SIMULATION OF RADIAL-SHEAR ROLLING OF AUSTENITIC STAINLESS STEEL AISI-321

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ABSTRACT

This paper presents the results of modelling of a radial-shear rolling process of austenitic stainless steel AISI-321. The simulation is performed by Simufact Forming Program Complex. The conditions of simulation refer to those of 14-40 radial-shear mill of Rudny Industrial Institute. The various parameters of the stress-strain state (the effective plastic strain, the effective stress, the mean normal stress and the Lode-Nadai coefficient) as well as the microstructure evolution with the rolling force are considered. It is revealed that the radial-shear rolling is an effective process for obtaining high quality round billets from stainless steels of the austenitic class.

Keywords: radial-shear rolling, stainless steels, simulation, stress-strain state, microstructure evolution.

INTRODUCTION

The rapidly growing long-term demand for energy and the increasing importance of the environmental problems postulate the leading role of nuclear and thermonuclear energy among other sources of satisfying the mankind future energy needs [1]. The alternative energy sources (wind and solar) despite the conditional inexhaustibility and the eco-concept, have a number of common problems referring to a low efficiency, a high cost and low return on investment, climate and area requirements. Meanwhile, the energy consumption increases steadily requiring more effective solutions.

The nuclear power does not have the drawbacks pointed above, but is associated with great environmental risks. The problems attributed to accidents, leaks, and increase of the service life of nuclear power plants elements are mainly solved by the introduction of improved materials [2 - 5]. In addition, the properties of the latter are critical in respect to the future success of the advanced fusion reactors, which expose the metal structure to unprecedented high-energy neutron fluxes along with intense thermomechanical stresses [6 - 7].

Thus, based on the operating conditions of the nuclear power plant structures, the materials requirements can be listed as follows:

1) a high corrosion resistance;
2) a high temperature resistance;
3) a creep resistance;
4) a fracture toughness;
5) a stability of the structure and the properties under irradiation.

This makes it relevant to search for materials capable of withstanding long-term (including dynamic) loads at high temperatures, an aggressive environment and a gradual structural degradation under the influence of irradiation. The last factor is of utmost importance, because materials responding to other requirements are successfully used in industries of no relation to radiation – for example, chemical technology, heat power engineering, metallurgy, engine parts manufacturing.

The structural materials experience structural trans-
formations under irradiation that have a negative impact primarily on the mechanical properties and the corrosion resistance.

The corrosion-resistant steels and the aluminum alloys exhibit the highest resistance to radiation [8]. However, the corrosion rate of aluminum-based alloys in an aqueous medium increases by 2-3 times under irradiation, which is significantly less than that of the austenitic chromium-nickel steels, which are also subjected to intercrystalline corrosion and corrosion cracking in a wet steam. Therefore, the use of steel, and primarily austenitic stainless steel, is the most reasonable.

One of the ways to increase the radiation resistance refers to the use of nano- and ultra-fine-grained materials. Such materials contain a large number of grain boundaries in the structure because of the small grain size. This affects their physical and mechanical properties. At the same time, the grain boundaries should be predominantly small-angled, while the grains are expected to be equiaxed of a size less than 1 micron. Such structures provide a combination of good strength characteristics with high plasticity, which distinguishes them fundamentally from the conventional one. The numerous grain boundaries serve also as runoff surfaces for radiation defects preserving the structure, which increases their radiation resistance.

The severe plastic deformation is the most promising method among those applied to manufacture sub-ultra-fine-grained materials. This is determined by the possibility of obtaining isotropic products of a larger volume with no internal discontinuities. However, the successful structure grinding by SPD methods requires correspondence to special conditions, such as the creation referring to large, non-monotonic deformations under high hydrostatic pressure and low temperatures.

Many methods of SPD do not provide the formation of an isotropic structure throughout the cross section, or have significant restrictions in respect to the size of the resulting product, which significantly limit the scope of their application. Besides, their high energy and labor intensity is a significant drawback limiting their industrial application.

The best method providing to develop a technology suitable for industrial conversion of billets of an increased radiation resistance refers to the radial-shear rolling. Its application results in obtaining billets of an external UFG layer and a softer core. This may be very relevant for the production of fuel rod tubes for the fast neutron reactors of the new generation. Besides, the obtained billets of an increased radiation resistance can be used for the production of nuclear power fasteners and experimental thermonuclear installations.

The aim of this work is to study the radial-shear rolling process of austenitic stainless steel based on a computer simulation. The latter is carried out by Simufact Forming program, which along with the traditionally used Deform program, provides to simulate the processes of pressure treatment of any complexity. However, Simufact Forming has certain advantages over Deform: (i) it has more flexible options for building finite element meshes, including different mesh builders; (ii) it includes Matilda, an additional database of materials, which provides to simulate the microstructure evolution.

