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Microhardness and Surface Integrity in Turning Process of Duplex Stainless Steel (DSS) for Different Cutting Conditions

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Abstract The objective of the investigation was to identify microhardness of surface integrity (SI) after turning with wedges of coated sintered carbide. SI is important in determining corrosion resistance, and also in fatigue crack initiation. The investigation included microhardness analyses in dry and wet machining of duplex stainless steel. The microhardness of SI for various cutting speeds was compared. It has been shown that wet cutting leads to the decrease of SI hardening depth, while increasing the rounded cutting edge radius of the wedge increases the maximum microhardness values and the hardening depth. An infinite focus measurement machine has been used for the rounded cutting edge radius analysis. The study has been performed within a production facility during the production of electric motor parts and deep-well pumps as well as explosively cladded sheets.

Keywords coated inserts, duplex stainless steel, microhardness, rounded cutting edge radius, turning

Nomenclature

a_p	Depth of cut in mm
f	Feed rate in mm/rev
r_n	Rounded cutting edge radius in µm
$HV_{0.05}$	Vickers hardness scale for load 0.05 kgf
BUE	Built-up-edge
v_C	Cutting speed in m/min
DSS	Duplex stainless steel
SI	Surface integrity
IFM	Infinite focus measurement machine

1. Introduction

Duplex stainless steels (DSSs) are considered to be difficult to machine. Built-up-edge (BUE) and irregular wear are common challenges in machining operations (Ref 1). This degrades the surface finish of a machined product and results in reduced tool life. To utilize the useful properties of two-phase microstructure is necessary to study surface quality of machined stainless steels. According to Jang et al. (Ref 2), surface integrity (SI) is a measure of the quality of a machined surface and is interpreted as elements which describe the actual structure of both surface and subsurface. SI is generally defined by its mechanical, metallurgical, chemical, and topological states of surface properties. To ensure better SI, special attention must be paid when choosing cutting parameters (Ref 3, 4), tool material and geometry (Ref 5, 6), and tool coatings (Ref 7, 8). SI is important for the components' ability to adapt to high thermal and mechanical loads during their applications (Ref 9, 10). SI and surface microhardness are important in determining corrosion resistance, and also in fatigue crack initiation. The DSS is widely used for many industrial applications due to its unique properties. These are more important in the machining of expensive machine parts. Cabrera et al. (Ref 11) and Park et al. (Ref 12) considered that the good combination of their mechanical properties (high strength and toughness) and corrosion resistance makes them of great interest for a wide range of applications, especially in the oil, chemical, and power industries. Therefore it is very important to control their microstructure evolution, physical, and mechanical properties. According to Solomon and Solomon (Ref 13) in the case of materials with austenitic structure, plastic deformation can induce transformation of austenite structure into martensite structure. According to Kundrak et al. (Ref 14), turning performed at high speed is an intensive technology in terms of the heat generated in the process. The temperature of the workpiece material in the cutting edge area may reach the transformation temperature. Sasahara (Ref 15) demonstrated, using 0.45% C steel test material, that for tool corner radius of 0.2 and 0.8 mm, the hardness on the machined surface becomes higher with a smaller radius. In addition, the feed rate did not affect the surface hardness for values between 0.05 and 0.4 mm/rev. Ezugwu et al. (Ref 16) demonstrated that the cutting tool geometry in machining nickel-based alloys represents an important parameter in tool life and in the quality

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Table 1 **Chemical composition of 1.4462 duplex stainless steel**

Element	%C max	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	%N	Others
Wt%	0.021	0.54	0.77	0.028	0.02	22.65	5.70	3.28	0.19	…

Table 2 **Cutting tool specification**

Tool	Substrate	Coatings	Coating technique
MM 2025 Code: T1	Hardness: 1350 HV3 Grade: M25, P35	Ti(C,N)-(2 μm) (top layer) Al_2O_3-(1.5 μm) (middle layer) TiN-(2 μm) (bottom layer)	CVD
CTC 1135 Code: T2	Grade: M35, P35	TiN-(2 μm) (top layer) Ti(C,N)-(2 μm) Ti(N,B)-(2 μm) TiN-(2 μm) Ti(C,N)-(2 μm) Ti(C,N)-(2 μm) (bottom layer)	CVD

of the machined surface. Ezugwu and Tang (Ref 17) have found that a machined surface obtained with the rhomboid shaped insert has a higher microhardness as compared to the round inserts. Javidi et al. (Ref 18) showed that plastic deformation of the grain boundaries was found in the first 3-4 μm of the subsurface layer. They also confirmed that no significant variation in hardness was observed beneath the machined surface obtained by different cutting conditions. Ozturk and Altan (Ref 19) presented the effects of cutting edge radius on the cutting and thrust forces. They showed that cutting forces increase with increasing edge radius for CuZn30 workpiece material. Storch and Zawada-Tomkiewicz (Ref 20) showed distribution of unit forces on the tool nose rounding in turning process for C55 steel. But these publications did not mention problems related to the microhardness as physical parameters of SI.

