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Turning Residual Stresses in Functionally Graded Steel Components

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Introduction

Metallic components with graded materials properties are of particular importance for the realization of lightweight design. The scientific basis of such concepts was provided by the Collaborative Research Centre TRR 30, funded by the German Research Foundation DFG between 2006 and 2015. As part of the project, thermo-mechanically graded components were manufactured by hot metal forming processes [1, 2]. Their characteristic properties are to a large extent determined by final machining operations. In this context, residual stresses play an important role for strength and lifetime of the produced parts. A survey about near surface residual stress states after hard turning of differently heat treated quenched and tempered steel AISI 6150 (51CrV4) is given in [3]. In the present paper, results of similar investigations carried out of Jominy end quench samples are reported and compared with results of samples with homogeneous microstructures.

Experimental Setup

The Jominy end quench test samples had a diameter of 25 mm and a length of 100 mm. After austenitizing and quenching the shafts were machined using uncoated polycrystalline boron nitride (PCBN) inserts with the ISO-Code CNGA120408. The tool had a chamfer with a width of $b_\gamma = 0.15$ mm and an angle of $\gamma_f = 25°$. The tool holder was of the type DCLNL2525 and had a nominal rake angle of $\gamma = -6°$ and an effective rake angle of $\gamma = -31°$ in the chamfer area. The turning processes were carried out in two passes, part left and right, starting in each case from both ends of the six specimens (See Fig. 1).

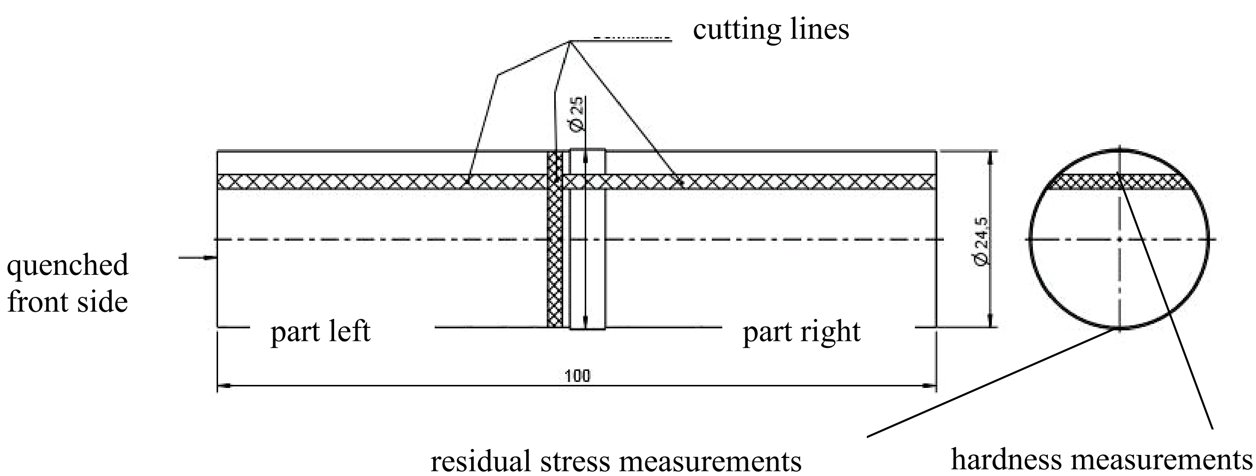

Fig. 1: Jominy end quench samples with cutting planes and measuring areas

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In Tab. 1 the process parameters used for the turning operations are listed, which are identical to those of experiments in [3]. From the hardened and turned Jominy-samples 5 mm thick segments were prepared by longitudinal cutting for hardness testing and microstructural investigations. Hardness measurements HV2 were carried out along the polished surface of both specimen parts and subsequently, the sample surfaces were etched for microstructural analyses. At both specimen parts (left and right part, see Fig. 1) residual stress depth distributions in axial and tangential direction were determined by stepwise electrolytical polishing and applying standard X-ray diffraction technique. A laboratory Ψ-diffractometer was used. Lattice strains of {211}-lattice planes in 11 Ψ-directions in the range $-45° \leq \Psi \leq +45°$ and $148° \leq 2\Theta \leq 164°$ were determined using CrKα-radiation. The measured area was circular with 1 mm diameter.

