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EVALUATION OF MICROHARDNESS, EFFECTIVE STRESS AND RESIDUAL STRESS IN COLD ROLLING OF COMPLEX PROFILES – COMPARISON BETWEEN EXPERIMENTS AND CALCULATIONS

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ABSTRACT

The methods of cold rolling of rods are widely used in manufacturing industries to obtain pieces with complex profiles. In this study, complex profiles with grooves have been formed by in-feed methods using two rolls. The microhardness has been measured by Vickers method in an axial section of the rolled piece. The process also has been simulated by means of finite element calculations using the Abaqus/Explicit code, giving the distributions of yield stress and residual stress at the end of the process. Finally, a comparison is made between experimental and simulated results.

KEYWORDS: cold rolling, groove profile, microhardness, numerical simulation.

1. INTRODUCTION

Complex profiles (threads, teeth etc.) can be found as part components in the automotive industry, air industry, appliances etc. Their processing by cold rolling has certain advantages as compared to the cutting process: the dimensional precision is situated at 6-7 level for the threads, 7-8 for the worms and cylindrical teeth and stages 6-8 for the notches; the roughness R_a is generally lower than 4 μm; and the physico-mechanical properties of the superficial layers are substantially improved (microhardness, thickness of the deformed layer, crystallographic texture, residual stresses, resistance to fatigue and mechanical resistance).

An important objective of the deformation processing of metals and alloys is the production of defect-free parts, with the desired microstructure and properties. This goal can be achieved through a better design and calculation method and a better control of the process parameters.

In recent years, a large number of studies have been devoted to the analysis and modeling of the mechanics of metal-forming processes, using more and more processing and simulation methods, which combine the classical research with the numerical simulation by means of the finite element (FE) modeling. The advances that were achieved using the accumulated knowledge have enabled the forming industry to improve product performance, service life and process competitiveness [3].

The FE modeling of cold rolling uses numerical models of the elements involved in the working process, blank material – tools, with the aim of computing the evolution of different quantities during the process: the stresses and strains within the deformed body, the material flow paths, the final profile of the parts.

The preoccupations of the FE modeling of the cold rolling process started in 1990's [1, 3], but the high volume of necessary calculations and the computers incapacity to simulate the process within a reasonable time, restricted these studies to the understanding of the deformation process [1 - 4], by analyzing the state of stresses and strains of circular profiles at different degrees of deformation.

The researches intensified after the year 2000, together with the development of the simulations software and with the growing computational capacity of computers [5 - 12]. The main elements of these researches are the material of the piece, piece profile and rolling process, with particular attention to the plastic behavior of the material, the meshing elements and the software's used for simulations (MARC, ABAQUS, DEFORM, MSC Super Form ...).

In this study, complex profile with grooves has been formed by in-feed method using two rolls. This paper focuses on the development of the three-dimensional FE models and validation results based on microhardness measurements. The experimental microhardness was measured on the axial section of the tooth by Vickers method and the process was simulated using the Abaqus/Explicit code.

2. EXPERIMENTAL PROCEDURE

Because threads are incrementally formed by progressive penetration of the dies into the blank surface during a fixed number of blank revolutions, external thread rolling operations can be represented approximately as plane strain compression of a workpiece using a parallel set of wedge-shaped indentors. For this reason, the profile generated by radial cold rolling using two rolls and in-feed method was a concentric channels surface (three grooves similar to trapezoidal thread Tr 30x6, fig. 1).

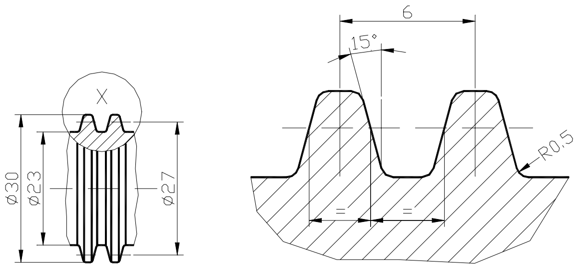

Fig. 1. Form of the profile rolling

The materials used in this investigation were steels OLC 15 and OLC 35. Their chemical composition and microhardness are given in Table 1.

The measurements of the microhardness were made by Vickers method. This method allows us, at the same time, to use small loads and to compare the results with other mechanical quantities. The load was taken equal to 200 g, in order to take account of estimated microhardness and of the size of grains after cold rolling. The pieces were cut by electro erosion and then they were finely ground for measurement of the microhardness in axial section of the tooth. The microhardness indentations were performed on several lines and along two directions, parallel to the flank of the tooth and to the axis of the piece, respectively. For each direction the distance between indentations was 0.5 mm.

3. NUMERICAL PROCEDURE

The numerical calculations were performed with the dynamic explicit FE code Abaqus/Explicit.