This paper focuses on research problems related to the SI after turning by coated carbide tools. The main purpose of this study was to determine the effect of rounded cutting edge radius r_n as a key process factor in controlling surface microhardness. The aim of this study was also to determine the DSS microhardness in machining process for various cutting conditions.

2. Experimental Techniques

2.1 Workpiece and Cutting Tool Materials

The machined material was 1.4462 (DIN EN 10088-1) steel with a ferritic-austenitic structure containing about 50% austenite. The ultimate tensile strength was UTS = 700 MPa, and Brinell hardness was 293 HB. The elemental composition of the machined material and technical details of the cutting tools is given in Tables 1 and 2, respectively. Cutting tool inserts of TNMG 160408 designation clamped in the tool shank of ISO-MTGNL 2020-16 type were employed. Based on the industry recommendations and conclusions from the earlier investigations (Ref 4, 5), a range of cutting parameters were selected, T1: $v_C = 50 \div 150$ m/min, $f = 0.3$ mm/rev, $a_p = 2$ mm. The experiments performed with the tool point T2 were comparative studies and that is why the cutting parameters were: $v_C = 100$, $f = 0.3$ mm/rev, $a_p = 2$ mm. The study was conducted within a production facility. The research program was carried out on a lathe CNC 400 CNC Famot Famot—Pleszew plc. The cooling and lubricating fluid used was a coolant compatible with water, with no chlorine content, based on Blasocut 4000CF mineral oils, a universal emulsion for medium hard machining of steel. The examination of the cutting tools was performed after a time of cutting corresponding to 30% of the tool life period.

The microhardness measurements were effected by Micro indentor Vickers Paar MHT-4, with 50 g of load, during 10 s for all the measurements. The Fig. 1 shows how the pieces were separated from the initial specimen to the microhardness measurements and microstructure analysis (from bar material to microhardness sample). After the cutting made in a cut-off machine with abundant abrasive disc and water fluid, the samples were prepared using standard metallographic techniques. The surface of the metallographic specimens was prepared by grinding, polishing, and etching.

The two-phase ferritic-austenitic structure of duplex steel determines the necessity of hardness measurements in the micro scale. The measurements of microhardness have been performed into the depth of material along a straight line perpendicular to the machined surface (radially). In the testing schedule, it was assumed that microhardness would be measured down to the depth for which hardness comparable to that of the core is obtained. At each measurement depth, hardness of ferrite and austenite were examined. The first point of microhardness measurement was located at the distance of up to 10 μm from the machined surface, depending on the profile hump or caving (Fig. 2). The second measurement was performed at the depth of 25 μm, the successive ones were performed at 50 μm intervals until the hardness of the core was obtained.

2.2 Cutting Tool Point Measurement

Cutting tool point measurement performed using infinite focus measurement machine (IFM). IFM is an optical 3D measurement device which allows the acquisition of datasets at a high depth of focus. The IFM 3.2 software version was used for the measurements.

Experimental studies were carried out using T1 and T2 tools with different configurations of the rake face. The real stereometry of used inserts determined using IFM. The

