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# MICROSTRUCTURE, TEXTURE AND RESIDUAL STRESSES AFTER COLD EXTRUSION - APPLICATION OF WHITE HIGH ENERGY SYNCHROTRON RADIATION -

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## ABSTRACT

Cold metal forming processes result in a severe change of the microstructure and the texture of the products. Due to the inhomogeneity of the deformation, texture as well as residual stress gradients develop across the sample diameter. The texture and the residual stresses can be analysed simultaneously with high local resolution using white high energy synchrotron radiation.

## 1. INTRODUCTION

Cold extrusion processes are known to give a high output capacity and to permit a near-net-shape-production e.g. of automobile parts. During cold extrusion, large plastic deformations develop due to the large reduction of the workpiece cross section. These large plastic deformations result in a grain elongation as well as in a change of grain orientation. The plastic deformation is inhomogeneous throughout the workpiece cross section, thus texture gradients as well as residual stresses arise. The sign, the magnitude and the distribution of the residual stresses severely influence the fatigue limit and the stress corrosion resistance of the workpiece. Here, in order to study the texture and the residual stress distribution of cold forward extruded steel samples a recently developed new method (Reimers et al. 1998, 1999) using white high energy synchrotron radiation has been employed in addition to X-ray and neutron diffraction.

## 2. EXPERIMENTAL DETAILS

The samples analysed, German steel grade C15 were full forward extruded to rods of 15 mm diameter at the Institut für Umformtechnik, Universität Stuttgart, Germany, varying process parameters, e.g. the conversion ratio φ (φ = 0,9; 1,2; 1,6) and the ejection mode (Zucko et al. 1997).

The microstructure of the samples was studied by optical and transmission microscopy. The domain size and the dislocation density as well as pole figures were determined using X-rays. Also for residual stress analyses in the near surface region X-rays were employed, while the residual stresses in the bulk of the samples were studied by neutron diffraction. Details are given in (Pyzalla et al. 1997).

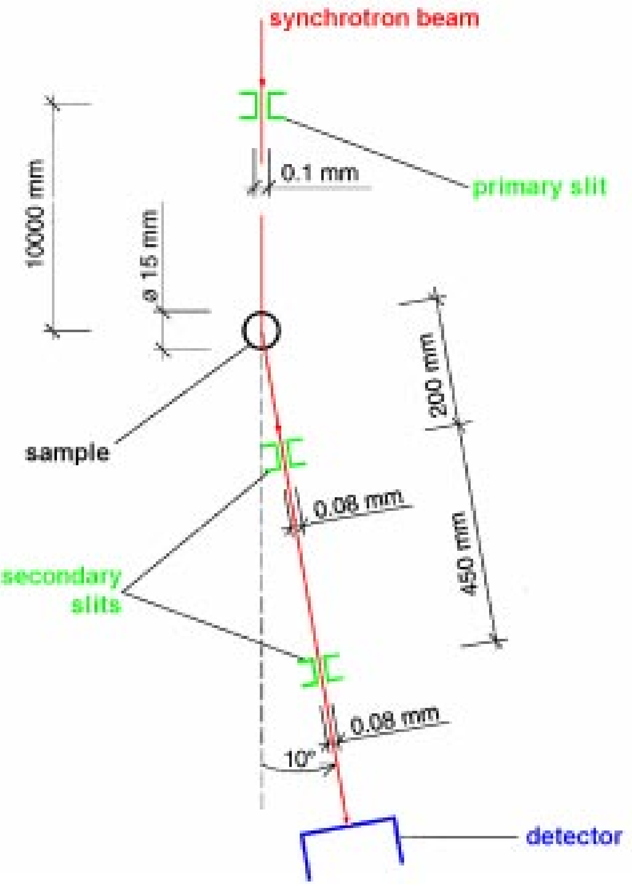

Fig. 1: Scheme of the set-up

Besides, white high energy synchrotron radiation was used for texture characterisation and residual stress analysis. This new method, due to the decrease of the absorption coefficient of the materials at increasing radiation energy, allows the determination of the triaxial residual stress state in the bulk of the steel samples. As a consequence of the high photon flux at the high energy beamline (P. Suortti et al. 1995) ID15A (Fig. 1) of the European Synchrotron Radiation Facility (ESRF), Grenoble, the gauge volume could be limited to a size of 145 µm width, 1653 µm length and 1000 µm height by using slits in the incoming and the diffracted beam and a diffraction angle 2θ = 10°.

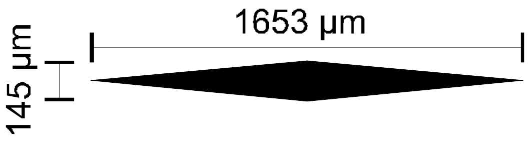

Fig. 2: Volume element

Within the beamtime available, one specimen (φ = 1.2) was investigated, whose residual stress and texture distribution were studied at four positions across its radius. In those positions measurements were performed in radial, hoop and axial direction.