Table 1: Turning parameter

Sample No.	feed [mm]	cutting speed [m/min]	depth of cut [mm]
1	0.050	100	0.25
2	0.050	250	0.25
3	0.125	175	0.25
4	0.200	100	0.25
5	0.200	250	0.25
6	0.300	250	0.25

Experimental Results

In Fig. 2 results of residual stress analyses in axial direction after hard turning applying different process parameters of identical materials states taken from [3] are summarized. In this case cylindrical specimen with homogeneous microstructures of differently annealed martensite, characterized by the hardness values indicated, were machined. Characteristic residual stress depth distributions result which are mainly influenced by the feed applied. For the softer materials states with a hardness of 322 HV tensile residual stresses were detected at the surface. With increasing materials hardness, these values are shifted in the direction of compression. Below the surface compressive residual stress maxima occur. Their amount and surface distance increases with increasing feed. Similar observations were made for the residual stress distributions in tangential direction.

The scientific issue of the present work was to clarify whether results of homogeneous materials states can be transferred to components with graded and locally inhomogeneous microstructures. For this purpose, Jominy end quench samples were investigated which before heat treatment had a line-shaped microstructure of ferrite and pearlite. After the quenching process at the quenched end a martensitic structure was determined which continuously changed to a ferritic-pearlitic structure with increasing distance from the end face. This can also be seen from the hardness distributions shown in Fig. 3. The pronounced hardness fluctuations especially in regions of lower hardness can be attributed to the inhomogeneous microstructure of the starting condition of the material. Note that maximum hardness values close to the end face of the material are quite higher than the highest hardness of the materials investigated in [3] (see Fig. 2).

In Fig. 4 axial residual stress depth distributions measured at Jominy end quench specimen are presented, measured at different distances from the quenched end face. In addition, hardness values measured at these positions as well as the characteristic parameters of the turning processes applied are indicated. In all cases near the surface small tensile or compressive residual stresses are measured followed by local compressive residual stress maxima. Their distance from the surface increases with increasing feed values applied. Accordingly, the thickness of the surface layer with compressive residual stresses increases.

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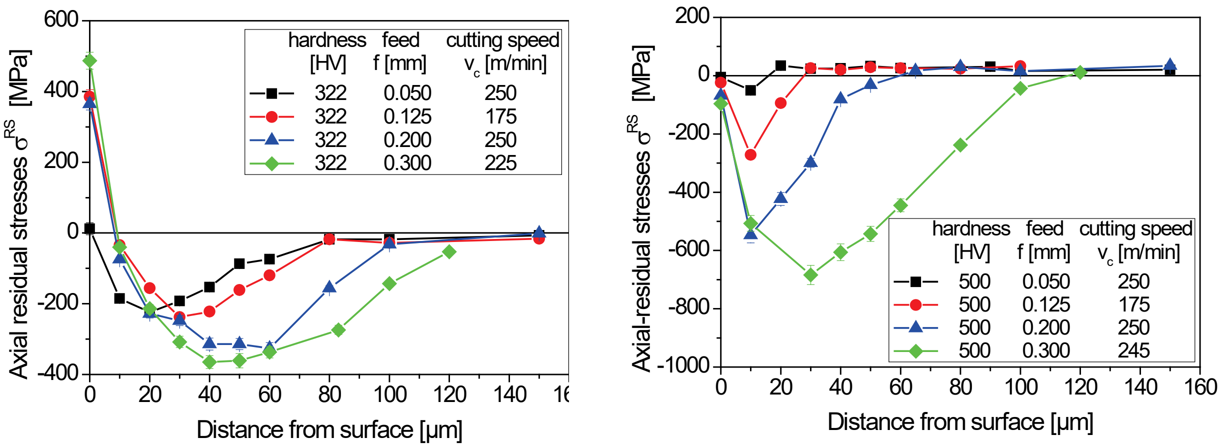

