COMPUTER MODELLING OF RADIAL-SHEAR ROLLING OF AUSTENITIC STAINLESS STEEL AISI-321

D.t.s., prof. NaizabekovA.B. [1], c.t.s. ass. prof. Lezhnev S.N. [1], PhD Arbuz A.S. [2], PhD Panin E.A. [3], d.t.s. Koinov T.A. [4]
[1] Rudny industrial Institute, Rudny, Kazakhstan; [2] Nazarbayev University, Astana, Kazakhstan
[3] Karaganda state industrial University, Temirtau, Kazakhstan; [4] University of Chemical Technology and Metallurgy, Sofia, Bulgaria
E-mail: sergey_legnev@mail.ru

Abstract: *In this paper the results of modelling of radial-shear rolling process of austenitic stainless steel AISI-321 are presented. The simulation in Simufact Forming program complex was performed. The conditions of simulation for radial-shear mill SVP-08 of Rudny industrial Institute were adopted. The various parameters of stress-strain state (effective plastic strain, effective stress, mean normal stress and Lode-Nadai coefficient) and also microstructure evolution with rolling force were considered. It is revealed that radial-shear rolling is an effective process for obtaining of high quality round billets from stainless steels of austenitic class.*

Keywords: RADIAL-SHEAR ROLLING, SIMULATION, STRESS-STRAIN STATE, AUSTENITIC STAINLESS STEEL

1. Introduction

Despite the current level of development of virtual computing technologies, the main method of research of any technological process is a physical experiment. Since only in natural experiment it is possible to take into account all parameters that affect the investigated process. At the same time, conducting only physical experiments is a very irrational task that requires a lot of effort, time and material resources.

The ideal compromise is the use of software systems of virtual modeling, which allow to simulate the investigated process, to take into account almost all parameters that affect it, as well as to optimize the process, i.e. to determine the values of all the dependent parameters at which the process will be the most stable. After that, when conducting a physical experiment with optimal values, the result will be the most successful, without rejection of the workpiece or equipment failure.

The aim of this work is the study of radial-shear rolling process of austenitic stainless steel based on computer simulation. For computer simulation the program Simufact Forming was chosen, which along with the traditionally used Deform program allows to simulate the processes of pressure treatment of any complexity. However, Simufact Forming has certain advantages over Deform: it has more flexible options for building finite element meshes, including different mesh builders; it also has an additional database of materials Matilda, with which it is possible to simulate the evolution of the microstructure.

2. Preparation of model

To create a model of radial-shear rolling, it was decided to use the parameters of the existing SVP-08 mill installed at Rudny industrial institute. The initial billet with a diameter of 30 mm and a length of 150 mm was rolled on the mill with a compression of 3 mm. The billet material is stainless austenitic steel AISI-321 (0.08% C, 17-19% Cr; 9-11% Ni; 2% Mn; 0.8% Si; 0.5-0.7% Ti). Since the initial temperature of recrystallization or diffusion annealing for the selected steel grade is 1020 °C [1], the heating temperature of the steel was 1000 °C, as the maximum possible to eliminate the recrystallization process; the rolling speed was 50 rpm, as the nominal value at the mill SVP-08. The coefficient of friction at the contact of the workpiece and the rolls was taken to be 0.3, as the recommended value for hot rolling [2].

In the course of modeling the obtained model was correct (Figure 1). Here the workpiece was captured by the rolls of the mill SVP-08 and completely rolled in them with a diameter of 30 mm to 27 mm. the Final dimensions of the workpiece after rolling were as follows: diameter 27 mm and length 185.2 mm.

In the study of any metal forming process, the main position before the laboratory experiment is the study of the stress-strain state (SSS) [3]. This makes it possible to identify the distribution of stresses and strains in the deformable workpiece, as well as to determine their critical values, which will make it possible to test the working tool for strength.

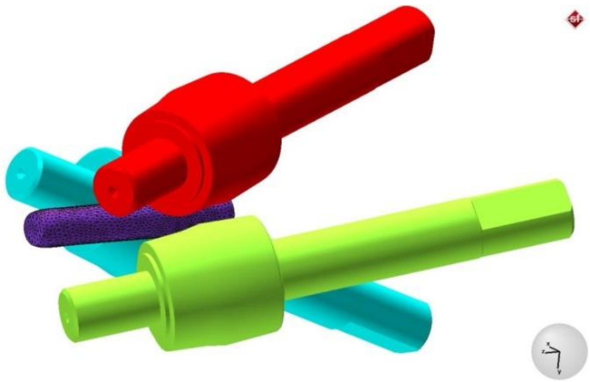

Fig. 1 *Model of radial-shear rolling*

To determine the stress and strain values, it is necessary to find the values of the components of the corresponding tensors, which is a very difficult task for the three-dimensional flow of metal. Therefore, usually when considering the parameters of the SSS use simple indicators of strain intensity and stress, or the so-called effective strain and effective stress.