**EXPERIMENTAL**

**Formulation of the model**

The parameters of the existing SVP-08 mill installed at Rudny Industrial Institute were used to create a model of the radial-shear rolling. The initial billet of a diameter of 30 mm and a length of 150 mm was rolled on the mill with a compression of 3 mm. Stainless austenitic steel AISI-321 (0.08% of C, 17% - 19% of Cr, 9% - 11% of Ni, 2% of Mn, 0.8% of Si, 0.5% - 0.7% of Ti) was the billet material. Since the initial temperature of recrystallization or diffusion annealing of the selected steel grade was 1020°C [9], the heating temperature of the steel was chosen to be 1000°C as it was the maximum one providing recrystallization process elimination. The rolling speed was 50 rpm as this was the nominal value used at SVP-08 mill. The coefficient of friction at a contact between the workpiece and the rolls was taken to be 0.3 in accordance with the hot rolling recommendations [10].

The program of solid modeling KOMPAS 16 was used to create the geometry of the rolls. The finished geometry in the STL format was preserved. Since the simulated process referred to a particular case of rolling, where the initial and the final cross sections of the workpiece had the shape of a circle, the Simufact Forming program was required to perceive the imported geometry as correctly as possible. This was determined by the fact that there were often cases when the forming roll was accepted by the program as a polygon rather than a circle in the course of rolling roll geometries import.
The accuracy of STL rendering was increased to 0.05 to eliminate this factor. The number pointed out meant the length of the chord in millimeters between two adjacent points on the circle. This level of precision allowed the Simufact Forming program to take into account the circumference of the rolling rolls.

The model obtained was corrected in the course of modeling (Fig. 1). The workpiece was captured by the rolls of SVP-08 mill and completely rolled by them decreasing its diameter of 30 mm. The final dimensions of the workpiece after rolling referred to a diameter of 27 mm and a length of 185.2 mm.

The study of the stress-strain state (SSS) [11] had to precede the laboratory experiment in the course of the study of any metal forming process. This provided to identify the stresses and the strains distribution in the deformable workpiece, as well as to determine their critical values, which in turn provided the strength test of the working tool.

It was necessary to find the values of the components of the corresponding tensors aiming to determine the stress and the strain values. This was a very difficult task in case of a three-dimensional flow of the metal. Therefore, simple indicators of strain intensity and stress, or the so-called effective strain and effective stress were used considering the SSS parameters. They included the strain and the stress components in accordance with:

\[
\varepsilon_{\text{EFF}} = \frac{\sqrt{2}}{3} \sqrt{\left(\varepsilon_1 - \varepsilon_2\right)^2 + \left(\varepsilon_2 - \varepsilon_3\right)^2 + \left(\varepsilon_3 - \varepsilon_1\right)^2},
\]

\[
\sigma_{\text{EFF}} = \frac{1}{\sqrt{2}} \sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2},
\]

where \(\varepsilon_1, \varepsilon_2, \varepsilon_3\) were the main strains, while \(\sigma_1, \sigma_2, \sigma_3\) were the main stresses.

It was necessary to study the parameters providing an estimation of the share of tensile and compressive stresses in the deformation zone in the course of investigating SSS parameters. These were the main stresses \(\sigma_1, \sigma_2, \sigma_3\). All three main stresses represented together the average hydrostatic pressure (stress mean):

\[
\sigma_{\text{mean}} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}
\]

The average grain size was identified in order to determine the level of processing of the initial structure of the metal. Its initial size was equal to 40 microns.

RESULTS AND DISCUSSION

Strain state study

The effective strain is often mentioned in many sources as the “accumulated strain”. The reason for this is that this is a cumulative parameter, i.e. this parameter is not reset, unlike the stress, after removing the load.

Since the radial-shear rolling refers to the transverse type of rolling, it is advisable to carry out the study of the effective deformation not only in the longitudinal but also in the cross section of the workpiece – this would provide to find not only the numerical values of the parameter, but also the nature of its distribution over the cross section during the deformation. Analyzing the effective deformation (Fig. 2), it is found that the distribution of this parameter is fully consistent with the transverse type of deformation when the workpiece made a rotational movement around its axis. Clearly visible annular zones of processing are found in the cross section. It is worth noting that the distribution of this parameter in the radial direction is rather large. In the axial zone (0 % - 35 % of the radius from the center) the level of deformation is about 0.45. In the peripheral zone (35 % - 80 % of the radius from the center) the shear deformation intensity increases to a deformation level of 0.5 - 0.55. A maximum action of the shear deformation is observed in the surface area (80 % - 100 % of the radius from the center). The deformation level there is 0.6 - 0.65.

