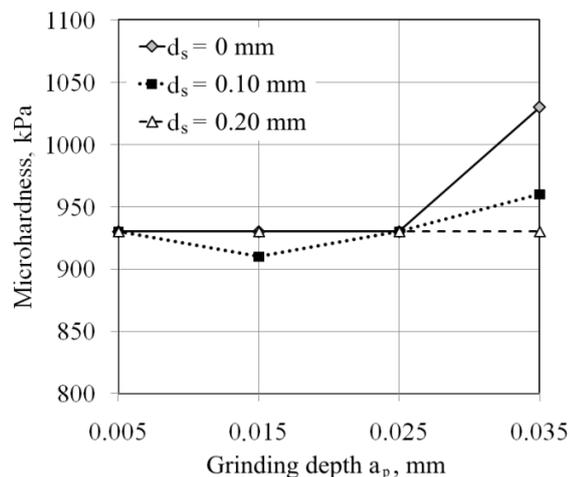
Fig. 1. Effect of grinding depth on microhardness of HS3-1-1 steel

### 3.2. Secondary austenite

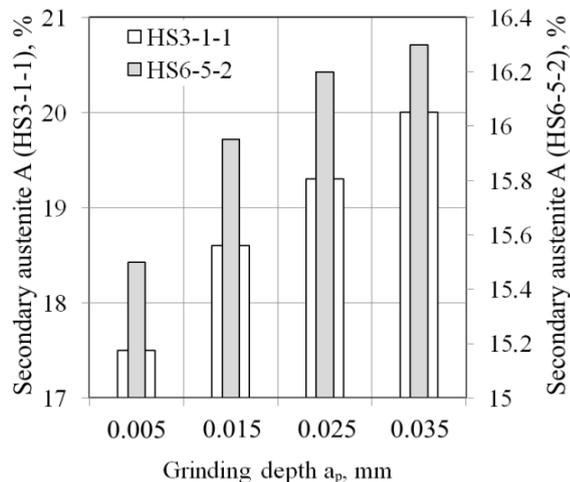
In many investigations (e.g., Bonek, 2014; Sinopalnikov and Grigoriew, 2003) the amount of secondary austenite is a main criterion in the evaluation of surface layer quality during tools sharpening.

**Tab. 1.** Low-alloy high-speed steel grades – chemical constitution and physical-mechanical properties

Steel grade	Chemical constitution in % wt.						Physical-mechanical properties			
	C	W	Mo	Cr	V	Si	Hardness HRC	Bending strength $R_g$ , MPa	Impact resistance, $J/m^2$	Hardening temperature, °C
HS3-3-3	1.00	2.98	2.83	4.27	2.30	-	64	3400÷3800	$3.2 \cdot 10^5 \div 4 \cdot 10^5$	1180÷1210
HS2-5-2	0.99	1.67	4.79	3.78	1.15	-	64	3000÷3400	$4 \cdot 10^5 \div 4.5 \cdot 10^5$	1080÷1170
HS3-1-1	1.11	3.35	1.15	4.65	1.75	2.05	63÷68	3000÷3600	$4.6 \cdot 10^5$	1080÷1170
HS6-5-2	0.82	5.55	5.13	4.27	2.06	-	64	3200÷3600	$4.8 \cdot 10^5$	1200÷1230

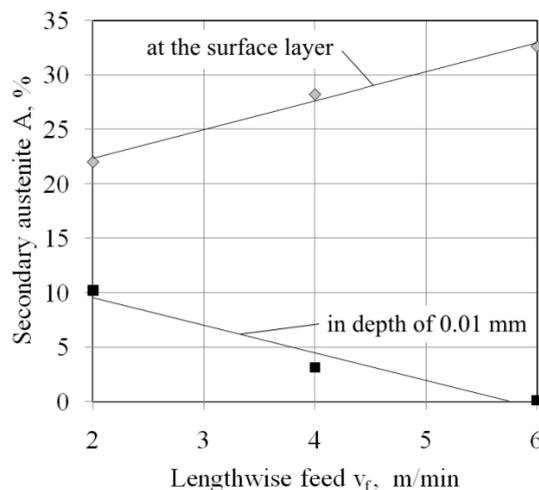

**Fig. 2.** Effect of grinding depth on microhardness of HS6-5-2 steel

The effect of grinding depth in a range of 0.005–0.035 mm on the amount of secondary austenite for HS3-1-1 and HS6-5-2 steels is presented in Fig. 3. The amount of secondary austenite for HS3-1-1 steel is larger than for HS6-5-2 steel and increases with increasing grinding depth.


