RESIDUAL STRESS DETERMINATION OF DUPLEX AND AUSTENITE STEELS MACHINED USING DIFFERENT TOOL GEOMETRY

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Abstract

The aim of this contribution was to compare residual stresses distribution of austenite with duplex stainless steel. Residual stresses were studied as a function of the tool geometry. For residual stresses determination, two methods were used: X-ray diffraction and hole-drilling. Both surface and sub-surface residual stresses were determined. The gradient of residual stresses of each phase in the duplex steel was compared with hole-drilling method.

Introduction

Duplex and austenite steels are usually used for their properties, primarily for high corrosion resistance. Duplex steels combine properties of both phases and moreover, due to two-phase microstructure, some properties are better than high-alloyed austenite steel, e.g. abrasion resistance [1].

Both, austenite and duplex steels have relatively low thermal conductivity (approx. 16 W/mK) [2] which leads to insufficient heat distribution into chip and workpiece and to excessive heat accumulation in cutting zone. This heat generation can result in microstructural changes, local changes of chemical composition, surface discoloration or inducing undesirable tensile residual stresses.

The residual stresses (RS) gradient is more important indicator of machined material than surface RS. A situation may arise that there are the favourable compressive RS on the surface but with a steep RS gradient which can result in very high unfavourable tensile RS in the subsurface layers, and reversely [3]. For this reason, it is very important to investigate the RS gradient.

The analysis of polycrystalline materials by X-ray diffraction methods is suitable for gaining information about state of RS of both the surface and subsurface layers. On the other hand, the other methods as hole-drilling determine the RS gradient from total deformation of material after disruption of RS balance.

1. Theory

Duplex stainless steels have high corrosion resistance in many environments, where the standard austenite steel is consumed, and where its properties significantly exceed austenite steel. Thereby, smaller amount of material from duplex steel is necessary to manufacture function components. Austenite and duplex steels are susceptible to mechanical reinforcement, i.e. local changes in mechanical properties of surface layers. Local changes, e.g. hardness, can lead to tools vibration during machining of the final component, which results in additional material inhomogeneity and blunting tool [4].

Realising that austenite steel has face centred cubic (*fcc*) lattice with close-packing structure of atoms, the primary slip system is {111}. The number of slip systems is 12, which is the sufficient amount to plastic deformation. Moving dislocations form so called stair-rod dislocations which have small stacking fault energy, i.e. high energy is necessary to have for intersect or cross slip of these dislocations [5]. Therefore, the austenite steels are prone to work-hardening, which cause mechanical modification and inhomogeneity on the machined surface, and leads to e.g. unstable chip formation. On the contrary, the ferrite crystallizes in a body centred cubic lattice (*bcc*). The direction slip in bcc materials is always . Since in the bcc lattice is not close-packing structure of atoms, more slip planes assert during the deformation, mostly planes {110} and {211}.

In engineering practice, the residual stresses are often determined on the basis of total sample deformation (e.g. hole-drilling method). This procedure considers the solid state as a compact continuous body, and therefore could not take into account degradation processes which rise separately into each phase components. Using X-ray diffraction (XRD) method, the residual stresses are possible to determine into both the phases separately [6].

2. Experiment

The tested samples of tube shape of 100/86 mm in diameter were made of AISI 304 (austenite) and AISI 318LN (duplex) type of stainless steel. The samples were annealed in air laboratory furnace for 5 hours at 420°C in order to reduce bulk macroscopic residual stresses.

For machining of the surfaces, four types of side rake angle were used (–6°; –2°; +7° and +12°). Side rake angles are considered in combination with particular insert holder, which has negative rake angle (–6°). DCLNR/L R-clamp tool-holders with lead angle of 95° (side cutting edge angle –5°) for four 80° negative rhombic inserts were used, namely F3M, SF, NF, and PP chip breakers of Iscar Cutting Tools. All inserts had the same tip radius 0.4 mm. For elimination of blunting tool effect, the cutting tool was always new for machining of each tube segment.