To study the parameters of the SSS it is necessary to study the parameters that allow to estimate the share of tensile and compressive stresses in the deformation zone. These are the main stresses σ_1, σ_2 and σ_3. All three main stresses together represent the average hydrostatic pressure (stress mean).

Also, to determine the level of processing of the initial structure of the metal, the average grain size was determined, the initial size of which was equal to 40 microns.

3. Study of strain state

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

Since the radial-shear rolling refers to the transverse type of rolling, the study of effective deformation is advisable to carry out not only in the longitudinal but also in the cross section of the workpiece – this will allow to evaluate not only the numerical values of the parameter, but also the nature of its distribution over the cross section during deformation. In the analysis of effective deformation (Figure 2), it was found that the distribution of this parameter is fully consistent with the transverse type of deformation when the workpiece makes a rotational movement around its axis, because in the cross section clearly visible annular zones of processing. It can be noted 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, here the deformation level is 0.5÷0.55. In the surface area (80÷100% of the radius from the center) the maximum action of shear deformation is observed, here the deformation level is 0.6÷0.65.

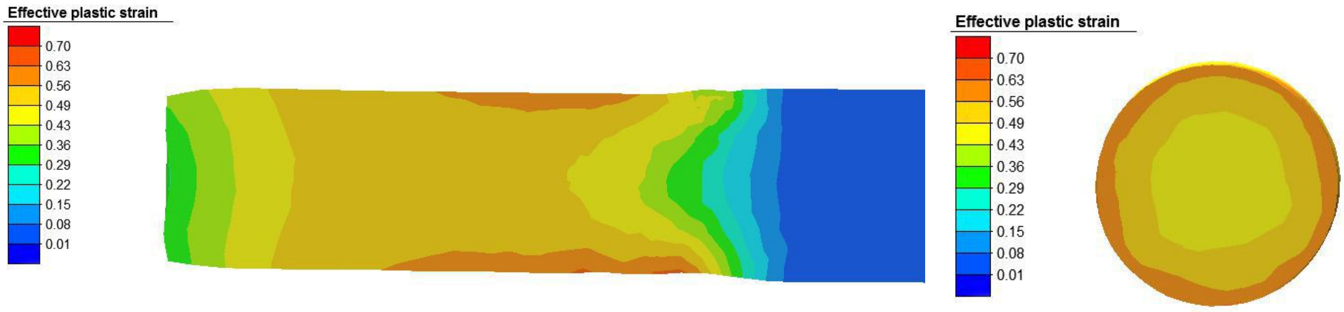

Fig 2 *Effective strain*

4. Study of stress state

When considering the effective stress, it should be understood that this parameter does not show what stress is acting at a particular point – tensile or compressive. 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 cumulative, i.e. they occur only in the places of application of loads, in other areas they are absent. Therefore, it is advisable to consider the stress state directly in the deformation zone.

In the analysis of the effective stress (Figure 3), it was noted that due to the simultaneous action of compression and shear strains in radial-shear rolling, the entire cross section of the workpiece is covered by the action of stresses. In this case, the maximum stress values are observed in the areas of direct contact of the metal with the rolls. In these areas, the effective stress reaches 140 MPa, gradually decreasing to 90 MPa towards the center of the workpiece. In contact-free zones the effective stress is much lower and reaches 70 MPa.

When considering the average hydrostatic pressure, it is possible to determine which type of stress acts at a given point – tensile or compressive. It was found that compressive stresses prevail in the entire cross section of the workpiece during radial-shear rolling (Figure 4). The maximum values of compressive stresses are observed in the areas of contact between the metal and the rolls. In these areas their value reaches -300 MPa, gradually decreasing to -120 MPa towards the center of the workpiece. In contact-free zones, the compressive stress is much lower and reaches -55 MPa.

In addition to these parameters, it was decided to use the Lode-Nadai coefficient [4]. This coefficient allows to assess the nature of the resulting deformation in the workpiece, i.e. to determine what type of deformation is realized at a particular point – tension, compression or shear. The value of the coefficient varies from -1 to 1. The value from 0.2 to 1 corresponds to compression; from -0.2 to -1 corresponds to tension; the coefficient value in the range of -0.2÷0.2 corresponds to the shear.

