PRODUCTION OF ROLLED PROFILE AND ITS VERIFICATION BY USING NUMERICAL SIMULATION

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The paper deals with a manufacturing technology of hot-rolled sections. A calibration system proposal of the solved section is described and its accuracy is subsequently verified by numerical simulation using Simufact Forming software. In this case, S355J2 steel is used as a material for a trial production of the rolled profile. Finally, according to the verified design, the trial rolling of the section is carried out. Therefore, a comparison between actual rolled section shapes of individual rolling passes and simulation results is performed. This makes it possible to assess the accuracy of the simulation and thus the suitability for use in the development of other rolled sections.

KEYWORDS

hot rolling, profile, S355J2 steel, FEM, numerical simulation, Simufact Forming

1 INTRODUCTION

Basic elements of almost all production technologies are semi-finished products, which are produced by forming. In terms of the total amount of production, one of the most efficient manufacturing technologies of above mentioned products is the hot rolling technology. Rolling of conventional semi-finished products can be considered as a relatively technically mastered. However, due to an ever increasing need for quality improvement, production intensity, energy savings and environmental impact, companies are trying to optimize the manufacturing process. The possibility is, for example, to focus on the implementation of numerical simulations, which can avoid many problems in production.

The solved problematic of the rolling production design with an aid of the numerical simulation is realized in cooperation with the rolling mill division of VÚHŽ company, which specializes in the production of special hot-rolled rods with a special cross-sections. The solved section in length of 10 400 mm serves as a guide bar, which is welded to the pipe segment of a deep drilling rod. This part is protected from external influences by other sections. Therefore, it is not subject to corrosion resistance requirements and it is not too mechanically stressed. The shape of the rolled section and its main dimensions are shown in Fig. 1. Unfortunately, due to the confidentiality, it is not possible to publish all dimensions [Sigmund 2018].

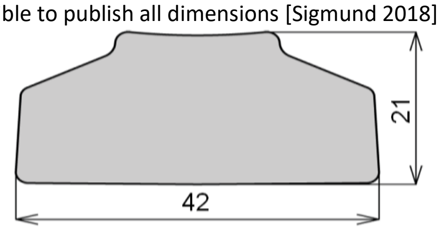


Figure 1. The shape and main dimensions of the produced profile

In a serial production, the section will be made of 25CrMo4 steel. However, for developmental purposes, cheaper structural steel S355J2 according to EN 10025 (1.0577) will be used for first tests and verification of simulations. Mentioned material is the most used in the product range of VÚHŽ, and therefore, the obtained results will be more useful in the subsequent implementation of other rolled profiles. Main mechanical properties and chemical composition of S355J2 steel are summarized in Tab. 1 and Tab. 2.

Minimal upper yield stress	R_{eH}	[MPa]	352–373
Ultimate strength	R_m	[MPa]	561–567
Minimal ductility	A_t	[%]	29.5–31.3
Relative contraction	Z	[%]	66.7–66.9

Table 1. Mechanical properties of S355J2 steel

%C	%Mn	%Si	%P	%S
0.220	1.250	0.390	0.019	0.010

%Cu	%Cr	%Ni	%Al	%Mo	%V
0.03	0.08	0.03	0.028	0.014	0.003

Table 2. Chemical composition of S355J2 steel

2 PRODUCTION DESIGN

For the preliminary design, it is necessary to take into account technical possibilities of the rolling mill. In VÚHŽ company, a rolling mill - reversible duo with a maximum roller diameter of 524 mm and a possible length of the rolls of 800, 872 and 932 mm can be used. The complete design of the rolling mill consists of 11 rolling passes through rolls over a total of 6 grooves. The rolls pitch diameter is 478 mm and their length is 800 mm. For clarity, in the case of describing the basic considerations of individual grooves design, they are named according to use in the manufacturing process as numbers from 1 to 6, see Fig. 2 [VUHZ 2017].