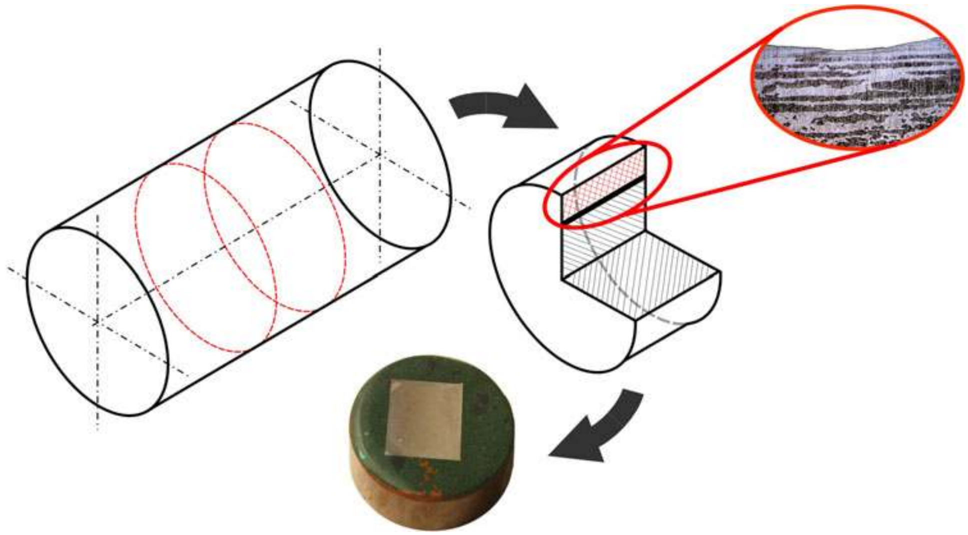

Fig. 1 Method of sample preparation for microhardness testing

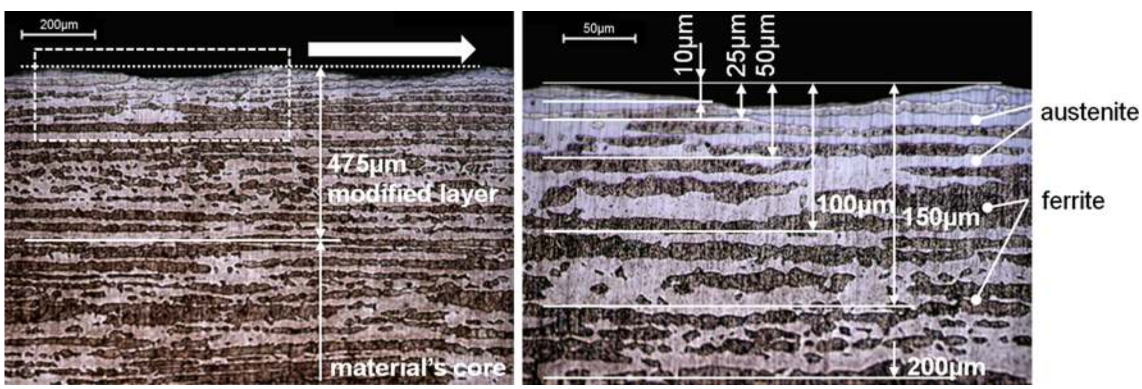

Fig. 2 Optical analysis of a specimen with an indication of levels of micro-hardness measurements (v_C = 100 m/min, f = 0.3 mm/rev, a_p = 2 mm, dry machining, tool code T1)

dimensioned cross-section of the tools created in the corner zone was presented on the Fig. 3. The T1 tool has a much smaller cutting edge radius (r_n = 0.047) in comparison to the tool T2 (r_n = 0.068). It can make the effect on the decohesion process of workpiece, and thereby impact on the changes the SI microhardness.

3. Results and Discussions

3.1 Cutting Speed Influence on the Surface Layer Microhardness

The characteristics of SI depend on many factors, among others, on the technological parameters, tool stereometry, and micro geometry, as well as the conditions of machining. In the process of constituting of that layer, cutting speed is an important factor. This parameter strongly influences intensity of heat generated in the cutting zone. It can be supposed that the heat penetrating into the surface layer of the material under machining will influence its functional parameters including microhardness. For this reason, the investigation is focused on the determination of the cutting speed influence on the microhardness of SI.

The influence of cutting speed on the microhardness of duplex steel surface layer can be seen in Fig. 4. Turning has been performed with the use of wedge T1 for constant parameters of the feed rate, f = 0.3 mm/rev, and cutting depth, a_p = 2 mm, for dry machining.