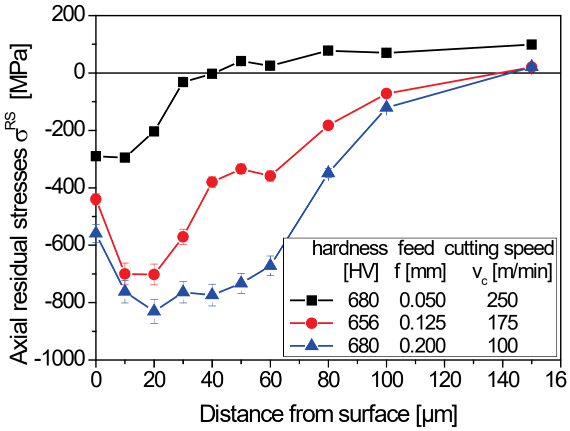

Fig. 2: Residual stress depth distributions at samples with homogeneous microstructures; above left: 322 HV; above right: 500 HV und below left: 680 HV

Similar observations were made for the residual stress component measured in tangential direction (see Fig. 5). For lower feed values, at the surface tensile residual stresses exist, which become compressive for higher feed values. Compressive residual stress maxima occur at surface distances between 10 µm and 30 µm. Amounts of compressive residual stresses are higher as in axial direction and have values between -500 MPa and -1000 MPa, depending on feed values applied.

