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DETECTION OF LOCAL INHOMOGENEITIES IN COMBINED WIRE DRAWING PROCESSES - DETAILED ANALYSIS OF RESIDUAL STRESS FIELDS[1]

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Abstract

Cold-formed products contain residual stresses which arise from the elastic response of the material to an inhomogeneous distribution of plastic strains. Very often these residual stresses are undesirable because they can be the cause of materials failure and may cause distortion at further manufacturing steps as during machining and heat treatment operations. On the other hand, forming parameters can be changed or forming processes can be improved in order to minimize these stresses or to generate “useful” stresses. In this work the redistribution of residual stresses in AISI 1045 steel as a consequence of forming operations to manufacture straight semi-finished cold-drawn bars was investigated. It was found that the process generated non-homogeneities of residual stresses.
Key words: Wire drawing; Residual stresses; Coating.

DETECÇÃO DE NÃO HOMOGENEIDADES LOCAIS NO PROCESSO DE TREFILAÇÃO COMBINADA – ANÁLISE DETALHADA DE TENSÕES RESIDUAIS

Resumo

Produtos conformados a frio contêm tensões residuais mais elevadas que surgem a partir da resposta elástica do material a uma distribuição não homogênea de deformações plásticas. Muitas vezes, essas tensões residuais são indesejáveis, pois podem ser a causa da falha de materiais ou podem provocar distorções em etapas de fabricação, por exemplo, após ou durante operações de usinagem e tratamento térmico. Por outro lado, os parâmetros de processo podem ser alterados ou melhorados a fim de minimizar essas tensões ou gerar tensões residuais mais benéficas. Neste trabalho foi investigada, a metodologia de detecção de campos de tensões residuais na região superficial de barras cilíndricas com diâmetro de 20,25 mm de aço AISI 1045, após o processo de trefilação. Em cada amostra analisada, realizou-se medições em diferentes posições ao longo das amostras na direção longitudinal em oito ângulos periféricos predefinidos, totalizando 250 pontos de medição em cada amostra. Verificou-se que o processo de trefilação gera não homogeneidades de tensões residuais.
Palavras-chave: Trefilação; Tensões residuais; Revestimentos.

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1 INTRODUCTION

Since the late sixties of the last century intensive research was carried out to optimize cold drawn cylindrical products.[1] With these early observations questions about measurement techniques of residual stresses also took part of research and development. [2] Continuous development of the process finally resulted in optimized products with high materials utilization and high productivity (mass per day) and good strength levels due to the strain hardening during the process. Optimizing of tools or sequences of tools with different amount of reduction resulted in reduced levels of residual stresses.[3] Nowadays these products in the form of long bars with different diameters and different materials are used to produce e.g. automotive parts without major machining operations or bars for reinforced concrete application. Development in the last years resulted in combined operations of cleaning raw material, straightening it before drawing and finally applying a combined surface finishing and straightening process after drawing. Further improvement of manufacturing is now involving minimization of the distortion in these manufacturing sequences of drawn products and, therefore, determination of residual stresses is required. As a limiting factor however, generally residual stresses are measured at some locations of a bar only or across one cross section only.[4] It is however expected and proved in this article, that inhomogeneities during the drawing process cause locally different material states and residual stress states.

The aim of this work was to implement measuring strategies capable of revealing the real influences of the manufacturing process on the residual stress fields that are present on near surface areas of cold drawn bars. X-ray diffraction is very sensitive to any local deformation that is present at the surface which can have strong variations from one small region to the next, besides that some of this plastic local deformation have no direct connection with the manufacturing process under investigation. Normally X-ray diffraction residual stress measurements can mislead conclusions on process parameters influences if not enough care is taken in the interpretation of the collected data and use of correct measuring strategies. Therefore in this investigation of residual stress fields for cold drawn bars a high amount of positions were measured by using the $\sin^2\Psi$ method with an without a surface polishing to remove local surface effects.