When considering this parameter (Figure 5), it was found that in the surface areas, at the contact of the metal with the rolls, the Lode-Nadai coefficient is 0.95, which corresponds to the compression. Immediately after leaving the rolls, the effect of compressive stresses decreases, shear strains act here and the Lode-Nadai coefficient is 0.15÷0.2.

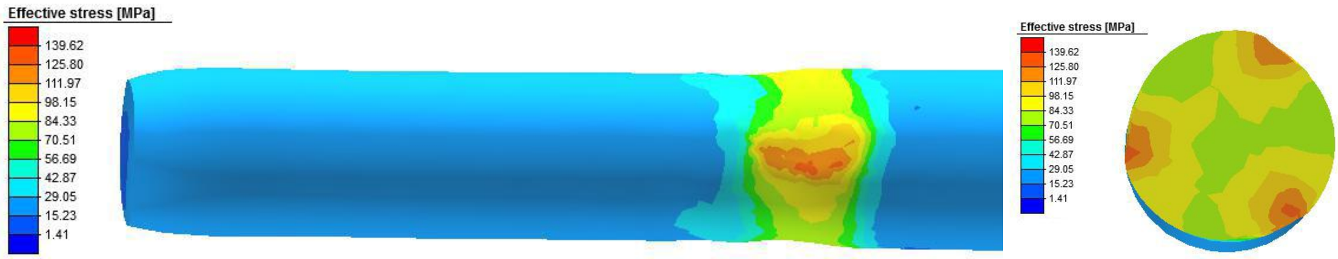

Fig 3 *Effective stress*

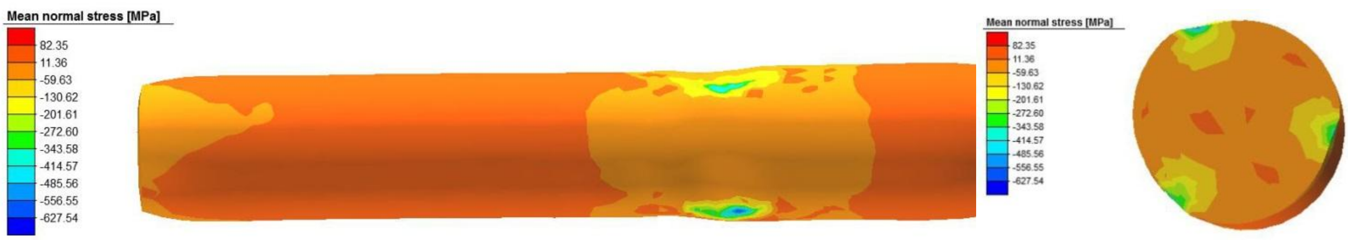

Fig 4 *Average hydrostatic pressure*

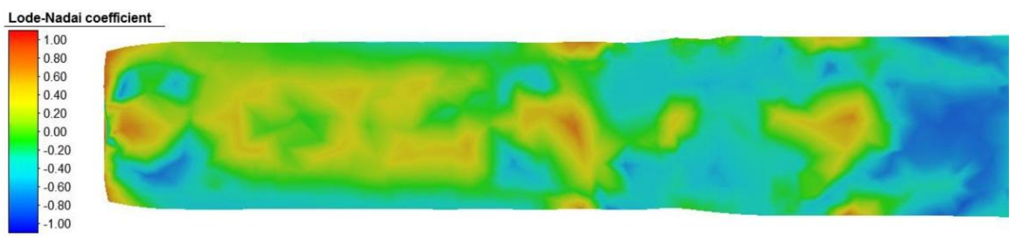

Fig 5 *Lode-Nadai coefficient*

5. Study of microstructure evolution and rolling force

When considering the microstructure evolution, it was noted that radial shear rolling is a very effective way of processing austenitic stainless steel AISI-321 (Figure 6). After one pass, the grain size decreased from 40 µm to 30 µm in the axial zone; in the peripheral zone, due to the intensification of shear deformations, the grain size was about 27 µm. The minimum grain size of 25 µm was recorded in the surface area, where the influence of shear strains and compressive stresses on the side of the rolls are the most intense.

The last studied parameter was the rolling force on the rolls (Figure 7). Analysis of the force graph showed that radial-shear rolling process on the SVP - 08 mill proceeds quite stable. With the steady-state rolling process, the force value is about 20 kN, increasing to 35 kN at the time of exit of the rear end of the workpiece from the deformation zone. Given the fact that the allowable force on the roll, according to the technical documentation, is not more than 100 kN, this mill can deform austenitic stainless steel AISI-321, heated below the recrystallization temperature.