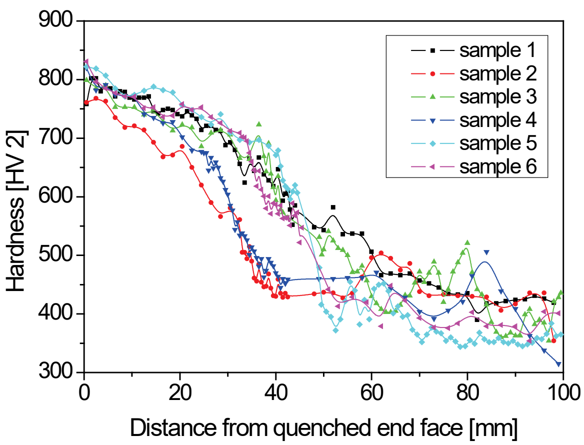

Fig. 3: Hardness distributions as function of the distance from end face

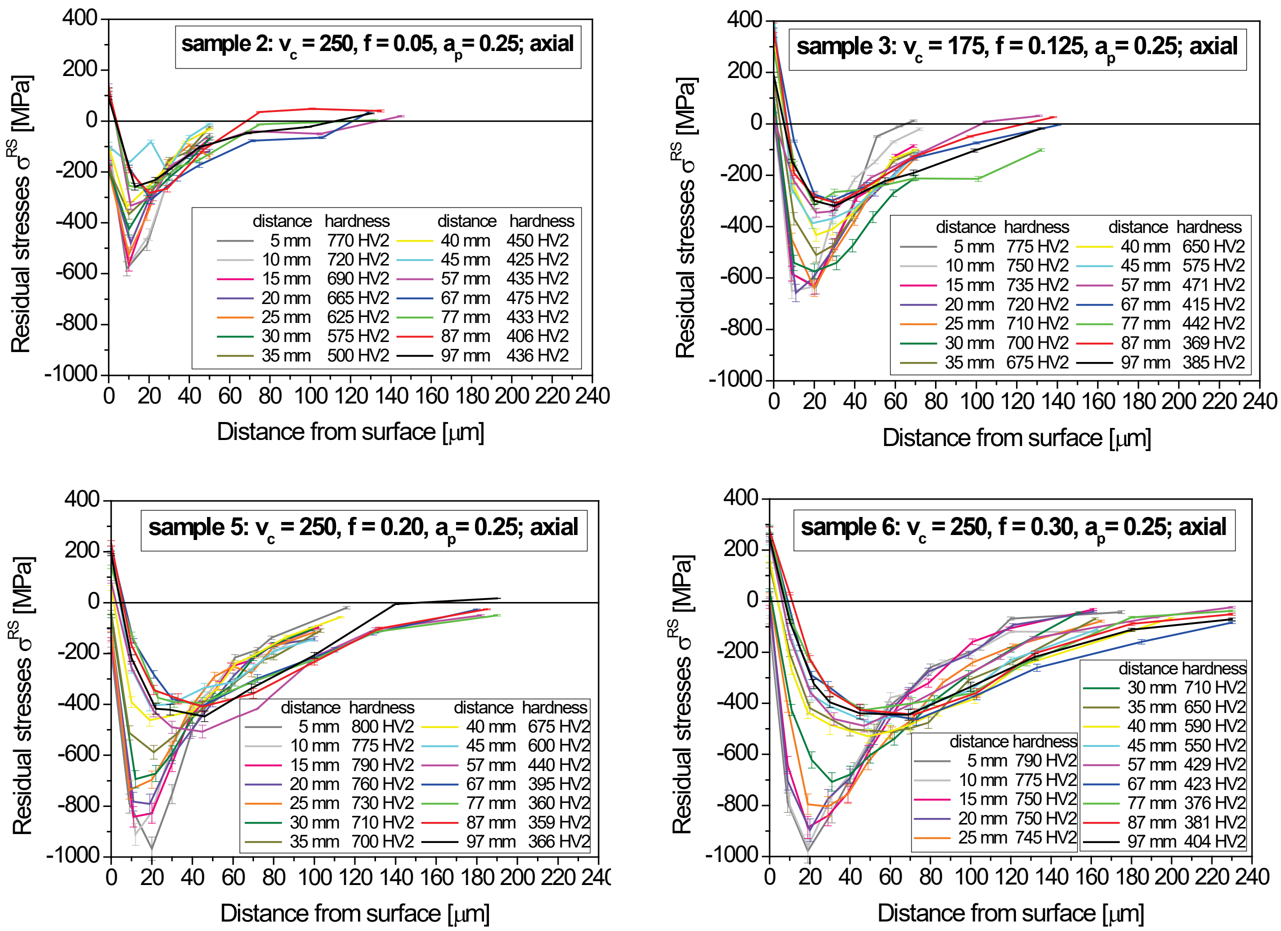

Fig. 4: Axial residual stress depth distributions of Jominy end quench samples after hard turning with different feed f (v_c: cutting speed; a_p: depth of cut)

While in axial direction shear components are small and reach maximum values of -50 MPa, in tangential direction distinct shear stress values are observed (see Fig. 6). Their depth distributions depends from applied feed values in a characteristic way. For smaller feed values higher shear stress amounts, but restricted to thinner surface layers are found compared to turning processes with higher feed values.

The thickness of the surface layer affected by the turning process can be assessed using the depth distributions of integral widths (see Fig. 7). For the cases presented in Fig. 7 (left) at a surface distance of roughly 50 µm integral width values comparable with those measured for the not machined state are found. For the harder materials states, turning leads to reduced integral width values while for softer materials states an increase can be found. This is a common observation in the case of plastic deformation of steels with different hardness and related to the formation and annihilation of dislocations as well as to different scattering domain sizes. For higher feed values (see Fig. 7, right) the thickness of the affected surface layer is increased and even larger than 150 µm.