The elastic behavior of the workpiece is modeled by assuming isotropic elasticity, with the values of Young's modulus, E = 200,000 MPa and Poisson's ratio, ν = 0.3. Strain hardening is described using the von Mises criterion with the assumption of isotropic hardening. Accordingly, the yield function is given by:

$$f = \sqrt{\frac{3}{2} s_{ij} s_{ij}} - \bar{\sigma} \quad (1)$$

where s_{ij} are the deviatoric stress components, $\sqrt{(3/2) s_{ij} s_{ij}}$ is the von Mises equivalent stress and $\bar{\sigma}$ is the current yield stress. In accordance with the best-fit curves obtained in torsion tests (see section 4), strain-hardening was described by the Ludwik law:

$$\bar{\sigma} = \sigma_0 + K \bar{\varepsilon}^N \quad (2)$$

where $\bar{\varepsilon}$ is the effective strain, and σ_0, K and N are material constants.

The workpiece was meshed using a non-uniform distribution C3D8R hexahedral element. The previous metallographic examination of rolled pieces shows that deformation is concentrated in the superficial layers of the blank with very little straining of grains in the workpiece interior. Based on this observation, a dense mesh was used in the deformation zone near the blank surface and a coarser mesh was applied in the blank interior to ensure compromise between the number of elements (68,955) and accuracy of results, fig. 2. In particular, the mesh is made of elements 0.2 mm long in the regions where grooves are formed.

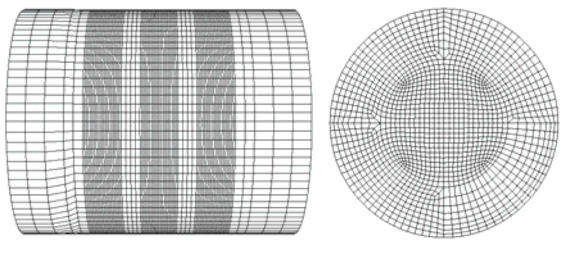

Fig. 2. Finite element mesh used for the workpiece

Table 1. Chemical composition and initial microhardness of the steels

Materials	Chemical composition (wt %)							Microhardness (average) Vickers 200 g [MPa]
	C	Si	Mn	Cr	Ni	Mo	P, S	
OLC 15 (SAE 1015)	0,13	0,21	0,9	0,23	0,24	0,07	< 0,035	1570
OLC 35 (SAE 1035)	0,33	0,16	0,85	0,14	0,15	0,03	< 0,035	2060

The tools are defined by discrete rigid surfaces. Friction between the contact surfaces is defined with Coulomb's friction model. The friction coefficient is taken equal to 0.3 between tools and workpiece and to 0.01 between workpiece and piece-support. Boundary conditions, fig. 3, are defined as follows:

- the workpiece is free;
- one roll-die has two freedom degrees: a rotation around its axis and an in-feed translation;
- the other roll-die has a rotation around its axis;
- the piece-support is considered to be fixed.

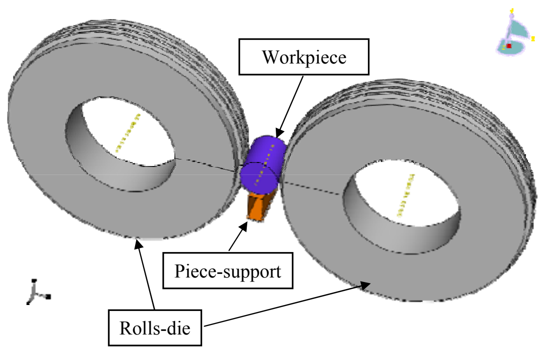

Fig. 3. ABAQUS model for numerical simulation

4. RESULTS AND DISCUSSION

For blank materials, the microhardness HV measured by Vickers method is found to be proportional to the initial yield stress σ_Y, i.e.:

$$HV = \alpha\sigma_Y \tag{3}$$

where the proportionality factor α is close to 3. For plastically deformed materials, σ_Y in equation 3 should be replaced by the current yield stress $\bar{\sigma}$ in order to take account of strain-hardening.

A comparison between experiments and calculations will thus be made by considering the distributions of HV and $\bar{\sigma}$ in an axial section of the piece. The von Mises equivalent stress, calculated after unloading of the piece, is also examined to quantify the level of residual stresses.

In order to model strain-hardening in the FE simulations, the effective stress-strain law of the materials was determined using torsion tests. The results obtained in tension tests were not considered, because of the very low level of uniform elongation which could be reached in these experiments ($\varepsilon = 3\%$ for OLC 15, $\varepsilon = 2\%$ for OLC 35). The shear stress (τ) and shear strain (γ) at the surface of the specimen were calculated using the recorded values of torque (M_t) and rotation per unit length (θ_u) by means of the classical formulae:

$$\tau = \frac{1}{2\pi R^3}\left[3M_t + \theta_u \frac{dM_t}{d\theta_u}\right] \tag{4}$$
$$\gamma = R\theta_u$$

where R is the radius of the torsional specimen. The results were then converted to effective values of stress ($\bar{\sigma}$) and strain ($\bar{\varepsilon}$) according to the von Mises criterion, i.e.:

$$\bar{\sigma} = \sqrt{3}\tau \; ; \; \bar{\varepsilon} = \gamma / \sqrt{3} \tag{5}$$

An example of the fit obtained with the Ludwik law is given in fig. 4 for OLC 35. The hardening parameters of the two materials are reported in Table 2.