**Fig. 3.** The influence of grinding depth on the amount of secondary austenite

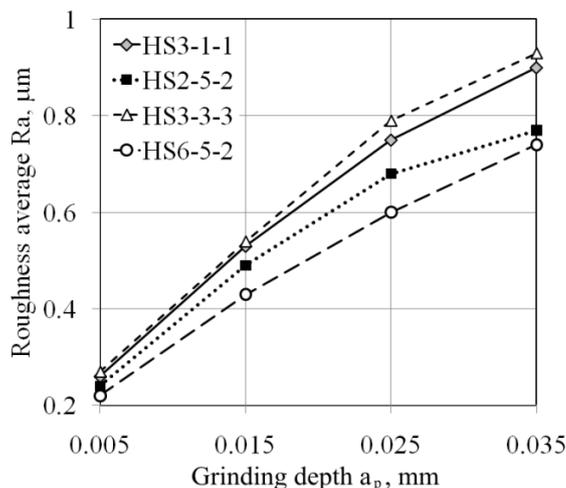
The influence of lengthwise feed on the amount of secondary austenite for both on the surface layer and at the depth of 0.01 mm is shown in Fig. 4. The amount of secondary austenite at the depth of 0.01 mm decreases with increasing lengthwise feed; however at a lengthwise feed  $v_f = 6$  m/min, the amount of austenite is almost imperceptible. With lengthwise feed increase, austen-

ite is located in more thin layers, which is proved by decreasing its content at a depth of 0.01 mm, although its amount is considerably higher on the surface layer (Fig. 4). The impact of grinding depth on the amount of austenite on the surface layer is presented more distinctly.


**Fig. 4.** The influence of lengthwise feed on the amount of secondary austenite for HS6-5-2 high-speed steel

### 3.3. Surface roughness

Results of the measurement of the  $R_a$  parameter are presented in Fig. 5 and Tab. 2. Substantial differences of surface finish for selected steel grades are not observed.


**Fig. 5.** Effect of grinding depth on the  $R_a$  parameter value

The value of Ra parameter increases together with an increase of grinding depth (Fig. 2) and lengthwise feed (Tab. 2), for all steels used. Furthermore, the quite linear relation between the roughness average Ra and the grinding depth is observed (Fig. 5). Differences in the surface finish do not have an impact on the machinability of tools.

**Tab. 2.** Effect of lengthwise feed  $v_f$  on the roughness of the average Ra value

Steel grade	$v_f$ , m/min	Ra, $\mu\text{m}$
HS3-1-1	4	0.67
	6	0.80
HS3-3-3	4	0.63
	6	0.77
HS6-5-2	4	0.71
	6	0.86
HS2-5-2	4	0.63
	6	0.74

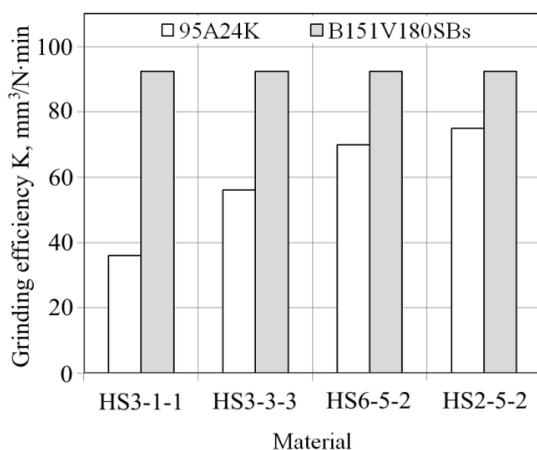
### 3.4. Grinding ratio

The value of grinding efficiency can be, to a certain degree, the characteristic of efficiency and quality of low-alloy high-speed steel grinding process. The value of this parameter is evaluated using (Jaworski, 2002):

$$K = Q_m/P_y \quad (1)$$

where:  $Q_m$  – the amount of material that is removed,  $P_y$  – inverted grinding force.

The values of grinding efficiency are shown in Fig. 6. Low-alloy high-speed steel has poorer grinding properties than HS6-5-2 steel, with the exception of HS2-5-2, where that ratio is slightly higher. Other investigations of the grinding efficiency value (Masłow, 1974) have shown that in the case of grinding of HS3-1-1 steel using a CBN grinding wheel, the grinding efficiency value is 2.5 times greater than in the case of grinding using a corundum grinding wheel. Furthermore, in the case of grinding using the corundum wheel, the value of the grinding efficiency is the same for each grade of low-alloy high-speed steel.



**Fig. 6.** The grinding efficiency for selected grades of low-alloy high-speed steels during grinding using corundum (B151V180SBs) and CBN (95A24K) wheels at  $v_c = 20$  m/s,  $v_f = 2$  m/min and  $a_p = 0.005$  mm

Because there is a direct relationship between the grinding temperature and the quality of the surface layer, to improve the grinding efficiency it is necessary to create the conditions allowing us to reduce cutting forces and the temperature in the surface layer of high-speed steel. This can be achieved by using cutting-tool lubricants (Brinksmeier, 1999). However, in industrial conditions, tool sharpening is usually carried out without the use of cutting-tool lubricants and therefore more efficient in this case is the use of cubic boron nitride (CBN) grinding wheels (Sallem and Hamdi, 2015).

## 4. CONCLUSIONS

We have shown that the characteristics of ground surface layer depend on the depth of microhardness variation, the depth of occurrence of structural modifications in the surface layer, and the amount of secondary austenite and process parameters. To ensure a lack of burn and micro-cracks during the sharpening of tools made of low-alloy high-speed steel, the grinding temperature should be maintained as low as possible. To achieve this aim, the following criteria must be met: use of a borazon abrasive disk, decreasing the sharpening parameters, or selection of optimal grinding fluids for the specific conditions. To increase the efficiency of sharpening by means of increasing its parameters, it is better to increase the lengthwise feed than the grinding depth.

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