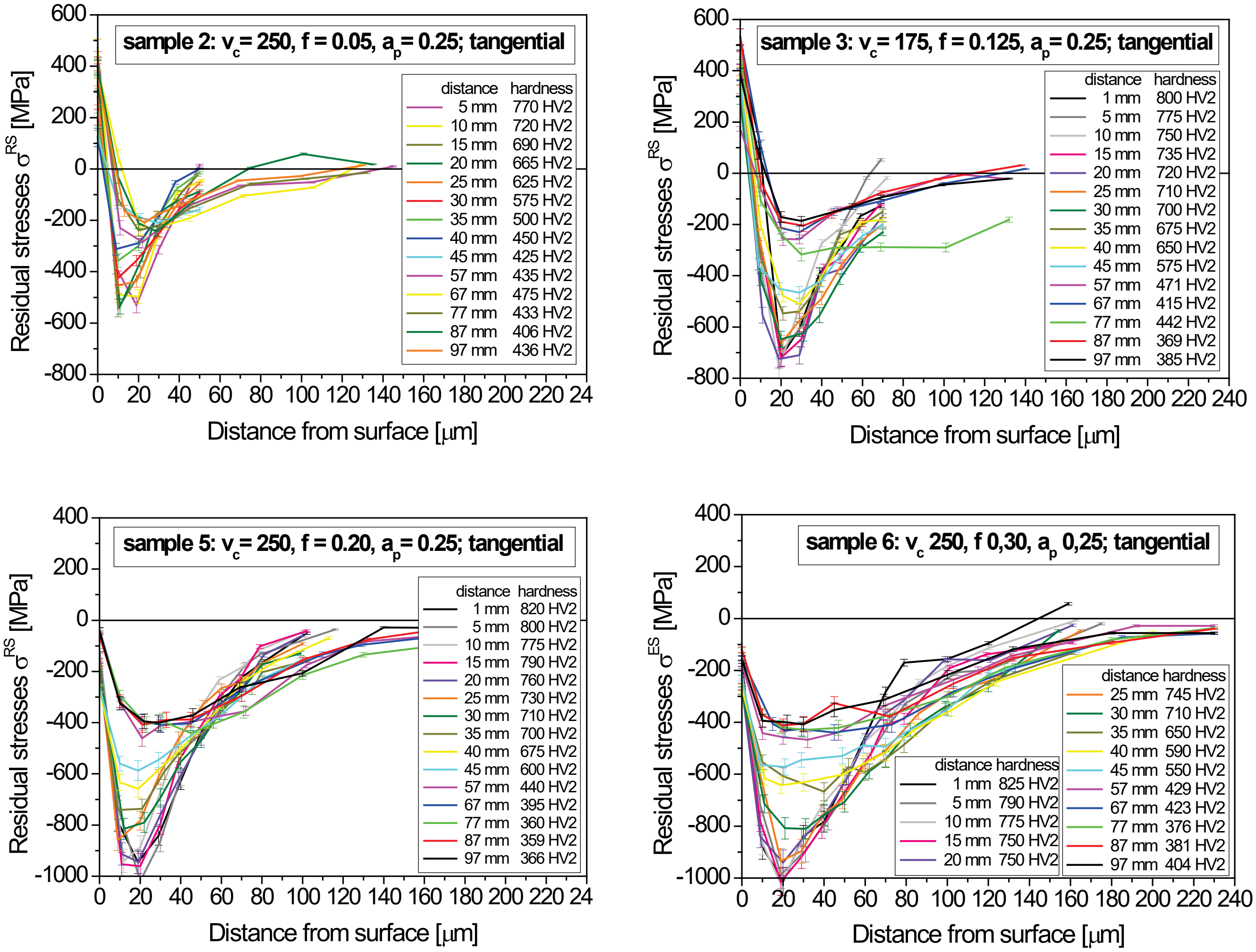

Fig. 5: Tangential residual stress depth distributions of Jominy end quench samples after hard turning with different feed f (v_c: cutting speed; a_p: depth of cut)