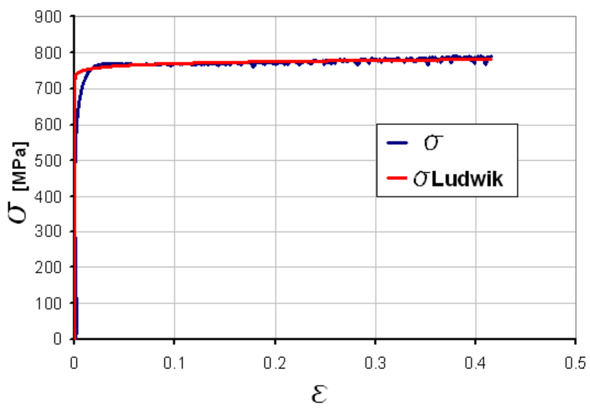

Fig. 4. Effective strain-strain law identified in torsion

Table 2. Coefficients of the Ludwik law

Material	σ_0 [MPa]	K [MPa]	N
OLC15	480	327	0.1906
OLC35	550	313	0.1174

The distributions of microhardness (HV) measured in an axial section of the piece are presented in figs 5a and 6a for OLC 15 and OLC 35, respectively. The distributions of calculated yield stress ($\bar{\sigma}$) are shown in figs 5b and 6b. In spite of a fairly large scatter in the microhardness measurements, the comparison tends to shown a good correlation, with the higher levels of HV and $\bar{\sigma}$ at the bottom of the tooth flank, and lower values in the central part of the tooth. The proportionality factor α between HV and $\bar{\sigma}$ approximately varies between 2.5 and 2.7, a value slightly lower than usually reported in the literature.

Another important information obtained from numerical simulations is the very high level of the von Mises equivalent stress after unloading of the piece, figs. 5c and 6c, which indicates very high values of residual stresses in the superficial layers of the piece.

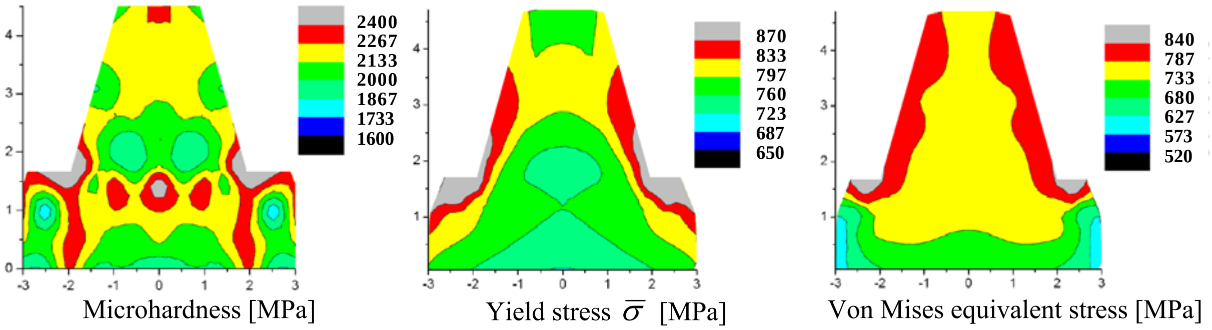

Fig. 5. Experimental microhardness, calculated yield stress and equivalent residual stress - OLC 15

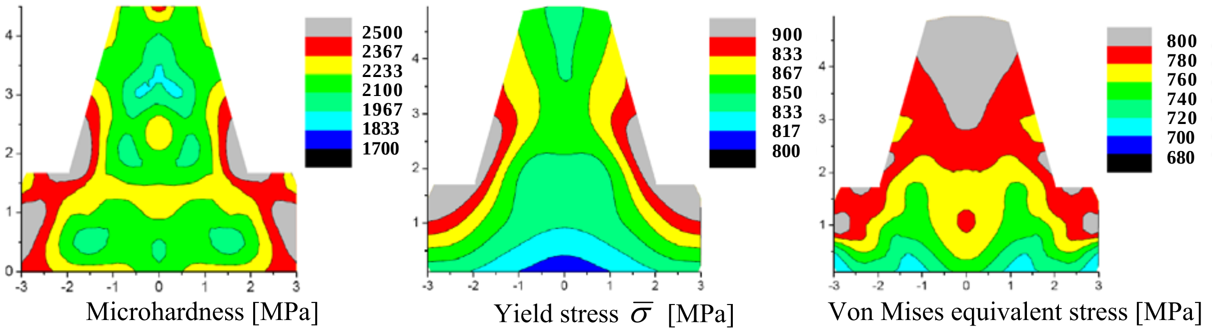

Fig. 6. Experimental microhardness, calculated yield stress and equivalent residual stress - OLC 35

5. CONCLUSIONS

The results presented in this work have shown that valuable informations can be obtained by means of FE simulations of the cold rolling process, concerning the mechanical properties of the piece, in particular: the distribution of yield stress in the superficial layers, in reasonable agreement with experimental measurements of the microhardness, and the very high level of residual stresses at the end of the rolling process.

6. ACKNOWLEDGEMENTS

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