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PRODUCTION PROCESS

Residual stresses in surface layer after dry and MQL turning of AISI 316L steel

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Abstract Residual stresses in the surface layer exert a significant impact on functional aspects of machined parts. Their type and value depend on the workpiece and tool material properties, cutting parameters and cooling and lubrication conditions in the tool-chip-machined surface interface. As the effects of material properties and cutting parameters have been widely studied, the influence of cooling and lubrication conditions, especially minimum quantity lubrication (MQL) on the surface layer residual stresses and the relationships between them have not been investigated. In this paper the effects of dry, MQL cutting and cutting with emulsion conditions together with cutting parameters on residual stresses after turning AISI 316L steel were investigated. X-ray diffraction method was used for measuring superficial residual stresses in the cutting (hoop) and feed (axial) directions. Tensile residual stresses were detected in both directions and the values in the cutting direction turned out to be higher than in the feed direction. The effects of cooling and lubrication conditions largely depend on the selected cutting parameters, whose influence is linked to the cutting zone cooling and lubrication mode. Elaborated regression functions allow calculation and optimization of residual stresses in turning AISI 316L steel, depending on cooling and lubrication conditions as well as cutting parameters.

Keywords Residual stresses · Surface layer · MQL · Dry turning

1 Introduction

Residual stresses in the surface layer determine many application related characteristics of a machined part. Their type and value depend on the work piece material and tool properties, cutting parameters as well as on the cooling and lubrication conditions in the tool-chip-machined surface interface. Replacing the traditional method of cooling and lubrication of the cutting zone with emulsion with dry and MQL cutting significantly changes the prevailing cutting conditions in the chip and machined surface formation zone. An increase in the heat energy transferred into a machined component which affects the surface layer tensile residual stresses is particularly important. The residual stress in the surface layer originates from two sources: the interactions between factors characteristic of the employed technological process and the stress present in the part before the actual machining starts. The level of stresses in the surface layer results from complex phenomena of the following processes: mechanical—leading to inhomogeneous plastic deformation, thermal—causing thermal plastic flow, and physical—leading to phase transformations and specific volume variation. The experimental results indicate that residual stresses in the surface layer are mostly a consequence of complex interactions of the mechanical and thermal effects leading to inhomogeneous plastic deformation associated with the process of chip formation and an interaction between the tool and the freshly machined surface [1–8].

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The type of residual stresses and their level deeply depend on the mechanical properties of the machined material. With an increase of mechanical properties (material hardness, tensile strength, strain rate dependency, thermal conductivity, mechanics of plastification), the level of residual stresses also increases [6, 7, 9, 10]. High mechanical properties and severe work hardening of austenitic stainless steels during the chip formation process, combined with low thermal conductivity generate high cutting forces along with high localized interfacial temperatures and adhesion in the cutting zone which are the main reasons for high level tensile residual stresses both in the hoop and feed direction [5, 10–14].

It has been generally accepted that for a given material as well as cooling and lubrication method of the cutting zone the nature of the residual stress distribution in the surface layer depends on the cutting parameters [2, 7, 11]. With an increase of the cutting speed, the magnitude of all the stress components also increases [10–12, 15]. Experiments [11, 15] showed that higher cutting speeds in dry turning of austenitic stainless steels AISI 304 and 316L cause higher tensile superficial stresses in the hoop and axial direction. The great influence of the cutting speed on the thermal effects and its variation in making large differences in the residual stresses generated in the machined surface was confirmed by [7]. However, in wet turning with an increase in the cutting speed the residual stress values can change from compressive to tensile because as the cutting speed increases machining process becomes more adiabatic [16]. The influence of the feed rate on their type and value is not conclusive. An increase in tensile residual stresses alongside a higher feed rate has been showed in papers [3, 6, 12, 17]. An analysis of residual superficial stresses in the axial direction after dry turning has demonstrated that an increased feed rate leads to an increase in residual stresses and may also cause them to change from tensile to compressive [6]. On the other hand, it has been found that in dry turning of AISI 316L steel the surface residual stresses barely vary as the feed rate increases [11], or its influence on surface residual stresses in turning stainless steel depends on other cutting parameter values, which can cause their values to increase or decrease and its effect should be analyzed in combination with all parameters and not just one [7]. A large influence of depth of cut in turning stainless steel on the tensile residual stresses both in the primary and feed motion direction was demonstrated in [6, 13–15], however the research performed by [7] did not show any unique correlation between the depth of cut and residual stresses.