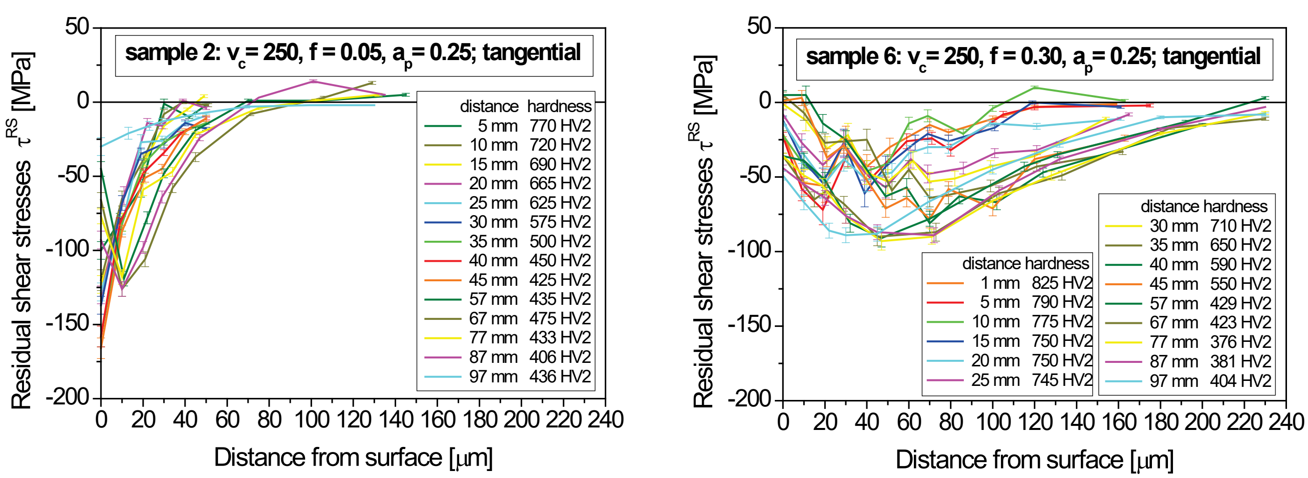

Fig. 6: Shear stress depth distributions in tangential direction for different feed f

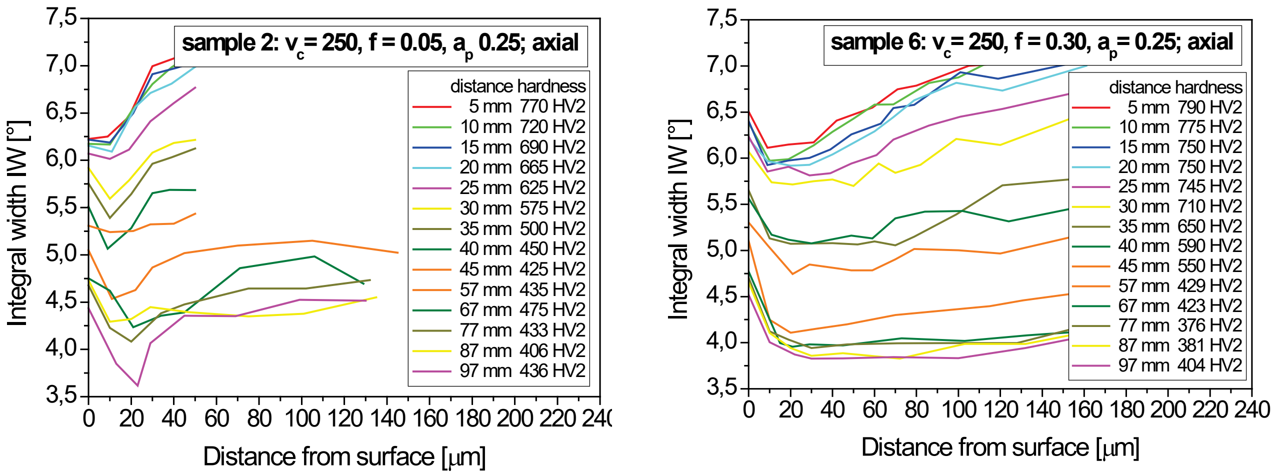

Fig. 7: Integral width depth distributions for different feed f

Summery and Conclusion

For given process parameters turning operations at steels with graded microstructures result in locally different residual stress depth distributions depending on local materials hardness. From the results presented it can be concluded that residual stress data gained from hard turning experiments with uncoated polycrystalline boron nitride (PCBN) inserts at samples with homogeneous microstructures can be transferred to graded inhomogeneous parts, if comparable materials states are considered. In all cases, in axial as well as in tangential direction, a pronounced residual stress maximum below the surface is formed, the amount and the surface distance of which increases with materials hardness and turning feed.

Acknowledgement

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