Cutting conditions were as followed: feed rate 0.14 mm/rev, cutting speed 140 m/min, and depth of cut 2 mm. Direction of feed rate was parallel to axis of the sample (tube) A and perpendicular to tangential direction T. According to the principles of design of experiments (DOE) method, three 1cm tube segments were machined using the same cutting conditions.

Using Mn*K* and Cr*K* radiation, *X'Pert PRO MPD* diffractometer was used to measure lattice deformations in austenite and ferrite, respectively. The average penetration depth of X-ray radiation is approx. 4 μm and 6 μm for ferrite and austenite phase, respectively. Diffraction angles 2 ^{hkl} were determined from the peaks of the diffraction lines K_{1} of planes {311} and {211} of austenite and ferrite, respectively. Diffraction lines K_{1} were fitted by Pearson VII function and Rachinger's method was used for separation of the diffraction lines K_{1} and K_{2}. For residual stress determination, Winholtz & Cohen method [7] and X-ray elastic constants $\frac{1}{2}s_2 = 7.18$ TPa^{-1}, $s_1 = -1.20$TPa^{-1} and $\frac{1}{2}s_2 = 5.75$ TPa^{-1}, $s_1 = -1.25$ TPa^{-1} were used for austenite and ferrite phase, respectively. In order to analyse the stress gradients beneath the samples surface, layers of material were gradually removed by electro–chemical polishing in the centre of the sample.

Hole-drilling method was performed using sintered carbide milling cutters of 1.8 mm in diameter and the holes had depth of 2 mm. The detection of released deformations was done by 3 rectangular tensometric rosettes. The stresses were calculating using macroscopic elastic constants: Young modulus 200 GPa and Poisson ratio 0.3.

3. Results and discussions

3.1 Surface residual stresses

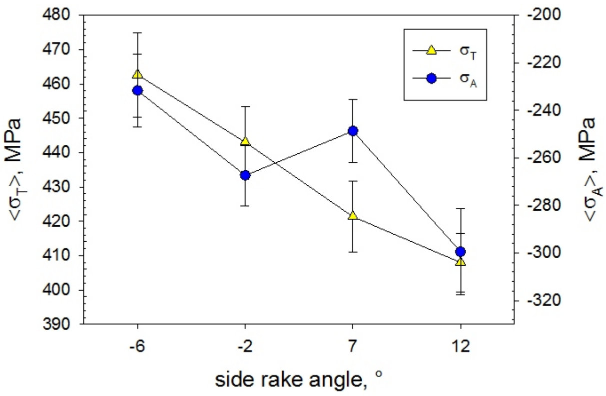
In Figs. 1a–c, there are influences of surface macroscopic residual stresses $_A$ $_A$, MPa on the side rake angle, °. These residual stresses were averaged from three values of RS of tube segments machined the same side rake angle.

Generally, the increasing of the side rake angle in the positive direction leads to a lowering of cutting force and temperature in the cutting zone [3]. For prediction of RS dependence on the side rake angle, the yield strength ratio $Rm/Rp_{0.2}$ of the given material is necessary to take into account. Generally, the temperature influence causes the tensile RS and contrarily, the plastic deformation leads to compressive RS. The type of the RS and their value deeply depend on the mechanical and thermal properties of the machined material [3, 8].

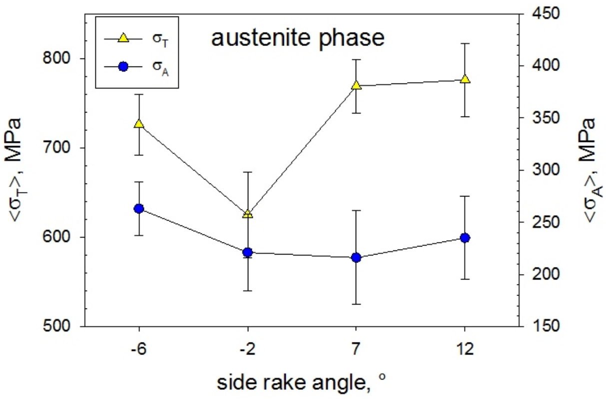
For austenite steel, the yield strength ratio is approx. 2.5, which is typical value for plastic material. The tensile RS are created during machining using great load on the cutting tool, i.e. using the negative side rake angle, and smaller load causes the compressive RS, i.e. using the positive side rake angle [3]. For this reason, higher compressive (axial direction) and smaller tensile (tangential direction) RS were determined with increasing of the side rake angle, see Fig. 1a.