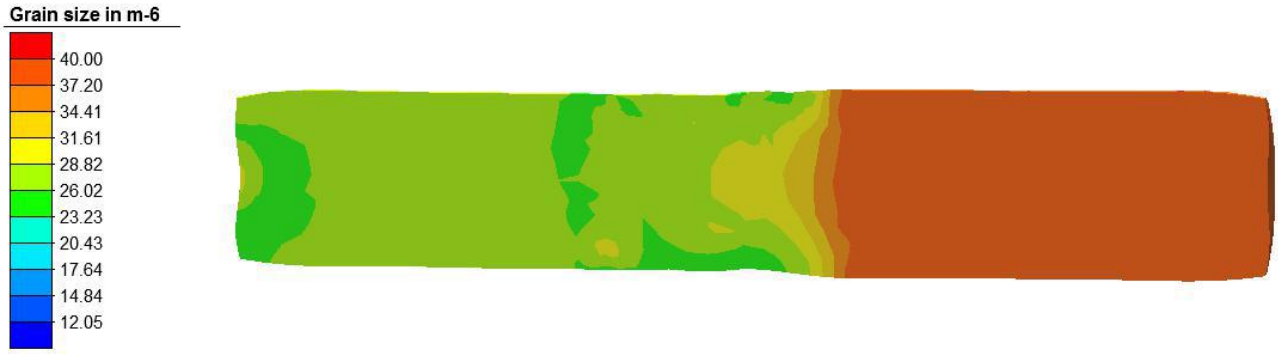

Fig 6 The change of grain size

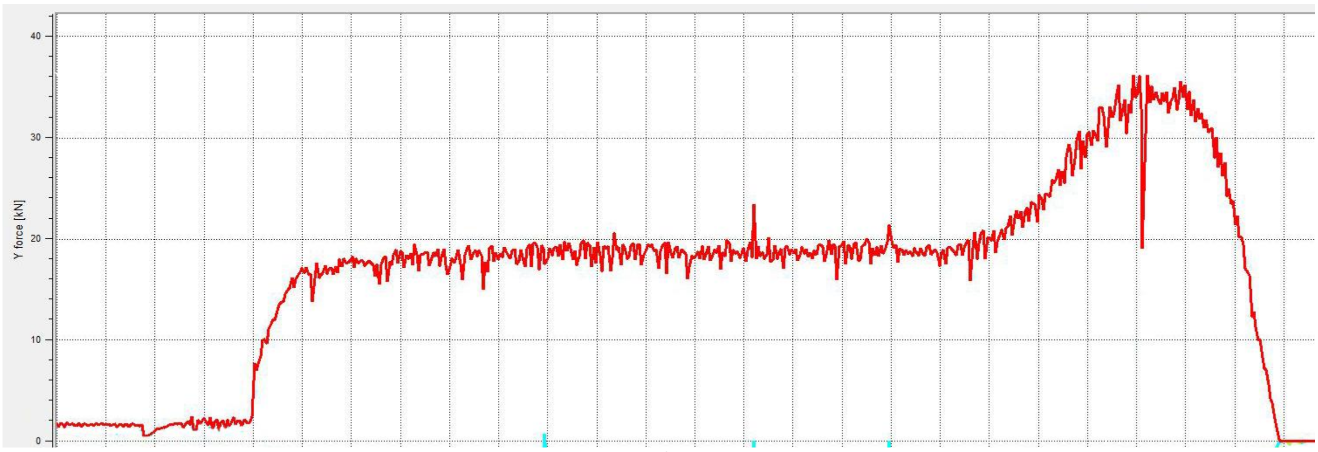

Fig 7 Rolling force diagram

6. Study of multi-pass deformation process

Despite the fact that the considered model is successful from the point of view of the emerging picture of the stress-strain state and the deformation force, it does not provide an UFG structure in the processed material. To achieve this goal, the workpiece must be processed with a much higher level of deformation. The used mill SVP-08 allows rolling blanks with a diameter of 9 mm. Taking into account the fact that the radial-shear rolling can not set the same level of compression in one pass, as in the longitudinal rolling, it was decided to increase the compression through 3 mm. As a result, it was found that for the workpiece with an initial diameter of 30 mm in this mill it is necessary to conduct 7 cycles of deformation (table 1.1). During simulation of all 7 passes the strain state study after each passage was performed. As a result, the following data were obtained (table 2).

Table 1 - Pass compression modes

	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass
Initial diameter, mm	30	27	24	21	18	15	12
Final diameter, mm	27	24	21	18	15	12	9

As can be seen from the data of table 2, in the axial zone the necessary level of deformation for the formation of the UFG structure (more than 4) is achieved only after 7 passes. This suggests the need for all 7 cycles of deformation at any temperatures and strain rates.