2 EXPERIMENTAL PROCEDURE

The investigated samples were taken after cold drawing. The material was an AISI 1045 steel. The manufacturing of the cold drawn bars followed standard procedures starting from hot rolled material in coils, then following an uncoiling and pre-straightening processing, shot blasting cleaning an drawing. The investigate cold drawn steel bars had 20,25 mm of diameter. The mean reduction applied was of about 12% by a drawing tool using a semi-die angle of 7,5°. Immediately after the drawing operation samples of 120 mm length were taken out of the process line for the analysis. The peripheral angular locations around the bars were used as reference for the measurements and the analysis. The “0º” location is a horizontal line on the upper most position of the rods as they pass through the machinery. By marking this “0º” location the angular peripheral positions on the surface of the samples relative to the machinery is defined. This reference is important to correlate residual stresses with the applied stresses during the process and will be used in this article to indicate the location of residual stress measurements. This reference

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system is shown in Figure 1. The chemical composition of the material is given in Table 1.

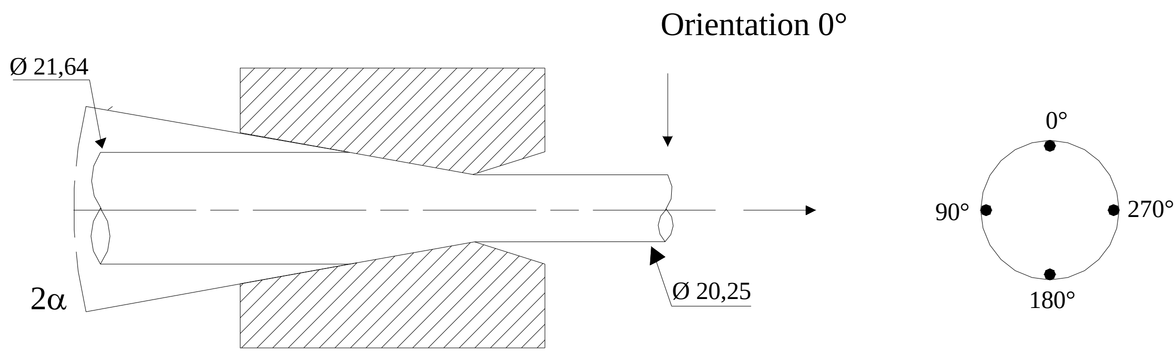

Figure 1 - Schematic view of the drawing process and orientation system.

Table 1 - Chemical Composition of AISI 1045 steel

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb
% in weight	0,43	0,21	0,73	0,01	0,02	0,19	0,01	0,19	0,08	<0,01

Figure 2 displays the microstructure of the medium carbon steel in a longitudinal cross section. Aligned bands of ferrite and pearlite with an ASTM grain size of 7.

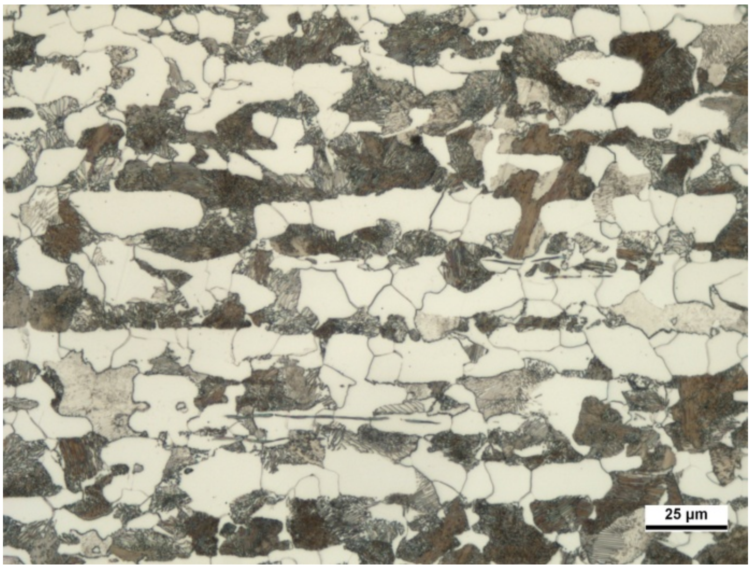

Figure 2 - Longitudinal cross section of the investigated material, Nital 2%.