On the other hand, for ferrite steel, the yield strength ratio is less than 1.25, which is typical value for elastic materials. According to [3], the shear type chips should be created which should cause the interruption of the connection between chips and the material. The additional effect of strain filed of chips is not transferred in the machined surface. For this reason, the greater force causes that the plastic deformation influence is predominant and higher compressive or smaller tensile RS may be determined with increasing of the side rake angle.

Furthermore, for duplex steel, which is consisted of both phases, it is possible to presume that the dependence of RS on the side rake angle is generally not monotonic for both the phases because of their mutual influence during plastic deformation, see Figs. 1b–c.



a) Austenite steel



b) Duplex steel - austenite phase

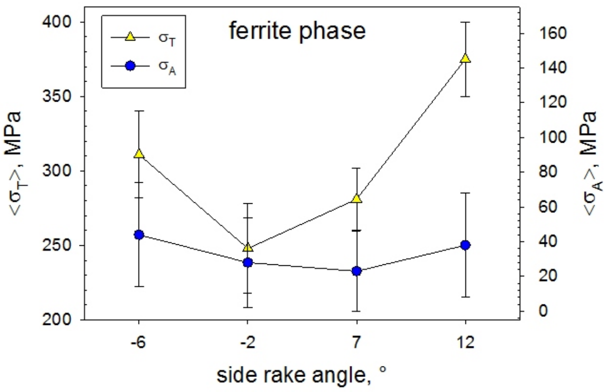
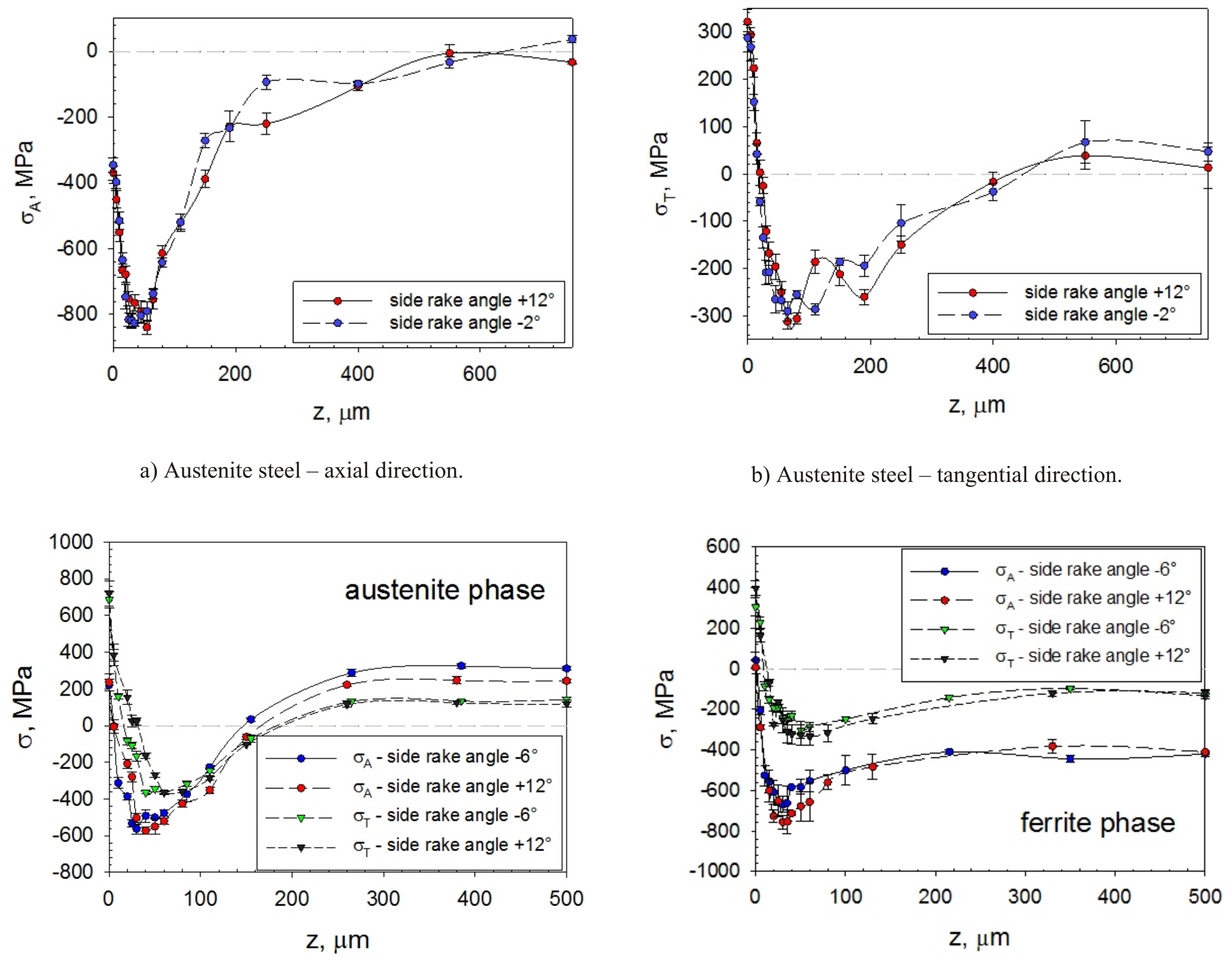