The values obtained have been presented separately for ferrite (a) and austenite (b). The technique of separate measurement of the two basic phases of duplex steel is rationally justified. Austenite, as compared to ferrite, is a stronger strain hardening phase. It could be expected, therefore, that austenite would have higher hardness due to strain hardening of the SI as a result of machining. It has been observed that SI microhardness decreases with the increase of the cutting speed. This is the case with both ferrite and austenite. Maximum microhardness values have been obtained for v_C = 50 m/min. They have been obtained in the layer closest to the machined surface, i.e., at the depth of up to 10 μm. In this case, for austenite, the microhardness was over 352 $HV_{0.05}$ and for ferrite 330 $HV_{0.05}$. For higher cutting speeds (v_C = 100 and 150 m/min), the microhardness obtained in that area was by 10% lower on the average. With the increase of the measurement depth, microhardness decreases and, in the case under analysis, reaches the hardness of the core at the

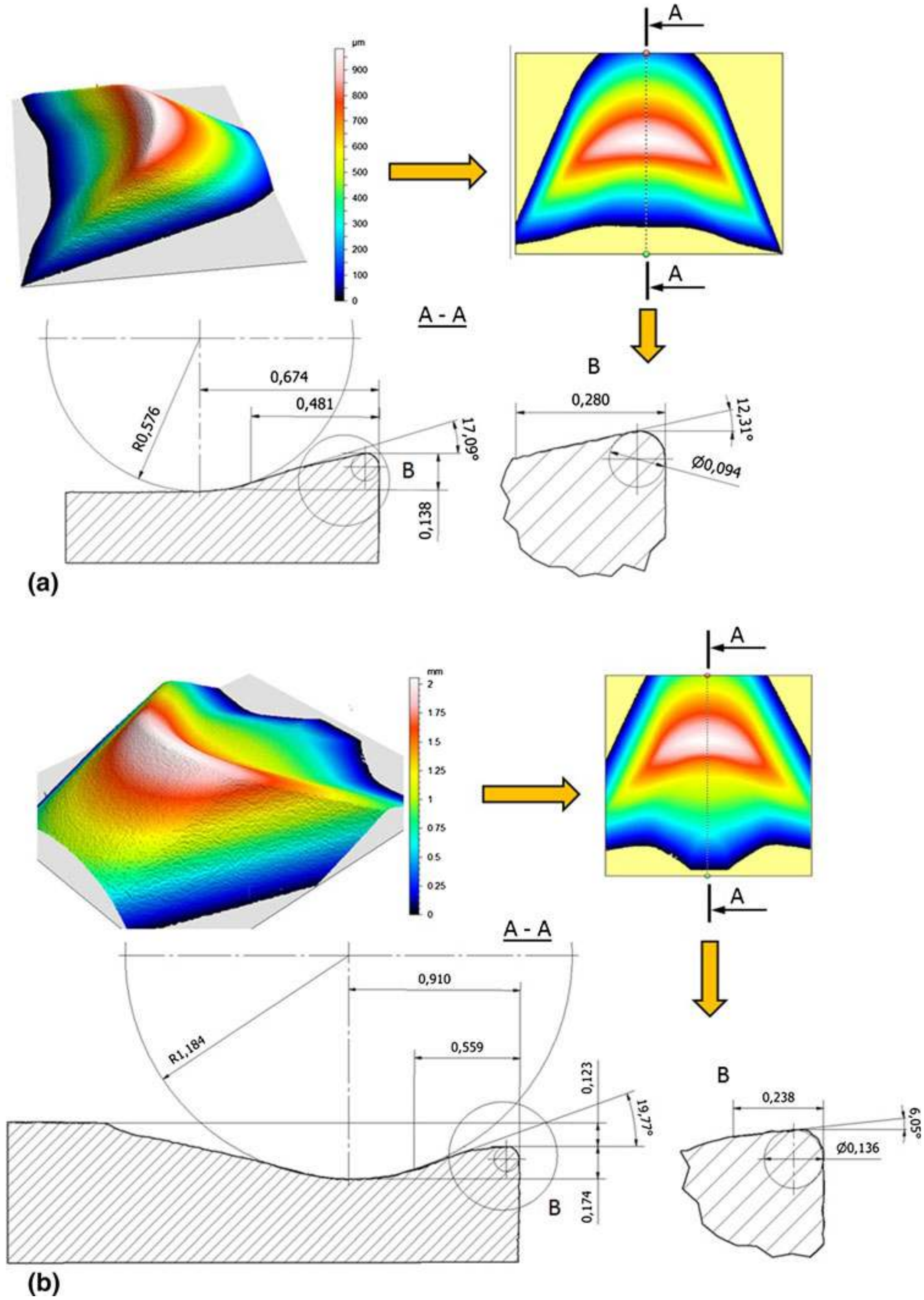

Fig. 3 IFM image of cutting wedge together with the dimensioned cross-section of the tool in the corner zone. Image for wedge T1 (a) and wedge T2 (b)

depth of about 400 μm (Fig. 4). The influence of cutting speed on the SI microhardness is clearly visible for its low values—v_C = 50 m/min. In that case, monotonic and slow drop of the $HV_{0.05}$ value with the cutting depth was observed for both examined phases of duplex steel (Fig. 4a). For higher v_C, the relationship is more disturbed. In addition, the measurement of austenite microhardness was characterized by more change fluctuations (Fig. 4b). The reason for it cannot be homogenous deformation of the material and, consequently, strain hardening of austenite.