The measurement procedure is given in Figure 3. All samples have been marked according with Figure 1. Starting with the zero degree line (upper position) lines at 45°, 90°, 135°, 180° and 270° were defined in a counterclockwise turn of the cylindrical sample as locations for the measurements. For each line 20 points were chosen for X-ray diffraction residual stress analysis, being the first point at 50 mm distance from the lower end and the last at 10 mm from the lower end of each sample. An automatic movement along each defined circumference allowed consecutive measurements at each 2mm distance from one measurement location to the next. As the size of the incident X-ray beam was 2 mm the irradiated areas connected each other as demonstrated in Figure 3.

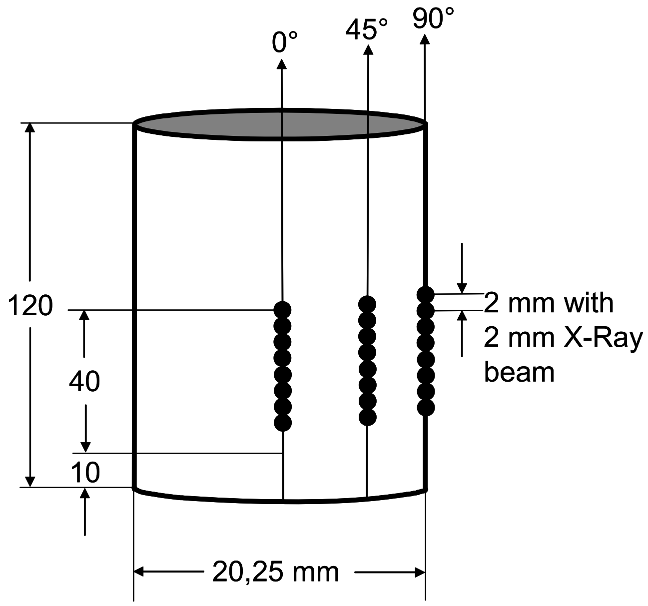

Figure 3 - Measurement procedure.

In this way residual stress fields were analyzed with a total number of 120 measurements. Residual stresses evaluation used the conventional $\sin^2\Psi$ method with a conventional Bragg-Brentano Geometry (Bruker-AXS D8) equipped with Vanadium filtered Cr-Kα radiation. A primary beam aperture of 2 mm diameter was selected for the local analysis along the length and around the periphery of the drawn cylinders. The diffracted beam slit had an aperture of 2 mm. The {211}-lattice plane of α-iron at 2θ around 156.03° was chosen for the analysis. The measured range in 2θ was from 150° to 162° in steps of 0.05° with measurement time of 5 s. $\sin^2\Psi$-plots for 11 Ψ-angles equidistant in $\sin^2\Psi$ and with a Ψmax equal to 45° in the positive and negative inclination branches. Finally for the calculation of residual stresses, the X-ray elastic constants½ s_2 was taken equal to 6.09 *10-6 MPa-1 and s_1 equal to -1,33 *10-6 MPa-1. The width of diffraction lines at 50% of the intensity after background correction (full width at half maximum - FWHM) can be used as an estimate of the materials state within the penetration depth of the X-ray radiation. FWHM (Full Width at Half Maximum) values were determined by mean values of all Ψ-angles for each measurement position.
Surface layer removal was executed by emerging the samples in a bath of 80% of H_2SO_4 acid and 20% of H_3PO_4 acid and applying an appropriate voltage (5V) and current (1A) to remove surface layers subsequently. A surface layer removal of 50 µm was chosen to detect differences between surface and subsurface layers. After surface layer removal residual stress analysis was performed at the newly created surface in the same manner as the procedure that had been already followed for the drawn surface.

3 RESULTS AND DISCUSSION

Following the measurement procedure in Figure 3 results of surface residual stresses of drawn bars are displayed in Figure 4. For clarification of the 120 data points, symbols of the 0°, 45° and 90° lines are full black squares, triangles and circles with bold lines. The axial lines 135°, 180° and 270° are displayed with open squares, triangles and circles with hatched lines. It is obvious that pronounced scatter in

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surface residual stresses can be observed even for a relatively small distance of 40 mm along the axial length of drawn material. No systematic dependence of e.g. minimum and maximum residual stresses for each vertical line or for each circumferential line can be detected. The mean standard deviation of these X-ray diffraction residual stress measurements is around 10 MPa. Overall minimum differences between circumferential lines occur at positions 4 and 18 mm distance from the chosen zero position and maximum differences can be seen for 28 mm and 30 mm.