The value of the accumulated deformation during the radial-shear rolling is calculated [12] on the ground of the formula:
\[ \varepsilon = 2 \ln \left( \frac{d_0}{d_1} \right) + \ln \left( \frac{90}{\gamma} \right), \quad (4) \]

where \( d_0 \) is the diameter of billet before rolling, \( d_1 \) is the diameter of the billet after rolling, while \( \gamma \) is angle of elevation of the helix determined by the diagram (Fig. 3). It depends on the angle of the conical part of the roll. The angle of the helix elevation amounts to 70°as the angle of the conical part is equal to 3°.

However, this formula provides the calculation of the amount of deformation only in the axial zone of the workpiece. Eq. (4) has to be used to find the strain values in the peripheral and the surface zones:

\[ \varepsilon = 2 \ln \left( \frac{d_0}{d_1} \right) + \left( 1 + \frac{K}{100} \right) \cdot \ln \left( \frac{90}{\gamma} \right), \quad (5) \]

where \( K \) is the estimated percentage distance from the beginning of the corresponding zone.

Thus, the effective strain value for the peripheral zone is determined with the application of:

\[ \varepsilon = 2 \ln \left( \frac{d_0}{d_1} \right) + 1.35 \ln \left( \frac{90}{\gamma} \right), \quad (6) \]

The effective strain the surface area is determined in accordance with:

\[ \varepsilon = 2 \ln \left( \frac{d_0}{d_1} \right) + 1.8 \ln \left( \frac{90}{\gamma} \right). \quad (7) \]

The application of Eqs. (4, 6, 7) leads to:
- the value of the effective strain in the axial zone, \( \varepsilon_{AX} = 0.46 \);
- the value of the effective strain in the peripheral area, \( \varepsilon_{PERIPH} = 0.54 \);
- the value of the effective deformation in the surface area, \( \varepsilon_{SURF} = 0.66 \).

The results obtained on the ground of the equations considered are very close to those obtained by the simulation indicating the high accuracy of the model.

**Stress state study**

It is recognized that the effective stress does not show what stress is acting at a particular point – a tensile or a compressive one. As a fully-rooted expression, its value is always positive. It shows the intensity of the stress, i.e. whether there is a stress at a given point or not. Its...
value characterizes the average value of all stresses acting at a given point. It is also necessary to understand that the stress state components, in contrast to the previously considered effective strain, are characterized by the absence of a cumulation, i.e. they occur only at the points of loads application, while they are absent in other areas. Therefore, it is advisable to consider the stress state directly in the deformation zone.

The analysis of the effective stress (Fig. 4) shows that due to the simultaneous action of compression and shear strains in the course of radial-shear rolling, the entire cross section of the workpiece is affected by the action of the stresses. In this case, maximum stress values are observed in the areas of a direct contact between the metal and the rolls. In these areas, the effective stress reaches a value of 140 MPa, which decreases gradually to 90 MPa towards the center of the workpiece. In the contact-free zones, the effective stress is much lower and reaches a value of 70 MPa.

It is possible to determine the type of the stress acting at a given point, a tensile or a compressive one when considering the average hydrostatic pressure. It is found that the compressive stresses prevail in the entire cross section of the workpiece during the radial-shear rolling (Fig. 5). The maximum values of the compressive stresses are observed in the areas of a contact between the metal and the rolls. In these areas it has a value of 300 MPa, which decreases gradually to 120 MPa towards the center of the workpiece. In the contact-free zones, the compressive stress is much lower and reaches a value of 55 MPa.

It is decided to use the Lode-Nadai coefficient [13] in addition to these parameters. This coefficient allows to access the nature of the resulting deformation of the workpiece, i.e. to determine the type of the deformation realized at a particular point – a tension, a compression or a shear.

The Lode-Nadai coefficient is calculated with the application of the equation:

\[ \mu = 2 \cdot \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1 \]  

where \( \sigma_1, \sigma_2, \sigma_3 \) are the main stresses.

![Fig. 4. Effective stress.](image)
The value of the coefficient varies from -1 to 1. The values from 0.2 to 1 correspond to a compression; those from -0.2 to -1 correspond to a tension; the coefficient values in the range of -0.2 - 0.2 correspond to a shear.

When considering this parameter (Fig. 6), it is found that the Lode-Nadai coefficient amounts to 0.95 at the contact of the metal with the rolls in the surface area. This corresponds to a compression. The effect of the compressive stresses decreases immediately after leaving the rolls. Shear strains act here and the Lode-Nadai coefficient is equal to 0.15 - 0.2.

Hence, the comprehensive review of the stress-strain state in the radial-shear rolling shows that during the implementation of this process there are favorable conditions for intensive processing of the initial structure of the metal – the entire cross section is dominated by compressive stresses combined with a sufficiently high level of shear deformation due to workpiece twisting.