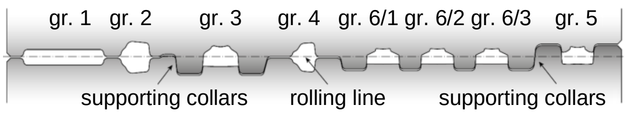


Figure 2. Calibration sections for the solved profile

Firstly, the semi-finished product, i.e. a rod with diameter of 70 mm, is rolled out by two passes through a box section 1. An alternate rolling system follows, for which the material is alternately moved between the box groove 1 and the next shaped groove 2, each time with lower gap between rolls. This method allows a gradual reduction of the input part shape with its external contour maintaining, which is required for entry into the section 3. Therefore, a change in the cross-sectional height is made without need for additional shape groove. The method is used up to the 7th pass. In the following, the rolled profile is moved into groove no. 3, 4 and 5. Finally, the last finishing groove 6 is used.

The rolled section shape for all passes through the shape rolling mill is schematically shown in Fig. 3, including values of the elongation coefficient for each pass. It can be determined in many ways, based on the law of volume conservation, for example from the ratio of a final and an initial length of the rolled section, a weight ratio or a cross-sectional ratio. The last mentioned option is most advantageous for rolling of sections with complicated shaped. The relationship between cross-sections and elongation coefficient is expressed according to equation 1.

$$\frac{S_0}{S_n} = \frac{S_0}{S_1} \cdot \frac{S_1}{S_2} \cdots \frac{S_{n-1}}{S_n} = \lambda_1 \cdot \lambda_2 \cdots \lambda_{n-1} \cdot \lambda_n \qquad (1)$$

where S_0 is the initial cross-section of the rolled stock before the pass [mm^2], S_1 and S_2 are the cross-sections of the rolled stock after 1st and 2nd pass [mm^2], S_n is the cross-section of the rolled stock in the n-th pass [mm^2], λ_1 and λ_2 are the elongation coefficients for 1st and 2nd pass [-], λ_n is the elongation coefficient for n-th pass [-].

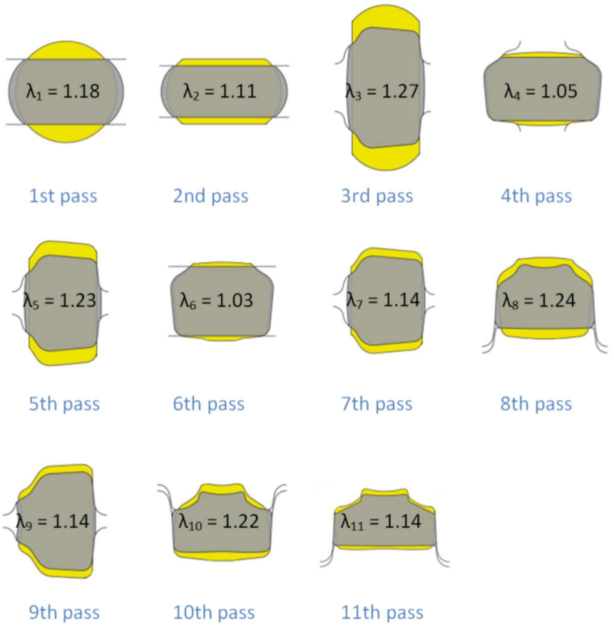


Figure 3. The rolled section shape for all passes [Sigmund 2018]

When all grooves are planed into the length of the rolls, there is still free space for another two finishing grooves, which will improve the life of rolls. Another reason for the duplicity of finishing grooves is also the preservation of the sufficient quality of the rolled product, which are the most affected just by the finishing groove shape. Therefore, it is necessary to prevent its wear.

A complete rolling mill assembly for the solved part, including upper and lower main profile rolls, roller guides and wipers, is shown in Fig. 4.

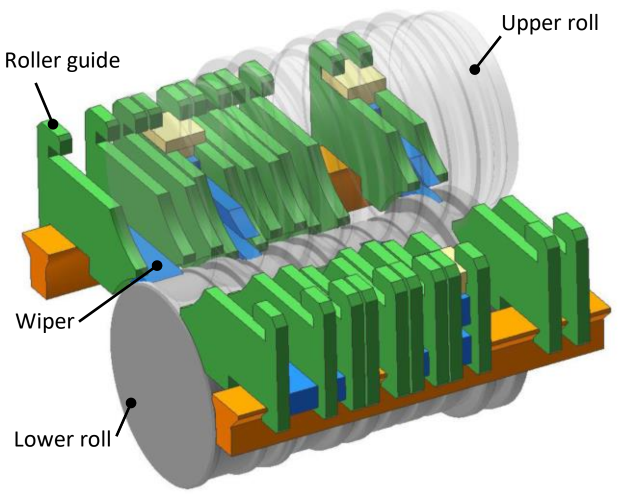


Figure 4. Assembly of the rolling tool for the solved profile [Sigmund 2018]