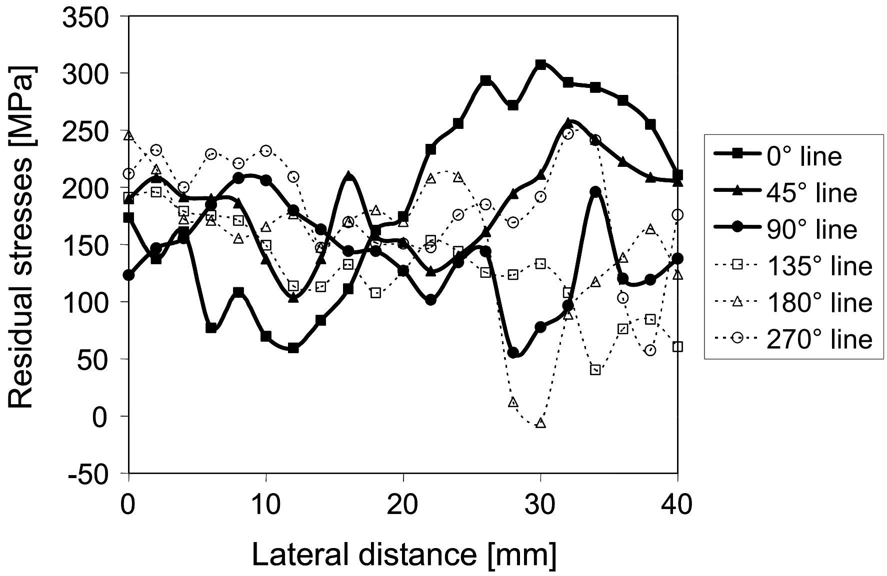

Figure 4 - Residual stresses plotted against axial distance along different lines around the circumference of a drawn bar (7,5° semi-die angle)

Similarly to the results in Figure 4, Figure 5 now presents results of the Full Width at Half Maximum (FWHM) of diffraction lines from the {211}-lattice planes of the α-iron. In despite the fact scatter of about 0.1° is always present in the analysis of FWHM values, differences can also be observed. It seems that lateral positions with small scatter in residual stresses exhibit higher scatter in the FWHM values and vice versa (compare Figure 4 and Figure 5). All data for the line measured at 135° circumference angle find themselves at the lower end of the FWHM scatter band. The residual stresses of the third kind are deviation from the average of stresses within regions smaller than a grain, and the strength of stresses is about the atomic force. They are caused by lattice defects and dislocation. Presence of the third kind stress is evaluated by changes of FWHM of X-ray profiles qualitatively.

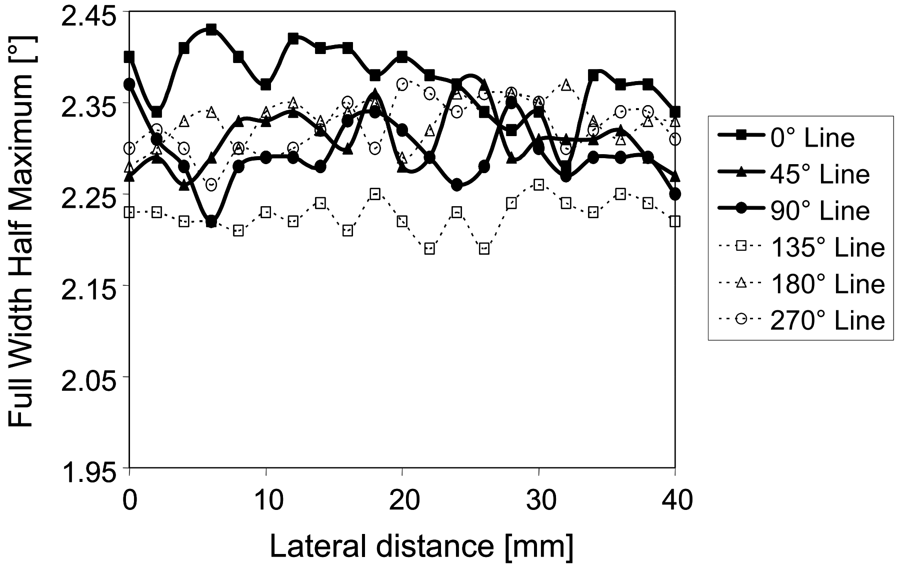

Figure 5 - Full width at half maximum of {211} diffraction lines plotted against axial distance along different lines positioned around the circumference of a drawn bar (7,5° semi-die angle)

