MULTISCALE COMPUTER SIMULATION OF METASTABLE STEEL ROD DRAWING BY USING STATISTICAL REPRESENTATION OF MICROSTRUCTURE

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Abstract

The article describes the state of the art computer simulation in the field of metal forming processes the main problem points of traditional methods were identified. The method, that allows predict the deformation distribution in the volume of deformable metal with taking into account of microstructure behavioral characteristics in deformation load conditions, was described. The article compares the results of modelling the TRIP effect and overlooking it. The comparison shows that martensite, which forms in the microstructure, causes a significant rise of equivalent stresses across the entire representative volume, which is extremely critical in the drawing process engineering. The method applied also gave a better understanding of how the microstructural elements interact in TRIP steel under strain, which helped explain more intense (2 or 3 times as high compared with the average values) radial strains in the plastic phases close to bigger grain clusters of stronger bainite and martensite phases. To save computing time, statistical representation of the microstructure was applied. Statistically Similar Representative Volume Element (SSRVE), representing meta-stable steel microstructure, was developed. Applying the SSRVE concept dramatically decreased the calculation time of the model while maintaining the overall accuracy. The study helped obtain initial data that can be used to design the drawing processes for TRIP steels. This will enable advanced and technically flexible materials to be used in the conventional drawing process, thus expanding the range of applicable steels.

Keywords: Multiscale modeling, drawing, Statistical Representative Volume Element, microstructure, stress-strain state

1. INTRODUCTION

Contemporary machine industry sets high requirements for mechanical and operational properties of machine and line parts. Units of mechanisms and machines should be not only sufficiently reliable, but also capable of being adapted to potentially unfavorable operating environment. Key manufacturing processes of workpieces for parts and elements of facilities are metal forming methods. New properties and operational characteristics of workpieces can be achieved either by expanding a range of materials used in metal forming, or developing new operating conditions or methods of metal forming [1-2]. In both cases, there is a need for modern engineering methods of design, ensuring an extreme high reliability of predicted results of the process under study. In terms of the required resources, the least consuming method of a manufacturing process design is computer simulation with commercial software, providing engineers with a wide range of opportunities for analysis and optimization. In general, it allows for a significant decrease in expenses for testing results of studied operating schedules and technologies. The majority of computer models in today research on metal forming processes does not factor into features of the processed steel structure. As a rule, operating conditions are designed from the position of an isotropic material. However, it is known that a main indicator of technological transformations in processed steel is its microstructure. Aggregate steel microstructure parameters reflect results of deformation, thermal and combined influence to the fullest extent possible [3, 4]. Contemporary metallurgical technologies intensively use materials with complicated metastable microstructure: for example, TRIP (Transformation-Induced Plasticity) and TWIP (Twinning-Induced Plasticity) steels [5, 6]. Dynamic structure and phase transformations, which are resulted from strains in these steels, provide engineers with a higher degree of freedom in selecting a design, optimization of the weight and a general manufacturing process. Therefore, simulation of the forming process of these steel grades, without factoring into a behavior of their microstructure under a loading condition, is not feasible. In view of the above reason, computer simulation methods should be developed to represent a microstructure of processed steel and a stress-strain state at its micro-level. At the same time, such transfer to the micro-level in computer models entails an inevitable reduction of the FE mesh size and, consequently, growth of the elements number, which required large calculation resources and time. So, contemporary simulation methods are not always technically available and prompt.

Thus, improvement of computer simulation approaches, factoring into the behavior of the steel microstructure in the research of metal forming processes, is a current trend in the engineering analysis. The applied methods should be optimized in terms of computing time and required computing resources. One of basic metal forming processes to produce long steel products used as semi-finished workpieces is rod drawing. During this process hot rolled round rod with 7 - 60 mm in diameter are subjected to a single-pass drawing through a solid die with reductions of 5 - 15 %, as a rule. This process is widely used to produce intermediate workpieces for rod parts (shafts, axis) in machine building, instrument engineering, agricultural machinery industry. In terms of the manufacturing process, drawing provides for wide opportunities to control parameters of steel rod.

2. SIMULATION

To assess a manufacturing potential of the process, a single-pass rod drawing, having an initial diameter of 38 mm was selected. This diameter is widely used in all fields of the machine industry. To study how reduction influences steel properties, a final diameter was varied from 37 mm to 35 mm. The die angle was varied within 18-12°. Drawing speed was 100 mm / sec. As an initial material, we selected TRIP 700.