Apart from cutting parameters also the tool point geometry exerts a significant influence on residual stresses in the surface layer. An important element of its geometry, which determines the level of residual stresses, is the effective rake angle. An increase of this angle value from 0° to 5° in dry turning of AISI 316L steel caused a decrease in the tensile stresses both on the surface and inside the surface layer [15, 18]. On the other hand, an increase of the negative rake angle leads to greater compressive stresses, which are an effect of the mechanical stress factor [15]. The experiments performed by [15] and [19] have shown that the surface residual stresses in the hoop and axial direction become higher as the tool edge radius r_n or edge hone increase. The tool nose radius r_ε and the tool cutting edge angle κ_r have a similar influence on the residual stresses [6, 20]. The tool nose radius affects significantly impact on the surface residual stresses both in dry and traditional cooling with liquid [21]. However, its influence in the initial phase of the cutting process becomes less pronounced as the tool wears out [22, 23].

The interactions of the above mentioned factors which are responsible for generating residual stresses largely depend on the cutting environment, including the cooling and lubrication mode of the cutting zone [10, 16, 21]. The advantageous effects of emulsion on the tribological phenomena in turning stainless steel and the improved lubrication in the tool—work piece interface was showed in [7]. The use of coolant reduces friction and increases heat removal from the surface, resulting in the dominance of mechanical effects, which cause compressive stresses. According to [10], an application of cooling liquids in turning at low cutting speeds reduces the maximum of superficial residual stresses compared to dry cutting. At high cutting speeds, its influence on residual stresses is negligible. Eliminating emulsion leads to an increase in the values of tensile stresses, reduction of compressive stresses as well as a lower dispersion of values as compared to turning with emulsion [16, 21].

Although the problem of residual stresses in the surface and subsurface layer has been widely investigated, the research performed so far has showed that the effects of the cutting environment on residual stresses are still not fully recognized. Residual stresses in turning stainless steels were studied in a specific cooling and lubricating condition (mostly dry or wet) and for a limited range of cutting parameters. Investigations of the effects of MQL on residual stresses as well as comparative investigations of residual stresses generated in dry, MQL and wet turning conditions are still scarce. Therefore, considering the significance of residual stresses in machining, the paper presents a more comprehensive study, which examines the effects of MQL and dry cutting technique in relation to traditional cooling and lubrication by copious supply of emulsion. To allow evaluation and optimization of the effects of cutting conditions on hoop and axial components of residual stresses in turning AISI 316L steel, the correlations between residual stresses and cutting parameters for dry, MQL and with emulsion cutting conditions have been determined.

2 Experimental procedure

The turning tests were realized on bars (60 mm diameter by 300 mm length) austenitic stainless steel AISI 316L (annealed at 1,050 °C) using a rigid lathe TUD 50 with a 6.7 kW main drive. On each bar 15 mm long segments for each cutting test were produced (Fig. 1). The surface of each bar was pre-machined with 1 mm depth of cut with low cutting parameters in order to ensure a minimized and similar level of residual stresses and other surface properties for all the specimens. For each set of cutting conditions 3 parts were machined. Table 1 presents the chemical composition and mechanical properties of AISI 316L steel as well as the tool characteristics, and environment. Cutting parameters were selected in accordance with the insert producer's recommendations and machine tool kinematics. The inserts used in the experiments were recommended for machining of stainless austenitic or heat resistant steels. In order to minimize the effect of tool wear on the investigated features, each set of turning tests was conducted using a new edge.