From the energy dispersive spectrum the intensity and the line position of the different reflections can be obtained by fitting the reflection profile using a suitable e.g. a Gauss distribution. The energy value $E^{hkl}$ representing the line position corresponds to the lattice spacing $d^{hkl}$ including the lattice strain.

The lattice spacing $d^{hkl}$ can be calculated from the respective energy value according to Bragg's law

$$d^{hkl} = \frac{h\,c}{2\sin\theta}\,\frac{1}{E^{hkl}} = \text{const.}\ \frac{1}{E^{hkl}} \qquad (1)$$

with hkl denoting Miller's indices, θ the Bragg angle, h Planck's constant and c the velocity of light. The strain $\varepsilon_i^{hkl}$ of the lattice plane hkl in the direction i of the sample can be determined using

$$\varepsilon_i^{hkl} = \frac{d_i^{hkl} - d_0^{hkl}}{d_0^{hkl}} = \frac{E_0^{hkl}}{E_i^{hkl}} - 1 \qquad (2)$$

Then the principal residual stress can be calculated from the residual strains obtained in the principal directions by Hooke's law using the diffraction elastic constants (DEC), whose values depend on the lattice plane hkl.

## 3. RESULTS

3.1 Microstructure of the samples. The material flow during the extrusion is visible in the microstructure of the samples. While in the rod kernel a homogeneous elongation of the grains exists (Fig. 3) the material flow is obstructed due to friction at the surface of the samples, thus the microstructure near the surface is less homogeneous and the grains are less elongated. Transmission electron microscopy reveals that at high conversion rates the dislocations build cell structures (Fig. 4).