Figure 6 demonstrates results of residual stresses for a tool with a similar die angle but covered with a hard and wear resistant layer of 4 µm TiCN [Balinit®]. Compared to Figure 4 residual stresses are generally shifted to higher values in Figure 6. In spite of the fact that the contact between tool and workpiece is far different, also significant local scatter can be observed. Comparing Figure 4 and Figure 6, maximum and minimum values after drawing with a conventional new tool are 307 MPa and -6 MPa and 359 MPa and 160 MPa respectively for the coated new tool. According to the information given in Figure 6 high negative values of residual stresses between 26 mm and 34 mm along the 0° degree line probably cannot be the result of a drawing process. Observing Figures 4 and 6, the residual stresses have tensile behavior, and at some isolated axial and peripheral positions this behavior changes to compression.

The pronounced scatter of surface residual stresses in Figure 4 and Figure 6 in the first moment was unexpected. If this variation of residual stress states would be due to local surface effects in the wire drawing process a surface layer removal should be able to reduce theses scatter.

Figure 6 therefore proves the presence of an indent at these positions introduced by a contact between bars during the transport from the manufacturing site to the Lab. The residual stress analysis with a dense mesh of points however is able to detect local residual stress changes introduced by the elastic-plastic deformation of the indent as showed in Figure 7.

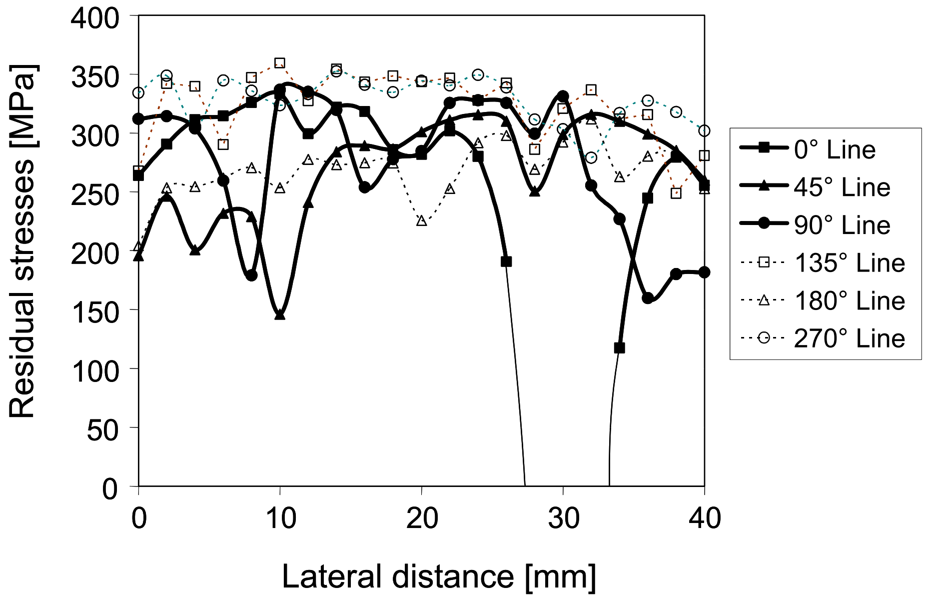

Figure 6 - Residual stresses plotted against axial distance along different lines around the circumference of a drawn bar (TiCN coated tool with 7,5° semi-die angle).