The MQL technique was executed by a Minibooster II applicator (produced by Accu-Lube Manufacturing GmbH). The lubricant from the oil reservoir was transported by the pump at an air pressure of 0.6 MPa to the booster chamber where the aerosol was produced and transferred to the reservoir. From there, at a pressure of 0.35 MPa, it was supplied to the cutting edge through holes built inside the tool holder and two nozzles of 0.8 mm in diameter, targeting the rake face and principal and auxiliary flanks. As a lubrication medium an Accu-Lube LB 8000 biodegradable vegetable oil with kinematic viscosity of 37 mm^2/s at 40 °C was used. The oil consumption rate was set at 50 ml/h. In wet turning, 6 % emulsion was prepared on the basis of emulsifying oil ARTEsol Super EP, supplied to the cutting zone with 4 l/min flow volume. The emulsifying oil comprised up to 35 % of mineral oil and additives increasing lubricity in the quantity of 15 % and was recommended for cutting operations of steel, cast iron and nonferrous metals.

For the residual stress measurement specimens were cut off from the machined bar, and fixed in the specimen holder on a Seifert 4-axis X-ray diffractometer produced by Richard Seifert & Co (Fig. 1). The Cr-Kα radiation was used ($\lambda = 2.2897$ Å, 40 kV, 38 mA), together with a 2 mm pinhole collimator to limit the measurement area which was located in the center of the specimen's surface. The residual stress components in the hoop (along the primary motion) and axial (along the feed motion) directions in the surface layer were analyzed by the conventional $\sin^2\Psi$ method with Ψ being the angle between the normal to the sample surface and the direction of the stress component to be determined. By measuring the interplanar spacing d of a specific crystallographic plane as a function of Ψ, the stress component can be derived from the slope of the d-$\sin^2\Psi$ plot with the help of a so-called X-ray elastic constant (XEC). A more detailed description of the measurement method can be found in handbooks of diffraction analysis of residual stresses, e.g. [24]. In the current work, the stress analysis was made on the austenite γFe-220 planes. Diffraction peaks from 13 sample directions spread between $\Psi = -55°$ and $+55°$ were recorded using a linear position sensitive detector. By fitting a pseudo-Voigt function to the experimental data, the diffraction peak centre was determined, from which the interplanar spacing d was calculated by Bragg law:

$$\lambda = 2d\sin(\theta)$$

The XEC for the γFe-220 was $1/2s_2 = 6.19 \times 10^{-6}$ MPa^{-6}. The depth of the X-ray penetration was approximately 5 μm. Due to the relatively large radius of the specimens, no correction was made for the curvature. The measurement uncertainty, estimated from the standard deviation of the linear regression analysis to determine the slope of the

d-$\sin^2\Psi$ plot was generally less than 50 MPa. The error bars shown in the graphs present their values for specific turning conditions.

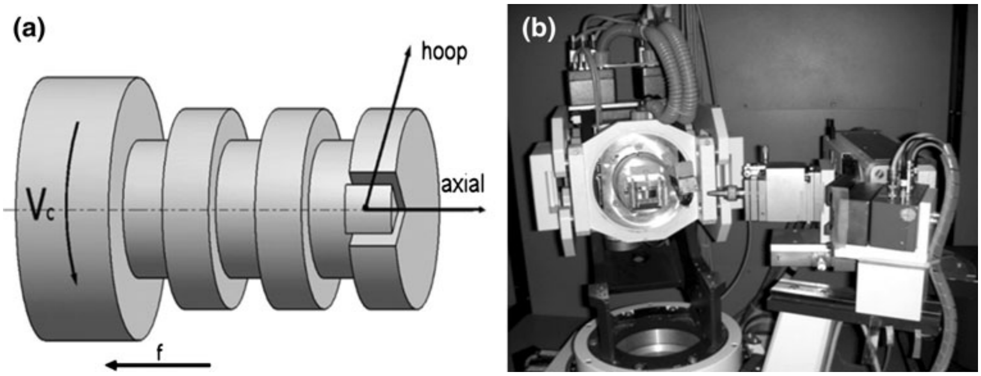

Fig. 1 Specimen with residual stress measuring directions (**a**) and residual stress measurement set up (**b**)