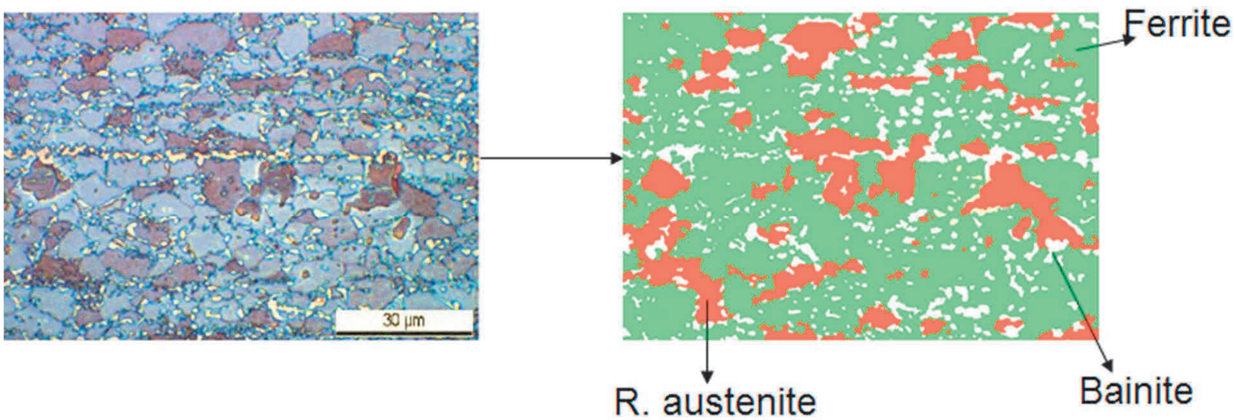

Figure 1 TRIP 700 microstructure

A standards solver of software package Abaqus 6.14-1 was used for the calculations. The model was axisymmetric. The rheological model was elastoplastic. The friction was described by the Amontons-Coulomb Law with friction coefficient of 0.05. The macro model mesh included 26,000 elements. Elements type was CAX4R (Standard Element Library): a 4-node bilinear axisymmetric quadrilateral, reduced integration, hourglass control. Drawing tool had type "Discrete rigid". The front end of the workpiece was moving with a speed 100 mm / sec. To perform the micro simulation, an image of the TRIP 700 microstructure (**Figure 1**) was used. An initial microstructure of the steel under study had the following composition: retained austenite (~22 %), ferrite (~66 %) and bainite (~12 %).

A binarized image of the microstructure was covered with a FE mesh with triangle elements of CAX3 type (a 3-node linear axisymmetric triangle) from the Abaqus standard library. The rheological model was elastoplastic. A plastic stress/strain relation for structural elements was presented with curves given the article [7].

To simulate the TRIP-effect, the following experimentally found mathematical relation [8, 9] was selected:

$$v_{\gamma} = v_{\gamma-initial} - 26.708\varepsilon - 0.003\dot{\varepsilon} + 53.516\varepsilon^2 - 0.018\varepsilon\dot{\varepsilon} - 1.06\times10^{-5}\dot{\varepsilon}^2 \quad (1)$$

where $v_{\gamma-initial}$ - initial volume of retained austenite in the TRIP steel microstructure, $\dot{\varepsilon}$ - strain rate, ε - strain degree. SSRVE concept has been used to create a representative volume, which requires less computational resources. The idea of the SSRVE proposed by Schroeder et al. [10] was used. The basic idea is to replace large representative volume (RVE) by statistically equivalent element (SSRVE) with similar morphology and stress-strain behavior under loading condition. This idea has already been successfully applied in the tests on the reconstruction of the DP-steels microstructure [10], but there are no works published on the application of this concept to conditions of real industrial processes.

The process of SSRVE creation consists of the steps presented in **Figure 2** [16].

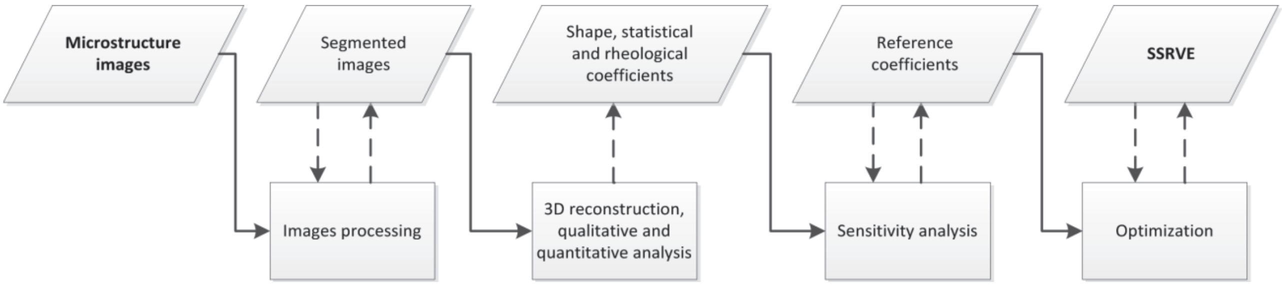

Figure 2 SSRVE creation scheme

The method is based on multi-criteria optimization objective function. It is given by the equation composed of three internal elements responsible for identification of shape coefficients, statistical measures and rheological behaviour:

$$\Phi = \sqrt{\sum_{i=1}^{k} w_i \zeta_i^2 + \sum_{i=k+1}^{k+l} w_i \varphi_{i-k}^2 + \sum_{s=1}^{3}\left(w_s \sum_{j=1}^{p} \sigma_{sj}^2(\varepsilon_j)\right)} \quad (2)$$

$$\zeta_i = \frac{\zeta_{iRef} - \zeta_{i\mathrm{SSRVE}}}{\zeta_{iRef}} \quad (3)$$

$$\varphi_i = \frac{\varphi_{iRef} - \varphi_{i\mathrm{SSRVE}}}{\varphi_{iRef}} \quad (4)$$

$$\sigma_{sj} = \frac{\sigma_{sjRef} - \sigma_{sj\mathrm{SSRVE}}}{\sigma_{sjRef}} \quad (5)$$

Where: equation (3) is a comparison of *i*-th shape coefficient, equation (4) is a comparison of statistical measures and equation (5) is a comparison of stresses obtained for three different deformations of referential microstructure and SSRVE, i.e. compression, tension and pure shear, w_i are parameters weights, k - number of shape coefficients, *l* - number of statistical measures, *s* - number of rheological curves, *p* - number of iterations in numerical simulations. Such approach allows comparison of not only individual numbers but also the whole rheological curves identified for microstructure and SSRVE.

3. RESULTS

Figure 3 presents distribution of the equivalent stresses in central layers of steel in the deformation zone.

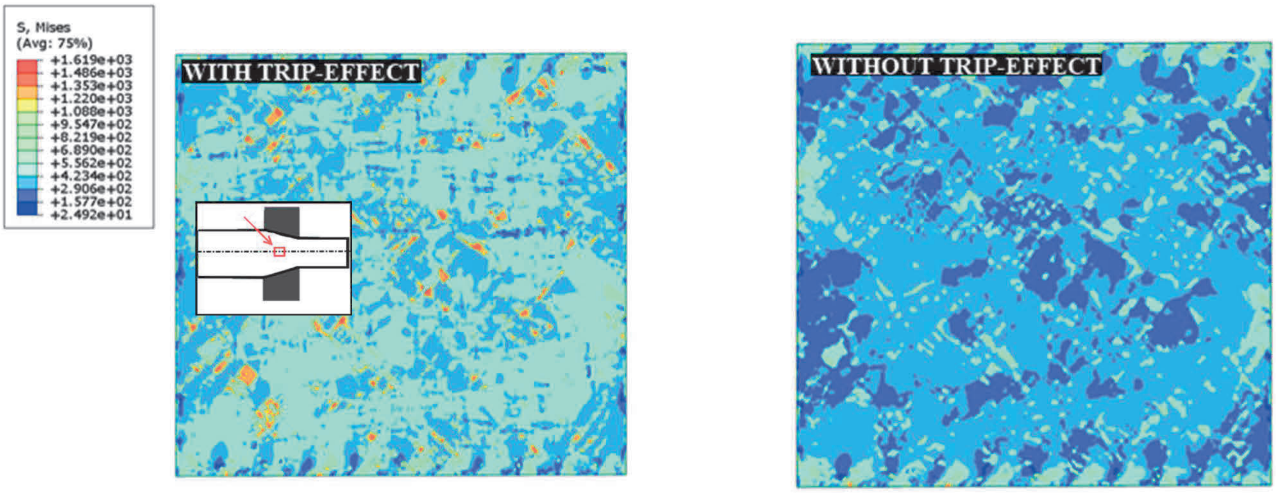

Figure 3 Distribution of equivalent stresses in a central layer of steel in the simulation model with the TRIP-effect and without it

Transformation of relatively plastic retained austenite in harder martensite entails local high values of equivalent stresses. As newly formed martensite is the hardest structural component in a total microstructure of TRIP steel, its aggregates stop their deformation. Values of radial strains and depth of their penetration in steel in a deformation area mainly influence the distribution of mechanical properties in finished products. It is especially important for studied TRIP steels, where mechanical properties change faster than in steels without metastable microstructural components due to the TRIP-effect. Radial strains (**Figure 4**) were analyzed in central and surface layers of steel in the center of the deformation zone.