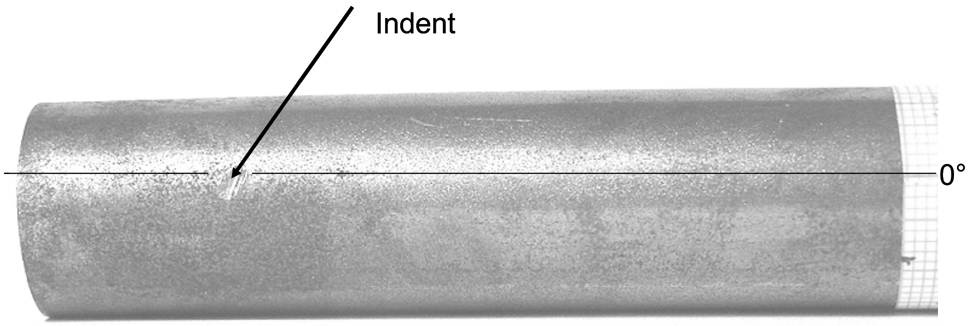

Figure 7 - Sample of results in Figure 7, indent within at the 0° analysis line.

Figure 8 summarizes mean values of residual stresses for each measured circumferential line. These mean residual stresses of the first sample manufactured with an uncoated tool decrease from a value of 190 MPa for the zero degree line to a minimum value of 129 MPa at 135 degrees around the circumference. Increasing mean values then again can be observed for higher circumferential angles. A mean for all 120 measurements can be calculated to 163 MPa, still lower than expected for this drawing process and the material used. It seems to be obvious that the distribution of residual stresses around the bar is not axisymmetric immediately after the drawing process. It should be noticed that additional straightening is necessary after the drawing to guarantee the required straightness of the product. For the coated tool Figure 8 again documents with mean values the shift to higher residual stresses. Additional circumferential lines have been measured for 225° and 315° and are plotted in Figure 8. The deviation from one line to the next is higher for the coated tool especially at 135°. Mean residual stress values of 323 MPa were calculated whereas at 225° a minimum of 198 MPa exists. The distribution of residual stresses around the circumference of the bar drawn with a coated tool also exhibits a significant deviation from asymmetry. The mean value of all the 120 measurements is 258 MPa.

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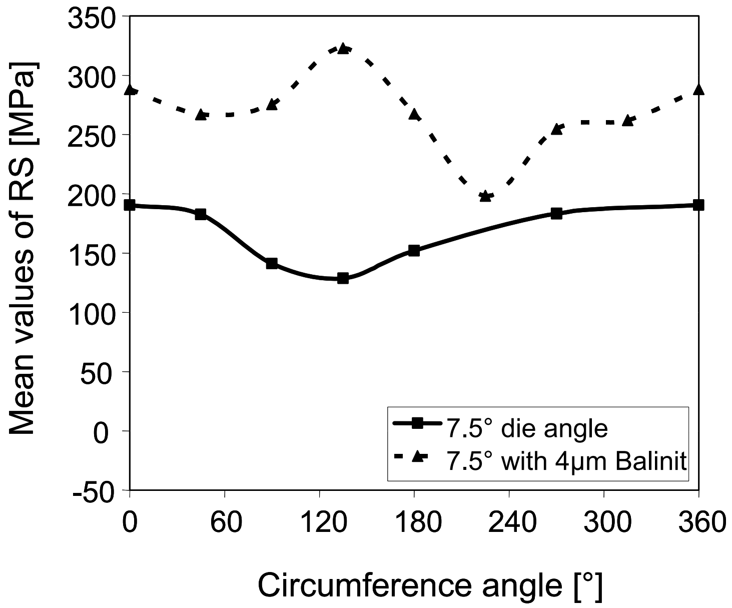

Figure 8 - Mean values of residual stresses (RS) plotted against the circumference angle. Values at 360° were set to be equal to 0°.

Figure 9 consequently presents the analysis after a surface layer removal of 50 µm. Comparing Figure 4 and Figure 9 the main difference is the reduced scatter of residual stress values. If some single points for lateral distances higher than 30 mm are ignored all residual stress values can be ordered within a band of about 50 MPa of width. Local differences from one point to the other do not anymore exist. The mean value of all measurements increases from 163 MPa to 191 MPa. The plots of residual stresses so far for the uncoated drawing tool gave an increase in the mean values for all measurements. On the other hand a materials properties gradient is to be expected for these drawing processes and the analysis of FWHM values is able to prove these assumptions in Figure 10.
This differences shows that the penetration of the bending residual stresses reached layers deeper than 50 µm. From the results it is obvious that within a surface layer of 50 µm different material states can be observed by just using uncoated and coated tools in the same wire drawing process. It is also obvious that within this surface layer significant changes of material states occur if only one specific wire drawing process is analyzed.