Table 2 - Effective strain by passes

	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass
Axial zone							
Effective strain	0,45	0,92	1,42	1,95	2,55	3,25	4,07
Peripheral zone							
Effective strain	0,52	1,07	1,66	2,28	2,94	3,77	4,65
Surface zone							
Effective strain	0,63	1,27	1,93	2,72	3,54	4,42	5,4

Analysis of the stress state in multi-pass deformation showed the following:

1) in all 7 cycles of deformation the nature of the stress distribution is completely identical. The reason for this is that in all passes the load application circuit remains constant.

2) as the number of passes increases, the stress values gradually increase. Despite the same amount of absolute compression in all passes, this is due to the fact that the workpiece cools during deformation, thereby reducing the ductility of the metal.

Similar results were obtained in the analysis of forces, but here the nature of the increase is less. The reason for this is that the force depends not only on the stress that increases, but also on the area of the contact surface of the metal with the rolls, which decreases with increasing number of passes. The common results of the analysis of power parameters are given in tables 3 and 4.

From the data in table 3 it can be seen that in all passes in the cross section of the workpiece in the deformation zone compressive stresses are formed, which is the most favorable factor for the study of the original structure. Analysis of the force values showed that the implementation of 7 cycles of deformation with the parameters of the basic model of excess load on the rolls is not observed, which leads to the conclusion about the possibility of deformation of this steel grade on the mill SVP-08 with the specified parameters.

Table 3 – Values of stress state by passes

	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass
Effective stress, MPa							
In the contact area, at the surface	140	147	155	164	189	204	224
In the contact area, periphery	90	94	97	108	116	131	147
In contact-free areas closer to center	70	74	80	90	102	118	130
Average hydrostatic pressure, MPa							
In the contact area, at the surface	-300	-312	-327	-344	-365	-378	-394
In the contact area, periphery	-120	-137	-145	-161	-180	-193	-210
In contact-free areas closer to center	-55	-67	-82	-94	-112	-126	-144

Table 4 - Values of rolling forces by passes

	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass
Average value, kN	20	22	25	28	32	36	41
Peak value, kN	35	37	40	44	47	54	62

When considering the evolution of the microstructure along the passages (table 5), the following was noted:

1) as the number of passes increases, the grain size values in all three zones decrease continuously. This is primarily due to the increase in the accumulated equivalent strain.

2) as the deformation level increases, the grain size difference between the axial and surface zones gradually decreases. This is due to the fact that during the deformation of the workpiece is lengthened and its cross-section is reduced. As a result, the action of compressive stresses in the axial zone becomes more intense, which leads to an increase in the study of this zone.

Table 5 – Values of the grain size by passes

	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass
Axial zone, μm	30	28	25	22	17	14	11
Peripheral zone, μm	27	26	21	19	14	11	9
Surface zone, μm	25	22	19	15	12	9	7

7. Conclusions

In this paper the results of modelling of radial-shear rolling process of austenitic stainless steel AISI-321 were presented. The conditions of simulation for radial-shear mill 14-40 of Rudny industrial Institute were adopted. The analysis of strain state by effective plastic strain was showed that there is a rather large uneven distribution of this parameter in the radial direction (from 0.45 in axial zone to 0.65 in surface zone). The analysis of stress state by effective stress, mean normal stress and Lode-Nadai coefficient was showed that during radial-shear rolling in the entire cross section of the workpiece compressive stresses are dominated. Studies of microstructure evolution and rolling force were showed that radial shear rolling is a very effective and energy-saved way for obtaining of high quality round billets from stainless steels of austenitic class.

8. Acknowledgment

Work is performed under the state budget-funded theme № AP05131382 "Research and development of the technology for obtaining ultrafine-grained materials with improved mechanical properties and increased radiation resistance for their use as materials of the first wall of thermonuclear reactors and in nuclear power engineering" with the program "Grant financing of scientific researches on 2018-2020" (Customer - the Ministry of education and science of the Republic of Kazakhstan).

9. References

1. V.G. Sorokin, A.V. Volosnikova, S.A. Vyatkin, HandBook of steels and alloys, M.: Mashinostroenie, 1989.

2. www.Simufact.com - Simufact Forming manual

3. ASM Metals HandBook Vol. 19 - Fatigue and Fracture. ASM International, 2002.

4. V.M. Segal, V.I. Reznikov, V.I. Kopylov, D.A. Pavlik, V.F. Malyshev, Processes of plastic structure formation of metals, Minsk: Science and technology, 1994.