Table 1 Experimental conditions

Work piece	Material: AISI 316L (austenitic stainless steel), diameter: 60 mm, length of cut 15 mm
	Composition: $C < 0.03$ %, $Si \leq 1.0$ %, $Mn < 2.0$ %, $P \leq 0.045$ %, $S \leq 0.015$ %, $N \leq 0.1$ %, Cr 16.5–18.5 %, Mo 2–2.5 %, Ni 10–14 %
Tool	Tool holder MSS 2525–12-EB (Mircona AB)
	Carbide insert SNMG 120408-TF, grade IC 907, PVD coating composition TiAlN, (Iscar Ltd)
Tool geometry	Rake angle $\gamma_0 = 5°$, clearance angle $\alpha_0 = 10°$, cutting edge angle $\chi_r = 45°$, cutting inclination angle $\lambda_s = 0°$, nose radius $r_\varepsilon = 0.8$ mm
Cutting conditions	Cutting speed: 82, 164, 255 m/min, feed rate: 0.08, 0.27, 0.47 mm/rev, depth of cut: 0.5, 1 mm
Cutting environment	Cooling and lubrication conditions: D-dry, MQL-minimum lubrication, E-emulsion

3 Results and discussion

The residual stresses measured in both the cutting (hoop) and feed (axial) direction are presented in Fig. 2. In the applied range of cutting conditions the residual stresses were tensile in nature, however, their magnitude varied, depending on the cooling and lubrication method and cutting parameters. The values of hoop stresses were higher, ranging from 327 to 575 MPa, than those of axial stresses, varying between 108 and 484 MPa. Elimination or reduction of cooling and lubricating liquids in the turning process resulted in an increase or decrease of residual stresses both in hoop and axial directions, depending on the used cutting parameters.

The cooling and lubrication method had the highest influence on the hoop and axial stresses in machining with a low feed rate of 0.08 mm/rev and a cutting speed of 82 m/min. In such cutting conditions the highest values of hoop and axial residual stresses were observed in turning with emulsion (494 and 370 MPa) and the lowest in dry machining (327 and 108 MPa), while their values in cutting with MQL lay in between. The lower values in both directions after dry turning compared to other cooling and lubricating methods may have resulted from an increase of the cutting temperature in the chip formation zone. The temperature increase caused softening of the material in this area and eventually led to a decrease in the main cutting force and lower resultant stresses. The application of lubricating aerosol in MQL turning reduced the friction and temperature in the cutting zone which led to increased plastic deformation and higher residual stress values as compared to dry turning [13]. Intensive flood cooling and easer penetration of emulsion in the tool- chip- machined part interface at low cutting speed significantly improved heat evacuation from the cutting zone and increased work hardening of the surface layer. A great tendency of AISI 316L steel to undergo plastic deformation, work hardening and formation of micro structural defects caused high tensile stresses even though the mechanical factor usually led to compressive residual stress after completing cutting process [11]. The existing relations between the values of residual stresses and the cooling and lubrication technique pointed to the mechanical factor as the crucial reason for tensile stresses in machining with emulsion [12]. With the increase of cutting speed to 164 m/min the influence of the applied cooling and lubrication methods on hoop stresses did not change. However, the increase of cutting speed to 255 m/min generated higher residual stresses both in the hoop and axial direction in dry turning (466 and 296 MPa) and MQL turning (508 and 320 MPa), than in turning with emulsion (407 and 212 MPa), indicating a change in the main mechanism of residual stress generation. An increase in the cutting speed from 82 to 255 m/min in dry turning increased the temperature and heat concentration in the cutting zone due to low heat conductivity of austenitic stainless steels. The absorbed heat remained longer in the