3 FINITE ELEMENT ANALYSIS AND EXPERIMENTAL VERIFICATION

The main prerequisite for the use of numerical simulations in a rolling process is the verification of the proposed manufacturing system before the production itself. Ideally, roll stock shapes design should be matched for individual rolling stages with simulation, and later with production stages. It is clearly evident, that the match will not always be 100 %. However, it is important to be able to assess how far these deviations are acceptable in terms of manufacturability [Valberg 2010].

Verification of proposed manufacturing design by using finite element method was performed for each individual pass considering full geometric model in Fig. 4. For this case, Simufact Forming software developed by MSC software was used. Semi-finished products with required section shapes and lengths of 250 mm were inserted into the simulations. Ideally rigid rolls were considered, whose velocity was set to 60 rpm.

Material model of rolled material was determined in accordance with material database. Flow stress of formed material is given by constitutive model according to:

$$\sigma_F = C_1 \cdot e^{(C_2 \cdot T)} \cdot \varphi^{(n_1 \cdot T + n_2)} \cdot e^{\left(\frac{l_1 \cdot T + l_2}{\varphi}\right)} \cdot \varphi^{(m_1 \cdot T + m_2)} \qquad (2)$$

where σ_F is the flow stress [MPa], φ is the effective plastic strain [-], $\dot{\varphi}$ is the strain rate [s^{-1}], C_1, C_2, n_1, n_2, l_1, l_2, m_1 and m_2 are material parameters [-] [Bernhardt 2013], [Simufact 2018].

Fig. 5 shows the flow stress plot of S355J2 steel for strain rate of 0.1 s^{-1} and different temperature values (800, 900, 100, 1 100 and 1 200 °C).

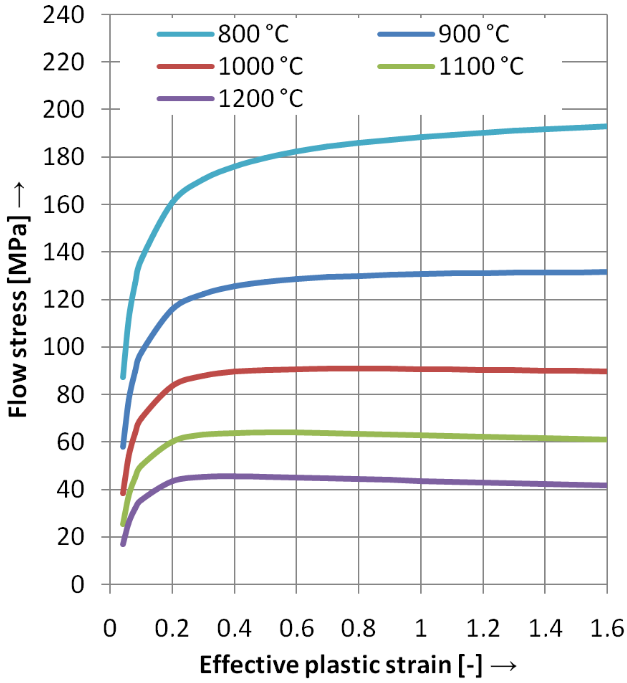


Figure 5. Flow stress of S355J2 steel

Initial rod temperature was set to 1 200 °C. Roll and ambient temperature was considered as 22 °C. Thermal properties were also determined based on data from the software database with considered thermal exchange with rolls α = 11 000 W·m^{-2}·K^{-1}. In the next, the Coulomb's coefficient of friction was considered as 0,3. After the calculation of the proposed rolling passages, it is possible in post-processing to focus on simulation results. Fig. 6 shows the prediction of effective plastic strain and rolled section shapes for passes through all proposed grooves of the rolling mill [Fabik 2009].