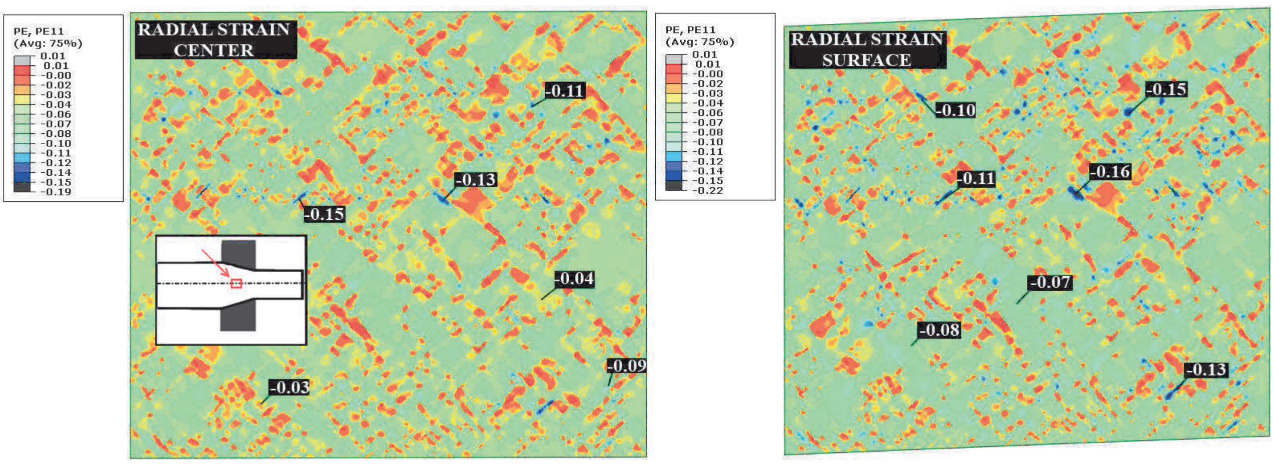

Figure 4 Distribution of radial strains on the surface and in the center of the deformation zone

Figure 5 Evolution of Statistically Similar Representative Volume Element during optimization

Localized near-zero strains are due to high strength of bainite and nucleation of martensite. More plastic phases (ferrite and retained austenite) subjected to compressive radial strains within a range of -0.03 to -0.15 (in the center) and -0.07 to -0.22 (on the surface). It is noted that the highest values of compressive radial strains of plastic phases are localized in areas where harder microstructural components are highly aggregated; it means that some microstrains in steel are due to deformation interactions of microstructural elements. Evolution of Statistically Similar Representative Volume Element, which was obtained during the optimization, is presented in **Figure 5**. The size of this element was 0.02x0.02mm. The error during the optimization was decreased below 2.5 %. Behavior comparison of the SSRVE and the RVE in conditions of drawing process simulation is presented in **Figure 6.** Analysis of the radial stresses in the central layers of the rod enabled to conclude that SSRVE calculations gave similar character of the stress-strain state distribution with the minimum error in absolute values. The calculation time was decreased more than 16 times comparing to the RVE simulation.