Clear definition of the depth of hardness changes location as result of the cutting process is difficult in those diagrams. That is why mathematical interpolation of the measurement point pattern by polynomial curves of the fifth order has been suggested, which is shown in Fig. 5.

For a polynomial of fifth degree the coefficient of determination, denoted r^2, reaches values in the range of 0.87-0.99. It is known, that the coefficient of determination represents the percent of the data that is the closest to the line of best fit. If $r^2 = 1$, it results in a perfect fit. A very good fit was achieved. The exact values for each curve are given in Table 3.

In a common assessment of the hardness of austenitic and ferritic structure, it has been found that, regardless of the cutting speed, hardness comparable to that of the core has been

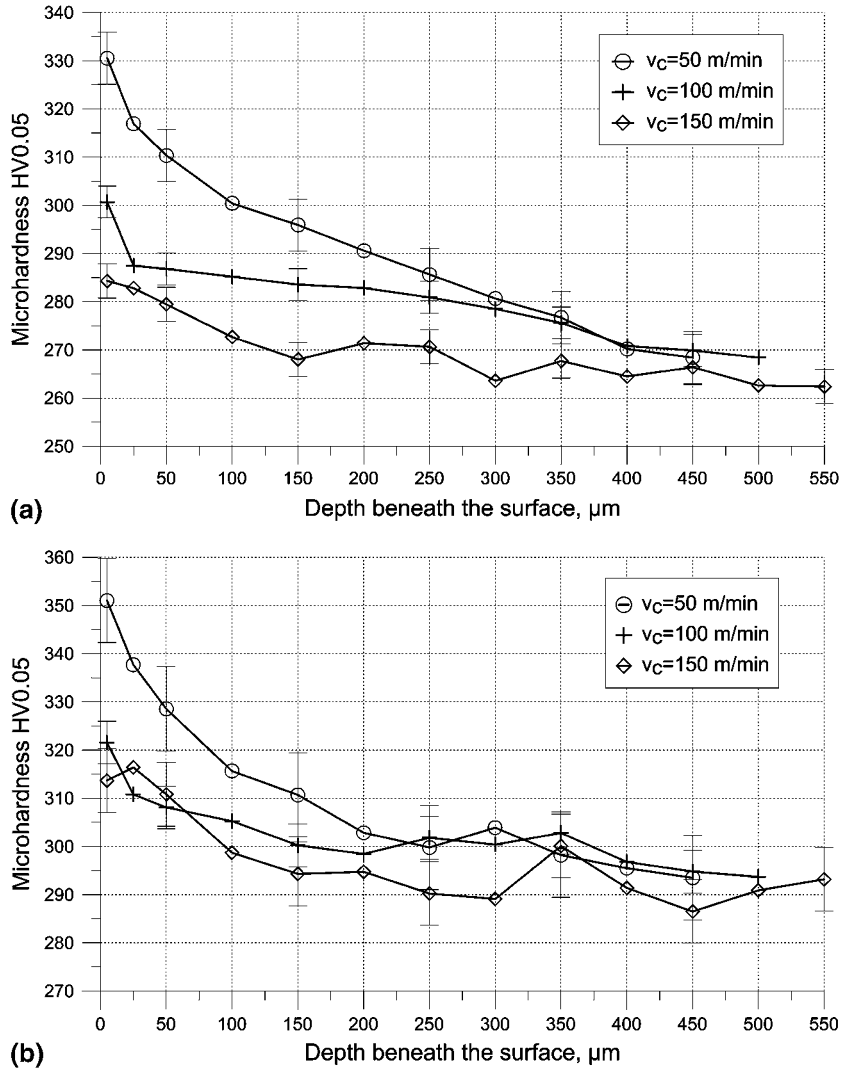

Fig. 4 Comparison of microhardness for different cutting speed vs. depth beneath the surface measured in ferritic (a) and austenitic (b) areas of duplex stainless steel (f = 0.3 mm/rev, a_p = 2 mm, dry machining, tool code T1)

obtained at the depth of about 475 μm. It has also been found that, for both structures and full range of cutting speed, the intensity of $HV_{0.05}$ decreases at the same depth from the machined surface. Furthermore, for the speed of v_C = 100 m/min the microhardness value in that area clearly stabilises at a level higher than that of the core hardness (Fig. 5—pointers A2 and F2). This can be an effect of cutting heat penetration into the material under machining, which has a significant influence on SI microhardness formation.