Figure 1. Axial and tangential residual stresses $_A$ $_A$ as a function of side rake angle, °.

3.2 Residual stress gradient

The RS gradients depending on the side rake angles were determined, see Figs. 2a–d. As can be seen in Figs. 2a–b, the RS gradients are without any dependence on the side rake angle in the case of austenite steel. On the contrary, for duplex steel, there are clearly differences of the RS values depending on side rake angle in both austenite and ferrite phase.



a) Austenite steel – axial direction.

b) Austenite steel – tangential direction.

c) Duplex steel – austenite phase.

d) Duplex steel – ferrite phase.

Figure 2. Residual stress gradients $_{A}$, $_{T}$ using side rake angles –6°, –2° and +12°.

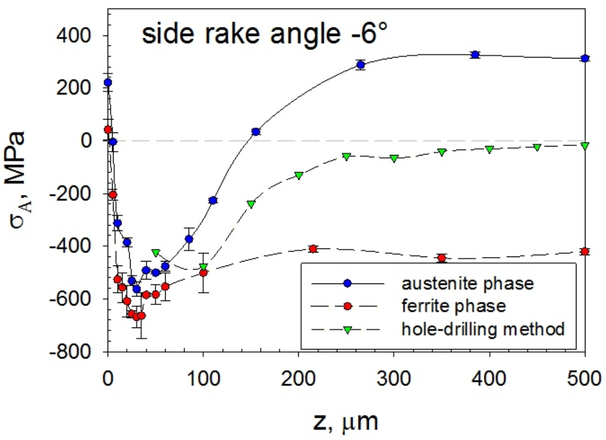
The reason resides in two phase material and mutual influence of both phases during plastic deformation. In the case of one phase steel, the difference of plastic deformation power is not so significant to change the state of RS in the sub–surface layers using the different side rake angle, see Figs. 2a–b. On the contrary, for two phase steel, the differences of RS are evident, see Figs. 2c–d. With the increasing side rake angles, the maximum stress position is moved deeper into the material which is in line with [9].

In Figs. 3a–d, there is a comparison of RS gradients determined by XRD and hole-drilling method. Mostly, the macroscopic RS of bulk material can be estimated as approx. zero, see austenite steel in Figs 2a–b. Nevertheless, the compressive RS of ferrite and the tensile RS of austenite phase of bulk are seen in Figs. 2c–d. By XRD, the determination of the RS is possible in each phase, separately. Because of the similar mass ratio of ferrite and austenite phase in the duplex steel, the RS of bulk can be approximately predicted by value $_{bulk}$ $_{ferrite}$ + $_{austenite}$)/2. However, the hole-drilling method is based on deformation of the measured material as the whole. From Figs. 3, there are evident that $_{bulk}$ $_{hole\text{-}drill}$ *0* which is in line with expectation [6]. Moreover, the continuity of both methods of RS determination was verified.