Microstructure evolution study

Two kinds of recrystallisation (static and dynamic) affecting the initial grain size proceed in the course of the deformation. The calculation of the dynamic recrystallisation is a part of the model, which refers to the processes in the forming zone. It starts when the effective log. strain $\varepsilon$ exceeds the critical strain $\varepsilon_k$. The Zener-Hollomon parameter [14] is the main data in this model:

$$Z = \varepsilon \cdot \exp \left( \frac{Q}{RT} \right)$$

where $\varepsilon$ is the strain rate, $s^{-1}$, $Q$ is the activation energy of forming, J/mol, $R$ is the universal gas constant (8.3144 J/mol * K), while $T$ is the forming temperature, K.

The critical strain to start the dynamic recrystallisation is defined by:

$$\varepsilon_k = [a_1 \cdot D_0^{-a_2} \cdot Z^{a_3} + a_4] \cdot a_5$$

where $a_1$-$a_5$ are model coefficients, $D_0$ is the initial gain size, $\mu m$, while $Z$ stands for the Zener-Hollomon parameter.

The log. strain required to reach 50 % of the dynamic recrystallisation is described by:

$$\varepsilon_{50} = [c_1 \cdot D_0^{-c_2} \cdot \exp(c_3 / T) \cdot \varepsilon^{c_4}] + c_5$$

where $c_1$-$c_5$ are model coefficients.

The dynamic recrystallised part is presented by:
The dynamic recrystallised grain size, µm, is calculated in accordance with:

\[ D_{\text{Dyn}} = d1 \cdot Z^{d2} \]  

where \( d1, d2 \) are model coefficients.

The calculation of the static recrystallisation is a part of the model referring to the moment when the workpiece segment leaves the forming zone. This is valid until the recrystallisation process is interrupted by a new forming or a phase transition. It starts when the effective log. strain \( \varepsilon \) exceeds the critical strain \( \varepsilon_k \) and it ends when the temperature is below that of the lower application range boundary.

The mean log. strain observed after the dynamic recrystallisation start is described as:

\[ \varepsilon_m = p2 \cdot (\varepsilon_k + \varepsilon_{50} \cdot \{1 - \exp[-(\varepsilon - \varepsilon_k)/\varepsilon_{50}]\} ) \]  

where \( p2 \) is a coefficient for a model adaptation.

The time required to reach 50 % of the static recrystallisation, \( s \), is presented by:

\[ t_{50} = g1 \cdot \varepsilon^{g2} \cdot D_{0}^{g3} \cdot \exp\left(\frac{g4}{T}\right) \cdot \varepsilon^{g5} \]  

where \( g1 - g5 \) are model coefficients.

The time required to begin and end the static recrystallisation, \( s \), is given by:

\[ t_{50} = b1 \cdot t_{50} \]  
\[ t_{55} = b2 \cdot t_{50} \]  

\[ \text{Fig. 6. Lode-Nadai coefficient.} \]
where \( w_1, w_2 \) are model coefficients.

The coefficients in Eqs. (10-21) are individual for the different materials and deformation modes. All of them are considered in detail in refs. [15-16], where a large number of values of these coefficients are presented for different grades of steels and alloys depending on the type of deformation and thermal treatment.

The consideration of the microstructure evolution shows that the radial shear rolling is a very effective way of processing austenitic stainless steel AISI-321 (Fig. 7). After one pass, the grain size decreases from 40 \( \mu \text{m} \) to 30 \( \mu \text{m} \) in the axial zone; in the peripheral zone, due to the intensification of shear deformations, the grain size is about 27 \( \mu \text{m} \). The minimum grain size of 25 \( \mu \text{m} \) is recorded in the surface area, where the influence of the shear strains and the compressive stresses on the side of the rolls are the most intensive.

**Rolling force study**

The last parameter considered refers to the rolling force on the rolls (Fig. 8).

The analysis of the force graph shows that the radial-shear rolling process on SVP - 08 mill is quite stable. In case of a steady-state rolling process, the force value is about 20 kN, increasing to 35 kN at the time of the rear end exit of the workpiece from the deformation zone. Given the fact that the allowable force on the roll, according to the technical documentation, is not greater than 100 kN, this mill can deform austenitic stainless steel AISI-321 heated below the recrystallization temperature.

**CONCLUSIONS**

This paper presents the results of modelling of a radial-shear rolling process of austenitic stainless steel AISI-321. The simulation conditions refer to those of 14-40 radial-shear mill of Rudny Industrial Institute. The analysis of the strain state on the ground of the effective plastic strain shows that there is a rather large uneven distribution of this parameter in the radial direction (from 0.45 in the axial zone to 0.65 in the surface zone). The analysis of the stress state in view of the effective stress, the mean normal stress and the Lode-Nadai coefficient...
shows that the compressive stresses dominate during the radial-shear rolling in the entire cross section of the workpiece. The studies of the microstructure evolution and the rolling force indicate that the radial shear rolling is a very effective and energy-saving way to obtain high quality round billets from stainless steels of the austenitic class.

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