The influence of cooling on the hardness of SI when machined with the T1 wedge is shown in Fig. 6. The investigation has been performed with constant cutting speed, v_C = 100 m/min. Turning with various cutting conditions (dry and with cooling) has not influenced the microhardness of the surface layer. For both examined structures of duplex steel (Fig. 6), comparable $HV_{0.05}$ values have been obtained at the depth of up to 10 μm. The use of a cooling and lubricating fluid, however, clearly influences the depth of hardening. Dry machining, in which the intensity of heat generated in the cutting zone is much higher, is characterized by much thicker SI with a microhardness higher than that of the core. Figure 6 indicates that, in the case of wet machining, the hardness of the core has been obtained at the depth of only 150 μm; in dry machining it was as deep as 475 μm.

This phenomenon can also be explained by the change of friction conditions in the zone of chip-wedge contact. The application of a water-oil film reduces friction in the process of machining. Reduced friction will influence deformation of the machined layer, which is a major factor determining microhardness of the SI. It is confirmed by comparable hardness of the surface layer for both cases of machining conditions. The temperature in the zone of machining has not reached the value necessary to "toughening" the steel. In this case, the intensity of deformation determined the material hardening but, due to the friction conditions, the deformation energy did not propagate to such depth for the case of wet machining.

The influence of cooling on the microhardness of SI when machined with the T2 wedge for the determined machining conditions has been shown in Fig. 7. The tests were performed with the same values of the technological parameters as before (v_C = 100 m/min, f = 0.3 mm/rev, a_p = 2 mm) for dry and wet machining. The tool had the same stereometry as T1, but it had

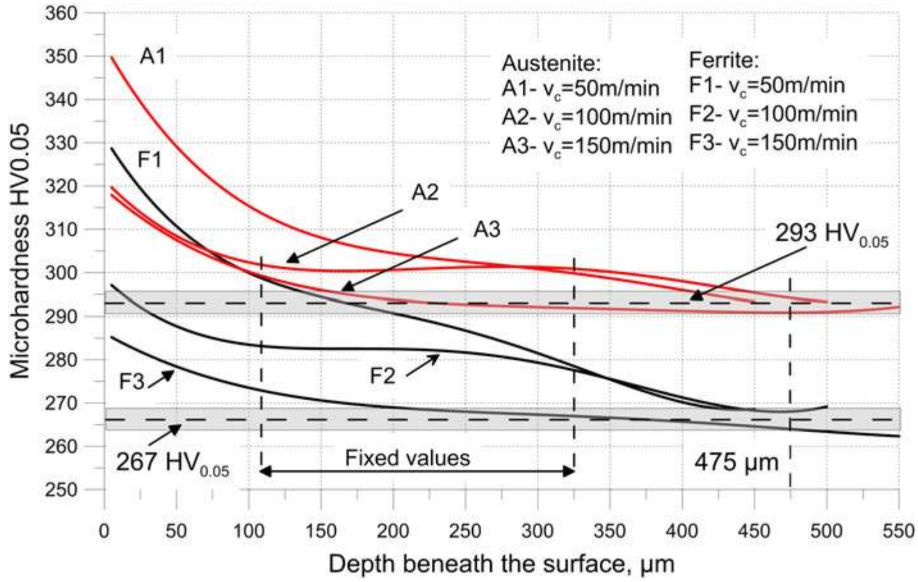

Fig. 5 Approximated functions of microhardness for various cutting speed vs. depth beneath the surface measured in ferritic and austenitic areas of duplex stainless steel (machining parameters see Fig. 4.)