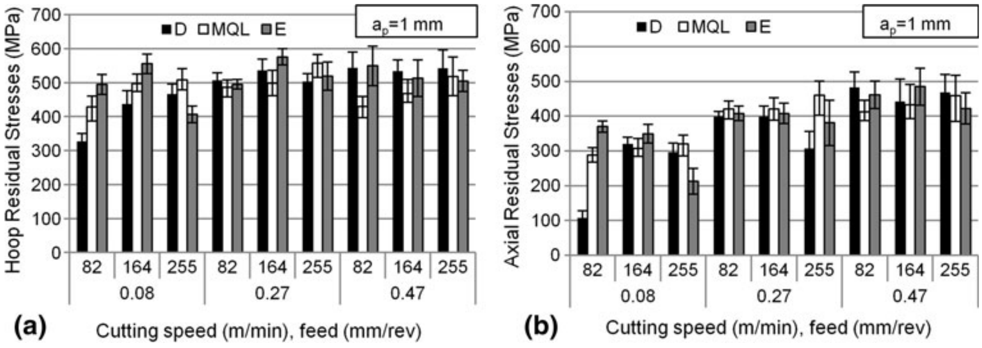

Fig. 2 Hoop (**a**) and axial (**b**) residual stresses in turning dry, with MQL and with emulsion

surface layer and the increased influence of the thermal factor could have a decisive role in the generation of higher tensile stresses [11, 15]. The application of MQL and the lubricating action of oil aerosol did not change significantly the residual stress values as compared to dry cutting. Applying emulsion to the cutting zone in these conditions reduced the influence of heat in generating tensile residual stresses. These results pointed to a combined influence of the mechanical and thermal factors on constitution of residual stresses in the superficial surface layer after turning austenitic stainless steel, which remains consistent with the research by [4].

With an increase of the feed rate up to 0.27 mm/rev at the applied cutting speeds the influence of the cooling and lubrication conditions on residual stresses in both directions was reduced. The changes of stress values remained in the range of standard errors, which pointed out to a conclusion that the thermal and mechanical action remained in the relative balance.

A further increase in the feed up to 0.47 mm/rev did not differentiate significantly residual stresses between turning dry and with emulsion. However, lower values in both directions were observed in the MQL conditions, especially in low cutting speed (82 m/min). The low values of the hoop (430 MPa) and axial (411 MPa) stresses could be attributed to the penetration and lubrication action of the oil aerosol. With an increase of the cutting speed to 255 m/min, the effect of cooling and lubrication became less pronounced, slightly lower in MQL turning than in dry turning. Similarly to [11], the obtained results confirmed a considerable influence of the cutting speed and feed rate on the process of generating residual stresses.

The research has revealed that dry and MQL turning at a low feed rate, recommended for finish turning, and at a low and medium cutting speed (82, 164 m/min) facilitated reduction of residual stresses compared to emulsion turning. However, a greater reduction of residual stresses can be achieved in dry turning. In higher cutting speed (255 m/min) lower values of residual stresses were generated in turning with emulsion than in dry and MQL turning.

The hoop and axial stresses in dry turning as a function of the cutting speed and feed rate are presented in Fig. 3. The analysis of these graphs has revealed significant differences between the hoop and axial stress components, especially at low speeds and feed rates. At the feed rate of 0.08 mm/rev, an increase in the cutting speed increased significantly the hoop stress, which could be attributed to the growing cutting temperature and concentration of heat in the cutting area.

Considerable differences between both stress component values were observed in the whole range of the used cutting parameters. The cutting speed exerted the highest influence on the increase of the values of hoop and axial residual stresses within a speed range of 82–164 m/min, at a low feed rate, and along with an increase of the cutting speed to 255 m/min its impact was limited. Increasing the feed rate value to 0.27 and 0.47 mm/rev resulted in increased values of residual stresses but reduced the influence of the cutting speed on the hoop and axial stresses. The reason may have been related to a greater chip cross-section and greater heat evacuation from the cutting zone by the chip, which led to reduced impact of the thermal factor on the generating process of residual stresses. The results partly confirmed conclusions presented in papers [7, 10, 15].