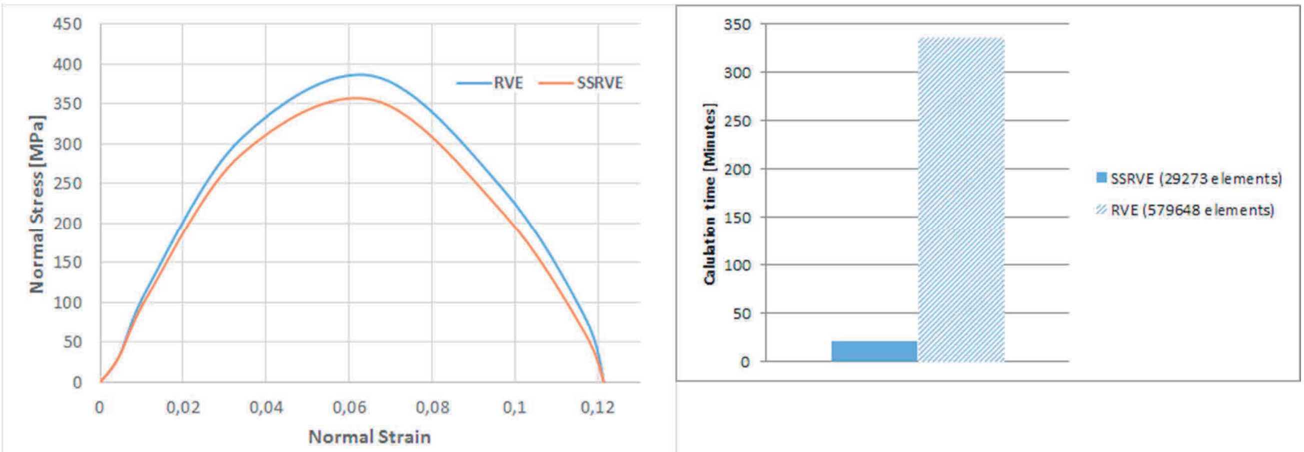

Figure 6 Comparison of RVE and SSRVE: comparison of stress/strain curves and calculation time

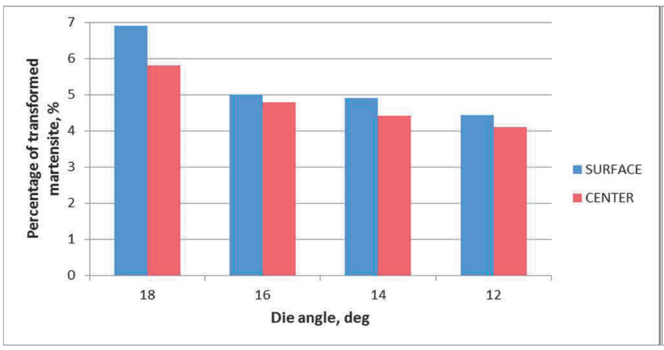

Figure 7 Influence of the die angle on the volume of martensite in the rod microstructure

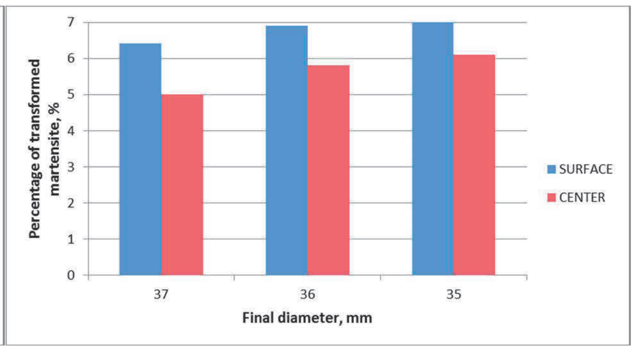

Figure 8 Influence of the reduction on the volume of martensite in the rod microstructure

4. DISCUSSION AND ANALYSIS

Interactions of microstructural elements should be accounted for when designing manufacturing processes of steel rods, consisting of plastic deformation and subsequent heat treatment in the form of recrystallization annealing, as a rule. In that case, it is necessary to avoid so-called “critical” strains when setting drawing schedules for steels rods. When the so-called “critical” strains are achieved, recrystallization does not follow a mechanism of forming new grains and their growth. In consequence, heating entails a rapid growth of initial non-recrystallized grains due to absorption of neighboring ones. Therefore, initial recrystallization occurs to a limited extent, and grains show almost no growth in secondary recrystallization. At critical strains it is detected that there are non-equally deformed neighboring grains and no conditions for centers of initial recrystallization in some volumes of steel. All this entails aggregation of lightly deformed grains by means of other grains, and deterioration of steel mechanical properties later on. Heterogeneity also has a negative impact on the stability of downstream processing and quality of finished products. Finally, investigation on how geometrical die parameters had influenced transformations of martensite in central and surface layers of rod was performed and the results are shown in **Figures 7** and **8**.

5. CONCLUSION

Multiscale simulation of the stress-strain state showed not only prospects of the engineering tool, but also a need for factoring into the microstructure and its behavior under a loading condition, when designing even conventional process for modern materials. The proposed method of generation of multiscale models in case of research on drawing of TRIP steel rod allowed us:

1) to prove how it was important to factor into the TRIP-effect in terms of the stress-strain state, as nuclei of high-strength martensite contributed to localized high values of Mises stresses.
2) to reveal high compressive strains within ranges of -0.03 to -0.15 (in the center) and -0.07 to -0.22 (on the surface) in ferrite and retained austenite.
3) to study deformation interactions of microstructural elements, which explained higher radial strains in plastic phases near a large aggregate of grains of harder phases of bainite and martensite.
4) to decrease model calculation time by more than 16 times and make its generation automatic, while maintaining accuracy of a conventional multiscale model. Thus, the method provided for not just an increase in the prediction accuracy of process models and their calculation speed, but also an expansion of a range of materials used in a conventional rod drawing process with modern, technologically flexible TRIP steels.

ACKNOWLEDGEMENTS

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