Table 3 The correlation coefficient for polynomials of analyzed experimental data

		Tool code T1		Tool code T2	
Conditions	**Cutting speed, m/min**	**Austenite**	**Ferrite**	**Austenite**	**Ferrite**
Dry	50	0.99	0.99	0.99	0.99
	100	0.94	0.95	…	…
	150	0.87	0.93	…	…
Wet	100	0.99	0.96	0.99	0.99

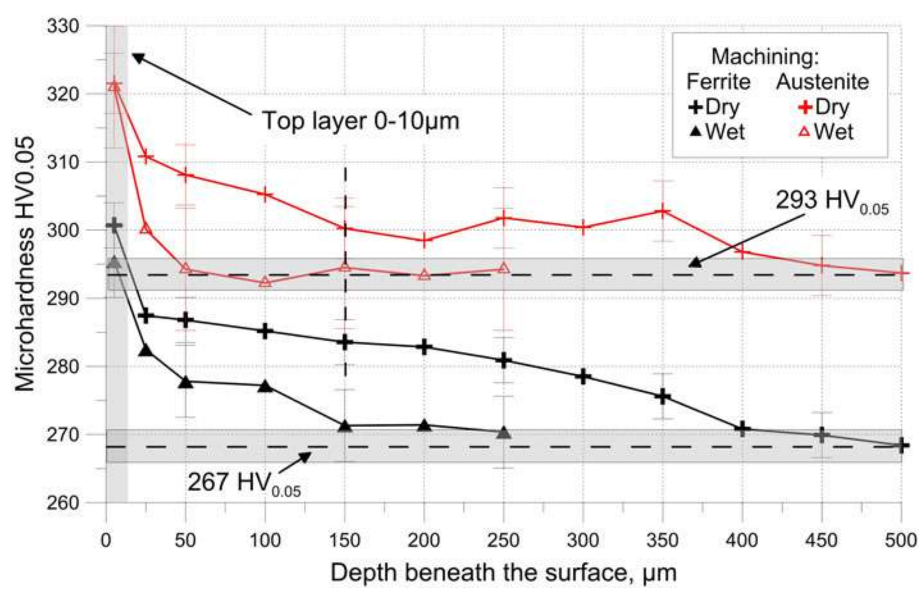

Fig. 6 Comparison of microhardness in ferritic and austenitic areas of duplex stainless steel vs. depth beneath the surface measured for dry and wet machining (v_C = 100 m/min, f = 0.3 mm/rev, a_p = 2 mm, tool code T1)

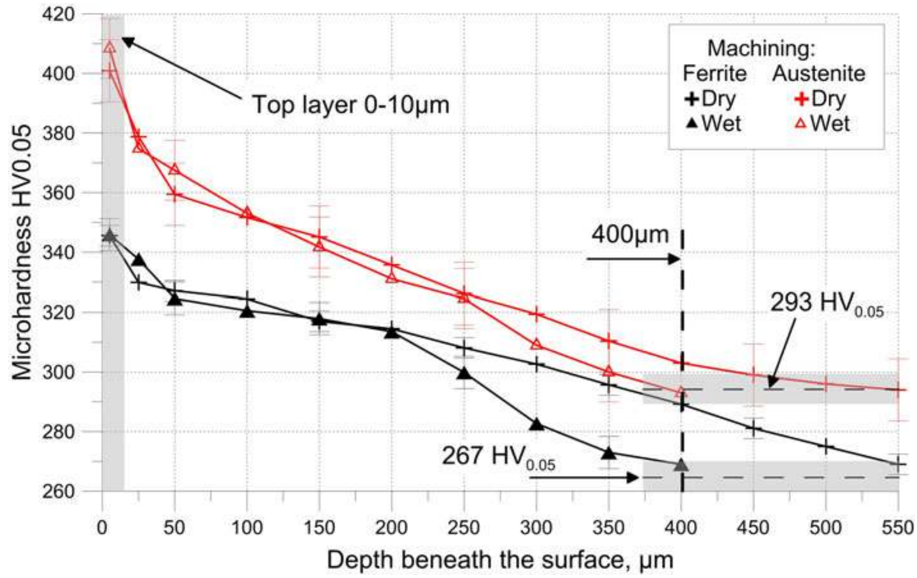

Fig. 7 Comparison of microhardness in ferritic and austenitic areas of duplex stainless steel vs. depth beneath the surface measured for dry and wet machining (v_C = 100 m/min, f = 0.3 mm/rev, a_p = 2 mm, tool code T2)