The relationship between hoop and axial residual stresses and cutting parameters in MQL turning are presented in Fig. 4. An analysis of these relations showed that a higher cutting speed led to larger hoop and axial stresses. On the other hand, the influence of the feed rate on hoop stresses did not reveal any clear tendency. Increasing the feed rate could result in higher or lower residual stresses depending on the cutting speed, which proved a complex influence of the mechanical and thermal factor on the residual stresses. The values of axial stresses at low feed rate were lower by about 100 MPa than those at feed rates of 0.27 and 0.47 mm/rev in the whole range of the cutting speeds. An increase of the feed rate from 0.27 to 0.47 mm/rev did not cause any significant increase in the values of axial residual stresses.

The influence of the cutting speed and feed rate on the hoop and axial residual stresses in turning with emulsion is presented in Fig. 5. An increase of cutting speed from 82 to 164 m/min at a feed rate of 0.08 and 0.27 mm/rev caused increased hoop stresses. A further increase of the cutting speed up to 255 m/min reduced the hoop stresses, especially at a feed rate of 0.08 mm/rev, from 555 MPa to their lowest value 407 MPa. At the feed rate of 0.47 mm/rev an increase of cutting speed did not exert a significant influence on hoop stresses, which was likely the result of a greater chip cross section and a greater amount of heat transferred from the cutting zone. The axial stresses were lower than the hoop stresses and their values increased considerably when the feed rate increased. This could be attributed to the increasing effect of the feed component of the cutting force. An increase in the cutting speed from 82 to 164 m/min did not have a significant influence on the values of axial stresses which, similarly to the hoop stresses, in the range of the used feed rates, decreased by 12–39 % when the cutting speed reached 255 m/min.

Figure 6 shows the dependence of hoop and axial residual stresses on the depth of cut in the used cooling and lubricating conditions. The values of the depth of cut were recommended for the finish turning operations. The conclusion drawn on the basis of these results showed that an increase in the depth of cut from 0.5 to 1 mm caused an insignificant increase in hoop and axial stresses. However,

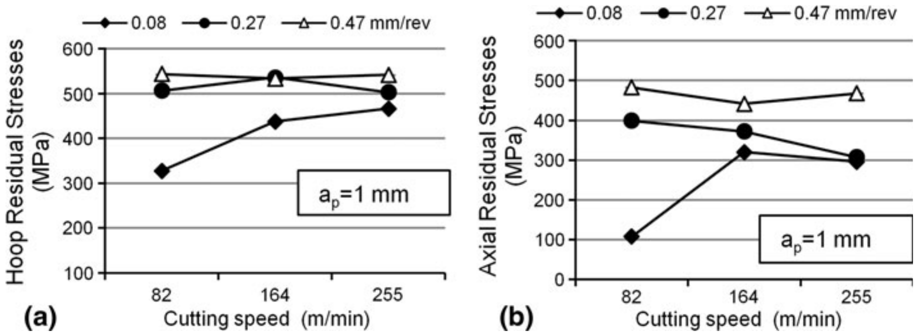

Fig. 3 Influence of cutting speed and feed rate on hoop (**a**) and axial (**b**) component of residual stresses in dry turning

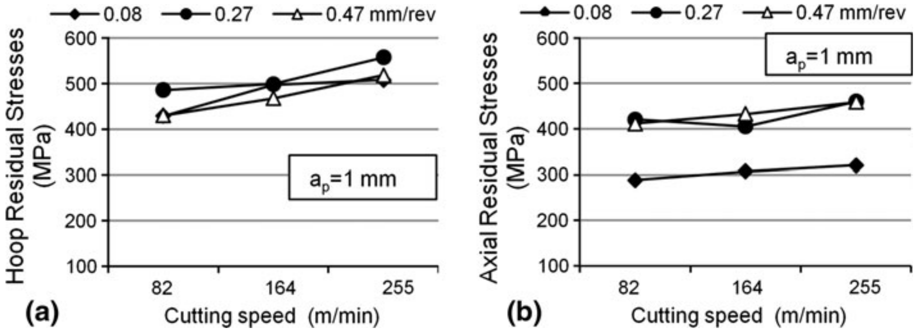

Fig. 4 Influence of cutting speed and feed rate on hoop (**a**) and axial (**b**) component of residual stresses in turning with MQL