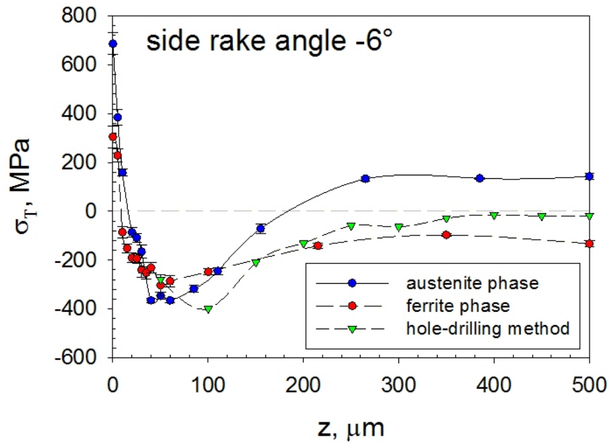
4. Conclusions

The present study showed:

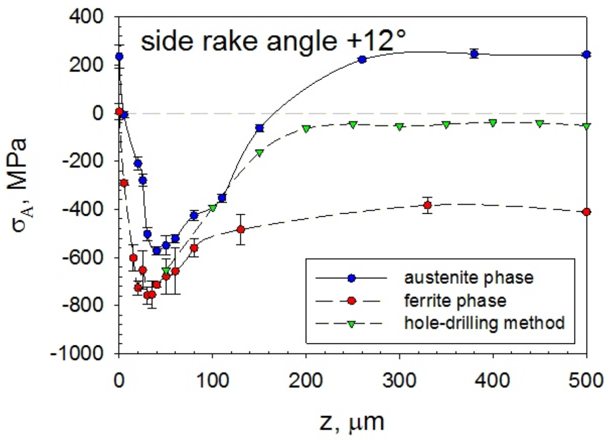
- The surface RS distribution is dependent not only on the side rake angle but on the material, too. For austenite (one phase steel), the dependence of RS on the side rake angle is decreasing. On the contrary, for austenite and ferrite (in the two phase steel), the dependence is not monotonous. The reason is yield strength ratio which is different for austenite and ferrite.
- The RS gradients are without any dependence on the side rake angle in the case of austenite steel. On the contrary, for duplex steel, there are clearly differences of RS values depending on side rake angle in both austenite and ferrite phase. The reason is mutual influence of both phases during plastic deformation.
- For the similar mass ratio of ferrite and austenite in the duplex steel, the RS determined by hole-drilling method are approx. the average between the RS determined by XRD of ferrite and austenite phase, separately.



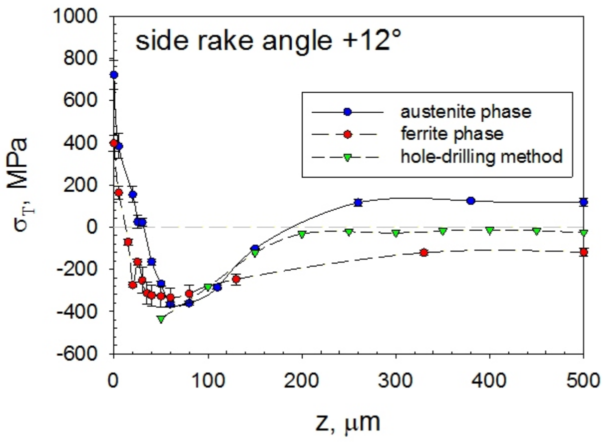
a) Axial direction; side rake angle –6°.



b) Tangential direction; side rake angle –6°.



c) Axial direction; side rake angle +12°.



d) Tangential direction; side rake angle +12°.

Figure 3. Residual stress gradients $_{A}$, $_{T}$ determined by XRD and hole-drilling method.

- Moreover, the RS of austenite phase are generally more tensile in comparison with the RS of ferrite phase; see Figs. 3, which is in correlation with [3].

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