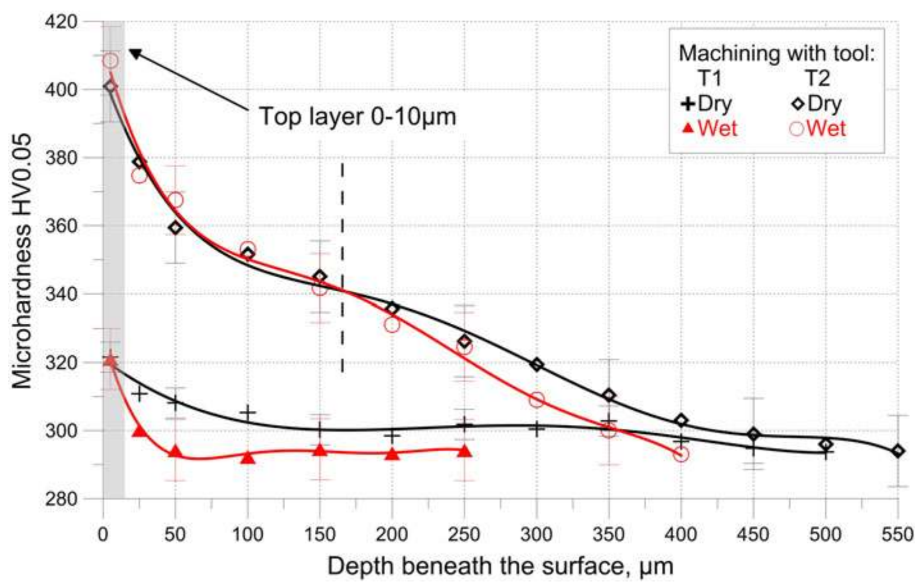

Fig. 8 Approximated functions of microhardness for different rounded cutting edge radius (tool T1 and T2) vs. depth beneath the surface measured in austenitic areas of duplex stainless steel (parameters of cutting see Fig. 7)

a multilayer coating with the thickness of about 12 µm and a structure presented in Table 1. The larger thickness of the coating (by almost 7 µm as compared to T1) has contributed to obtain a larger radius of the cutting edge rounding, r_n. For tool T1, r_n = 47 µm has been obtained; for T2, r_n = 68 µm. The rounded cutting edge radius, r_n, has a significant influence on the deformation characteristics in the chip formation zone. For larger radii, stronger forces are obtained during machining, as well as larger values of stresses in the machined layer, which influences the material microhardness in the SI. Dry and wet machining with the T2 wedge has not significantly influenced the SI hardening. However, it can be seen in Fig. 7 that, as in the case of T1, wet machining promotes the reduction of the hardened layer. In the case under analysis, the hardness of the core has been obtained at the depth of 400 µm. For wedge T1, it was only 150 µm. It seems that, in this case, of fundamental importance is the deformation intensity which is much greater for the wedge with the larger r_n.

Figure 8 presents the influence of the cutting edge rounding radius on the SI hardening. The analysis has been performed for austenite only. The curves plotted in the diagram are an approximation of measurement points of a polynomial of the fifth order. The accuracy of those curves fitting is in excess of r^2 = 0.94. Similar relationships have been obtained for ferrite too, but in that case the microhardness values were lower.

As expected, the HV0.05 values for the T2 wedge with r_n = 68 μm are much higher. The difference in the surface layer is in excess of 20%. The depth of the hardened layer location is also larger. It has been noticed that, for the case of dry machining, the thickness of the hardened layer for both tools is comparable (about 450 μm), however the intensity by which $HV_{0.05}$ changes is much less for the T1 wedge. In the case of wet turning, the cutting edge rounding radius significantly influences the depth of hardening. Probably, the influence of deformations arising in the process of forming the SI with a wedge of large r_n has a dominating character which could not be reduced by the application of cooling.

4. Conclusions

The results obtained in the present work allow us to draw the following conclusions:

I. Investigations of the influence of the technological parameters on the microhardness of the two-phase duplex steel require separate measurements of $HV_{0.05}$ for the individual phases of the steel, i.e., austenite and ferrite.
II. Increase of the cutting speed in the process of turning DSS decreases the maximum values of the SI microhardness for ferrite and austenite by about 10% and increases the depth of hardening by about 22%.
III. The use of cooling-lubricant substances reduces the depth of SI hardening by an average of 40%, depending on the wedges with various r_n.
IV. The depth of the SI hardening after turning duplex steel with coated sintered carbide wedges for the examined range of technological parameters reaches 550 μm.
V. Increasing the cutting edge radius, r_n, of the cutting wedge increases the maximum microhardness values of the individual phases of the steel and increases the depth of the SI hardening of the steel.
VI. No significant influence of cooling on the changes of surface layer hardness has been found for the tested wedges with various rounded cutting edge radius.

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