ISSN 1516-392X

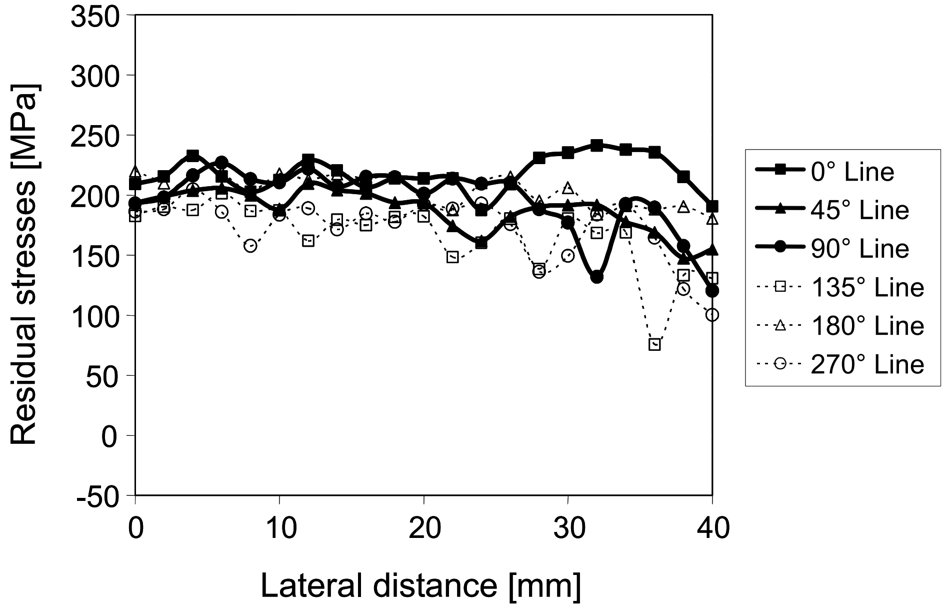

Figure 9 - Residual stresses plotted against axial distance along different lines around the circumference of a drawn bar after removal of a surface layer of 50µm in thickness (7,5° semi-die angle).

Figure 10 shows results of the FWHM analysis after 50 µm layer removal for cold drawing using the coated tool. The FWHM decreases from about 2.3^o in Figure 5 to about 2.05^o in Figure 10. In a surface distance of 50 µm the FWHM values of the 135° line still show the lowest values in despite of the fact that the total range of values is fairly well within experimental scatter of FWHM analysis of normalized medium carbon steel.

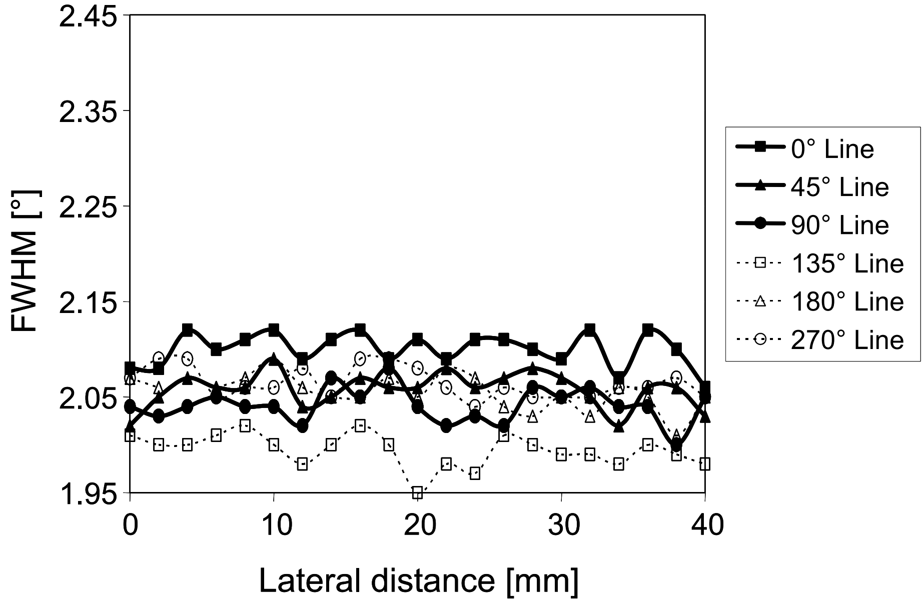

Figure 10 - Full width at half maximum of {211} diffraction lines of plotted against axial distance along different lines around the circumference of a drawn bar after removal of a 50µm thick surface layer (7,5° semi-die angle).