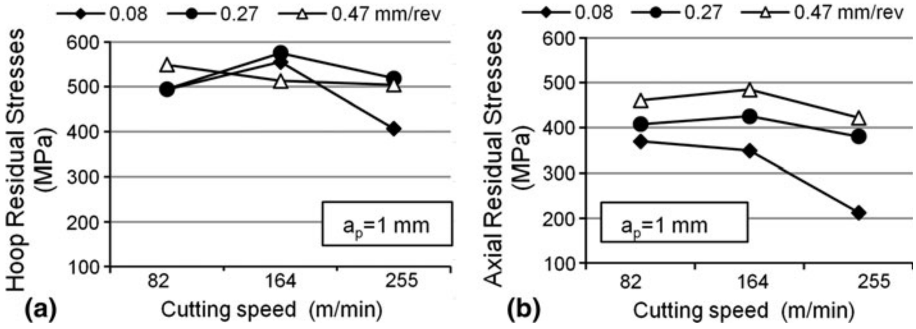

Fig. 5 Influence of cutting speed and feed rate on hoop (**a**) and axial (**b**) component of residual stresses in turning with emulsion

a minor increase of these stresses was observed. Presumably the increase of the depth of cut from 0.5 to 1 mm and the resulting chip cross section were not sufficient to change the relationship between the mechanical and thermal factors affecting residual stresses. However its influence may be significant in combination with the cutting speed and feed rate. The results did not confirm any meaningful influence of the depth of cut on residual stresses observed in [13] and require further investigation.

The existing correlations between residual stresses and the cutting speed, feed rate and depth of cut for the employed cooling and lubrication modes are expressed by regression functions in the form of polynomials of the second degree presented in Table 2. In the range of tested cutting parameters the created models facilitate calculations of the value of the hoop stress after dry and MQL turning and the axial stress after turning with MQL and emulsion at a significance level $p < 0.05$ or very close to this value. In other cooling and lubrication conditions the values of a significance level p and a coefficient of determination R^2 do not match the listed assumptions, indicating complex relations between residual stresses and cutting parameters.

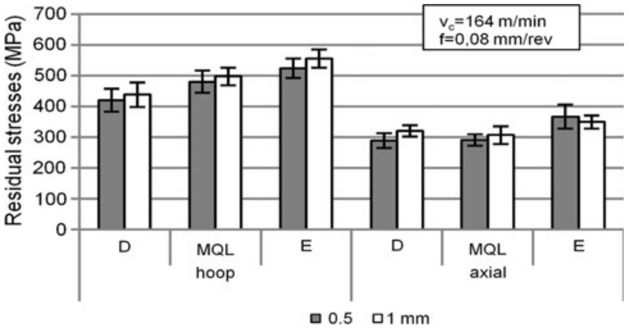

Fig. 6 Influence of depth of cut on hoop and axial component of residual stresses in turning dry, with MQL and with emulsion

Table 2 Regression functions for hoop σ_{hoop} and axial σ_{axial} residual stresses