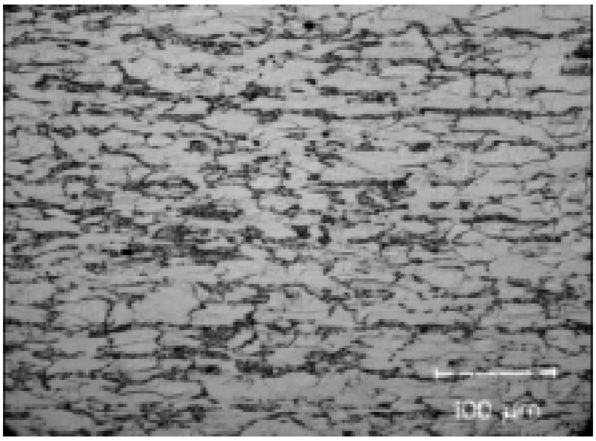

Fig. 3: Microstructure in the centre

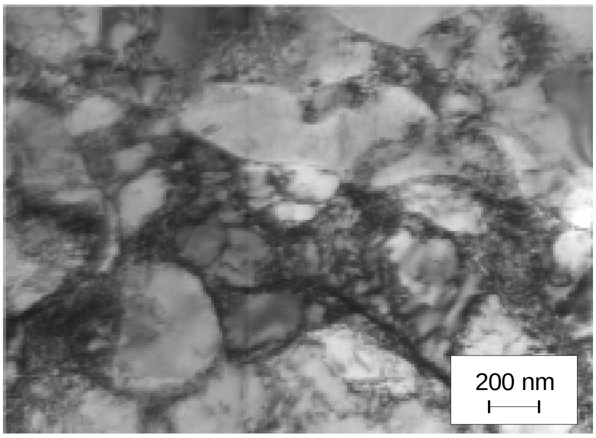

Fig. 4: Dislocation cells

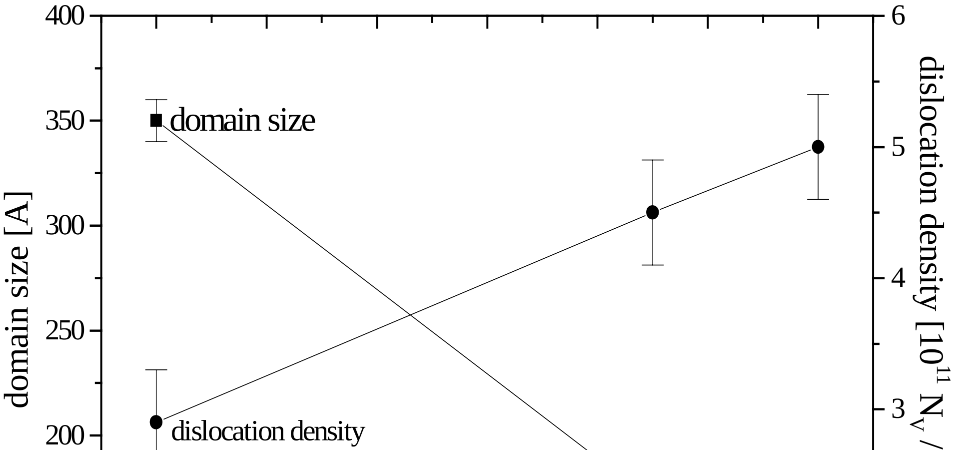

Fig. 5: Domain size and dislocation density vs. conversion ratio

The plastic deformation of the samples can be quantified further by the dislocation density and the domain size of the samples, given by the average of measurements using the 200 and 211 reflection in Fig. 5. As expected, the dislocation density increases with increasing conversion ratio, while the domain size decreases with increasing conversion ratio.

3.2 Texture. Due to the strong plastic deformation a texture develops also. X-ray analyses, integral across the sample diameter, reveal a <110> fibre texture, typical for extruded bcc materials. The strength of the fibre increases with increasing conversion ratio.

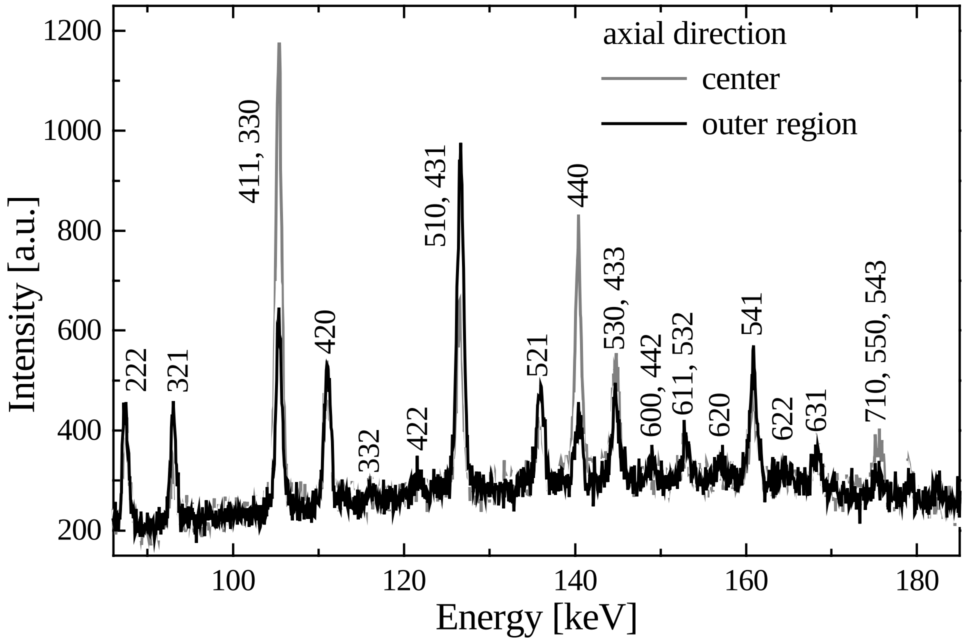

Fig. 6: High Energy Synchrotron radiation spectra

The <110> fibre texture also is clearly visible comparing the spectra obtained in axial and hoop direction by using white high energy synchrotron radiation. Further on, a variation of the fibre strength is obvious regarding the spectra obtained in axial direction in the centre and near the surface of the sample with a conversion rate φ=1.2 (Fig.7).

Due to the energy dispersive characteristic of the method, the whole spectrum is available. The

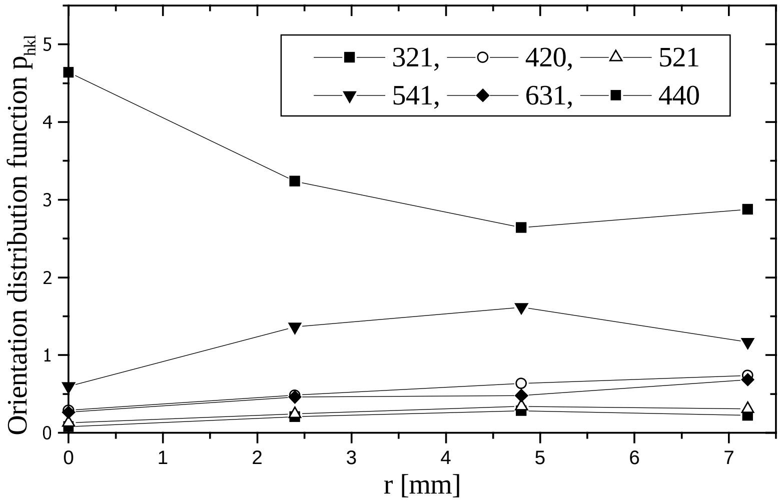

Fig. 7: Gradient of the 110 fibre texture

strength of the fibre texture thus can be characterised on the basis of the measurements in the axial direction and by comparing the intensity values, after corrections for the absorption, to the intensity values obtained from a powder of the same material. The values of the orientation distribution function, determined according to the formalism given in (Gerward et al. 1976) show, that the maximum strength of the <110> fibre is found in the centre of the samples and that the fibre texture is less distinct in the outer regions of the sample.