Finally, Figure 11 summarized mean values of residual stresses and FWHM plotted after the surface layer removal of 50 µm for the uncoated and the coated tool. For the coated tool also the scatter of residual values and FWHM is reduced considerably.

Bars which have been drawn with the TiCN coated tool exhibit a significant decrease in the residual stress values in a surface distance of 50 µm. In this surface layer distance bars of both manufacturing sequences now present a materials states with equal residual stress and FWHM values. Residual stresses do not differ more than about 50 MPa if mean values of each circumferential line are considered. FWHM values do not differ more than about 0.1° within experimental scatter of the analysis if mean values of each circumferential line are considered.

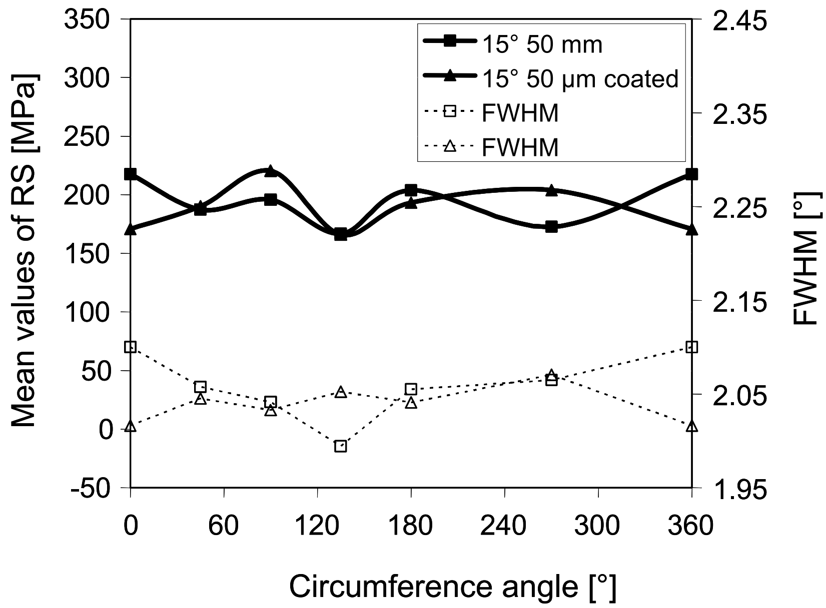

Figure 11 - Mean values of residual stresses (RS) and FWHM plotted against the circumference angle after a surface layer removal of 50 µm for the uncoated and the coated tool. Values at 360° were set to be equal to 0°.

Another important aspect can be observed in residual stress behavior, there are some variations along the sample. These differences have been observed in other studies,[5] it is believed that these residual stress variations along the periphery and axial positions are related to the level of pre-straightening during first step of the drawing process. During pre-straightening process, bending moments are applied to straighten the wire rod, during this process the bending levels depend on the straightening level of the wire rod. This process is necessary to ensure the quality of the drawn bar, and reduce the efforts in tool. After straightening process the residual stress distributions is not homogeneous and the deformation during the cold-drawing process does not eliminate these residual stress profiles.

4 CONCLUSION

Surface residual stresses after drawing process of AISI 1045 steel bars has been investigated. Some differences in the distribution of residual stresses along the surface of the samples were characterized. These differences are associated with the process and coated tool. Surface residual stresses after drawing are strongly affected by the die coating used which can change completely the residual stress values on surface and as a function of distance from the surface. Using TiCN coated tool the surface residual stress is more tensile. Comparing residual stresses of coated and uncoated tool after a surface layer removal of 50 µm the mean values are very close. For coated tool, after a surface layer removal of 50 µm the mean values

ISSN 1516-392X

of residual stresses and FWHM decrease, confirming that surface differences are caused by coating. From this work it's possible to see that to have average values of residual stresses in cold drawn bars is necessary to perform several measuring along the bar.

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