Cooling and lubrication conditions	Regression functions σ_{hoop}, $\sigma_{axial} = f\ (v_c, f, a_p)$	R^2	p
D	$\sigma_{hoop} = 137.0921 + 2.3979*v_c - 2.0373*v_c*f - 0.5834*v_c*a_p + 1,276.998*f*a_p - 0.003*v_c^2 - 1101.03*f^2$	0.934	0.0544
	$\sigma_{axial} = -81.869 + 3.4281*v_c - 2.8811*v_c*f - 0.8969*v_c*a_p + 1,191.931*f*a_p - 0.0047*v_c^2 - 252.857*f^2$	0.826	0.2091
MQL	$\sigma_{hoop} = 224.1831 + 0.1811*v_c + 0.2319*v_c*f - 0.4884*v_c*a_p + 1,168.171*f*a_p + 0.0014*v_c^2 - 1,592.67*f^2$	0.929	0.0594
	$\sigma_{axial} = 224.1831 + 0.181101*v_c + 0.2319*v_c*f - 0.4884*v_c*a_p + 1,168.171*f*a_p + 0.0014*v_c^2 - 1,592.67*f^2$	0.987	0.0048
E	$\sigma_{hoop} = 353.3383 + 2.1756*v_c + 0.6793*v_c*f - 0.2049*v_c*a_p + 365.2077*f*a_p - 0.007*v_c^2 - 698.403*f^2$	0.607	0.5620
	$\sigma_{axial} = 276.6404 + 1.5182*v_c - 0.0057*v_c^2 + 1.747*v_c*f - 616.622*f^2 - 0.51737*v_c*a_p + 420.3824*f*a_p$	0.961	0.0249

4 Conclusions

An experimental study of residual stresses induced by cylindrical turning of AISI 316L austenitic stainless steel in dry, MQL and wet cutting conditions was performed in the presented investigations. Considering the obtained results the following conclusions can be drawn:

- The cutting zone cooling and lubrication conditions exert a substantial influence on the superficial residual stresses in the machined surface layer. The values of the hoop stress component are larger than those of the axial component and depend to a large extent, in addition to cooling and lubrication, on the applied cutting speed and feed rate. The level of residual stresses results from a joint action of the thermal and mechanical factors. It is recommended to perform further research into residual stresses appearing inside the surface layer, depending on the cooling and lubrication mode.
- The influence of the cutting speed, feed rate and depth of cut on residual stresses depends on cooling and lubricating conditions in the cutting zone.
- An increase of the cutting speed during dry turning causes an increase in hoop residual stresses when a low feed rate is used (0.08 mm/rev). When the feed rate increases (0.47 mm/rev), the influence of this parameter becomes less pronounced. An increase in the feed rate causes higher hoop and axial residual stresses.
- In MQL turning, an increase in the cutting speed results in higher hoop and axial residual stresses. Increasing the feed rate does not considerably affect the hoop stress but causes higher axial residual stresses.
- In turning with emulsion, the influence of the cutting speed and feed rate on hoop residual stresses did not present any conclusive trend. An increased cutting speed may cause higher or lower hoop and axial residual stresses, depending on the used feed rate. Regarding axial residual stresses, the increase of cutting speed allows reducing their value at low feed rate (0.08 mm/rev) but with an increase of feed rate the effect of cutting speed decreases but values of axial residual stresses raise.
- In the applied conditions of cooling and lubrication an increase of the depth from 0.5 to 1 mm does not influence significantly hoop and axial residual stresses.
- The research showed that at low feed rate (0.08 mm/rev), recommended for finish turning, and a low and medium cutting speed (82, 164 m/min) elimination of emulsion or application of MQL allows reduction of residual stresses. At these cutting speeds lower values of hoop stress than after turning with emulsion (494, 555 MPa) occurred after dry turning (327, 438 MPa) and with MQL (428, 497 MPa). Increase of cutting speed to 255 m/min at low feed rate generates higher residual stresses in dry and MQL turning than in turning with emulsion.
- The results of the presented investigation and regression functions can make up guidelines for selection and optimization of cutting parameters taking into account the residual stresses produced in turning the AISI 316L steel as well as cooling and lubrication conditions.
- In the properly selected cutting parameters, the values of the residual stresses after turning the AISI316L steel dry and with MQL can be lower or comparable to those in emulsion turning and elimination of cooling liquid is advisable.

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