3.4 Residual Stress. From the energy values obtained for the 442, 440, and 541 reflection in radial, hoop and axial direction of the sample the residual stresses were calculated. The $d_0$ value (strain-free lattice distance) necessary for the determination of the three - dimensional residual stress state was calculated as an average of the lattice distance values obtained for the different reflections and volume elements.

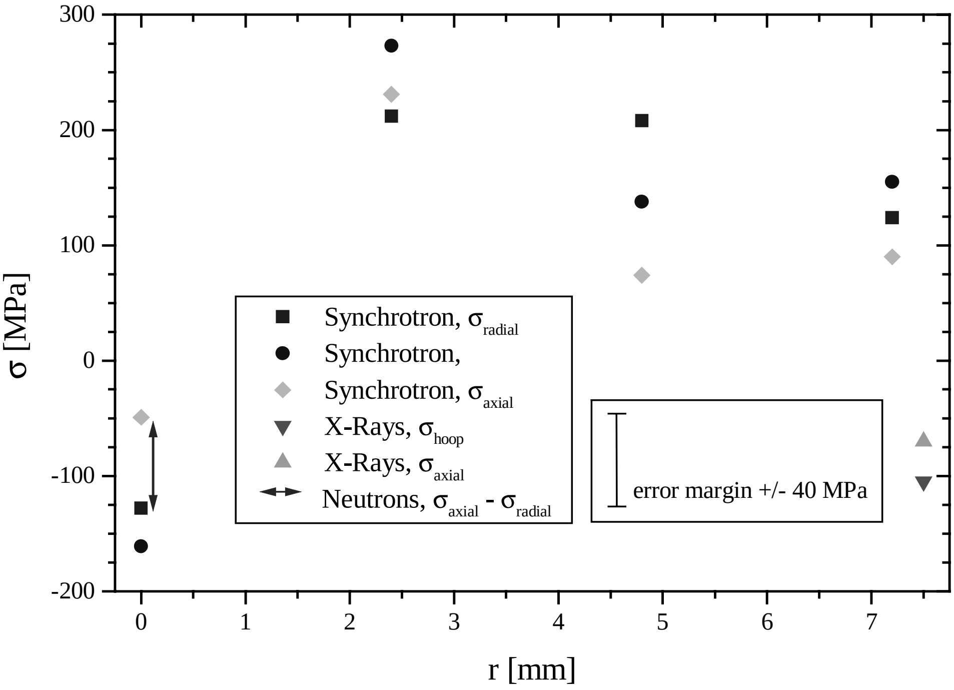

Fig. 8: Residual stress distribution

Neutron diffraction and synchrotron diffraction in good agreement reveal that in the inner part of the specimen the residual stresses in radial $\sigma_{radial}$, hoop $\sigma_{hoop,}$ and axial direction $\sigma_{axial}$, are compressive. These compressive residual stresses are balanced by tensile residual stresses in the outer part of the sample. The quantitative stress values also fulfil within an experimental error margin of ±80 MPa the mechanical equilibrium condition. At the surface of the sample again compressive stresses in hoop and axial direction where obtained by X-ray diffraction.

## 4. CONCLUSIONS

The characterisation of the microstructure and the texture of the samples reveal that the plastic deformation during cold forward extrusion is concentrated in the rod kernel. In the rod kernel and in the near surface region compressive residual stress are present, the part in between is under tensile residual stresses. The microstructure and the residual stress distribution can be linked to the deformation process during the cold forward extrusion (Tekkaya et al. 1985). Due to deformation obstruction at the shoulder of the die, the material flow at the surface is slower and more inhomogeneous than in the inner part of the specimen. Therefore, within the rod kernel the grains are homogeneously stretched whereas at the surface of the sample the grains are first compressed and then stretched, while passing the transient radius of the die. Thus, tensile residual stresses remain in the outer part, while the inner part of the sample is under compressive residual stresses. The compressive stresses near the surface are due to friction effects and their value depends on the lubricant (Pyzalla et al. 1997).

The experiments reveal that high energy synchrotron radiation, that has recently been introduced as a new tool for these analyses, allows for a simultaneous local analysis of texture and residual stresses.

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