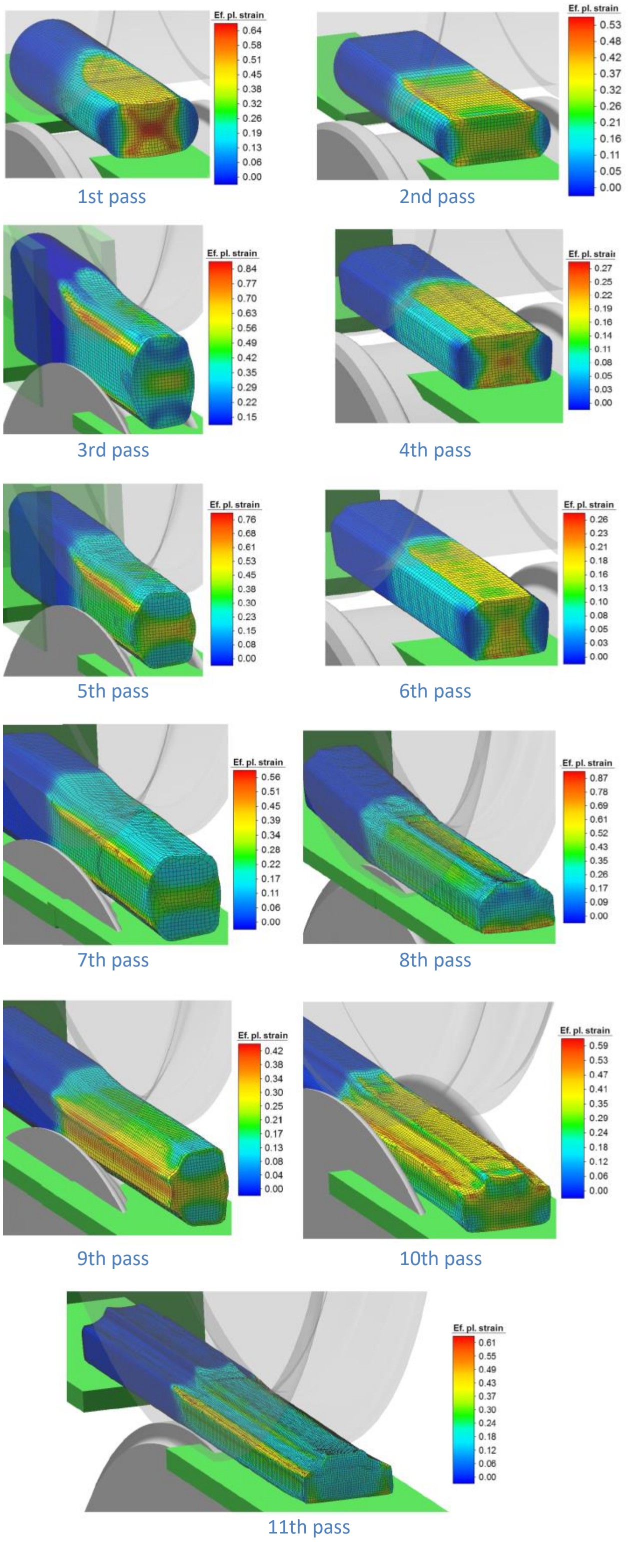


Figure 6. The predicted effective strain and rolled section shapes by using FEM simulation [Sigmund 2018]

Among other things, the numerical simulation confirmed the accuracy of the design. According to FE analysis results, the profile can be manufactured without bigger problems using the proposed tool.

According to above mentioned and numerically verified design, the practical production by test rolling was also carried out. For this case, strength parameters of the tool load were measured during the test rolling of the profile. Specifically, it is a vertical radial force (even rolling force), which affects bearings and set screws of the tool. In this way, it is possible to compare the detected forces with resulted forces of numerical simulation.

Comparison of measured force values with the FEM simulation for each pass is shown in the graph in Fig. 7. As it is clear from the figure, the maximal forces are deeply below the machine limit (2 000 kN). The assumption is that the biggest role in terms of force value has the draft of each pass. The largest drafts, over 20 %, were designed in the 3rd, 5th, 8th and 10th passes. However, it is clear from Fig. 7 that it is not possible to clearly determine where the largest rolling forces will occur based only on the size of the drafts since the maximum forces were found already at the beginning of the process, where the roller has a large contact surface with rolled stocks. At the last pass, a rolling temperature is determinative that greatly affects the size of the rolling force. The unevenness of the force in the last pass is caused by lower temperatures at the ends of the rolled stock and the increase of the rolling speed after an engagement.

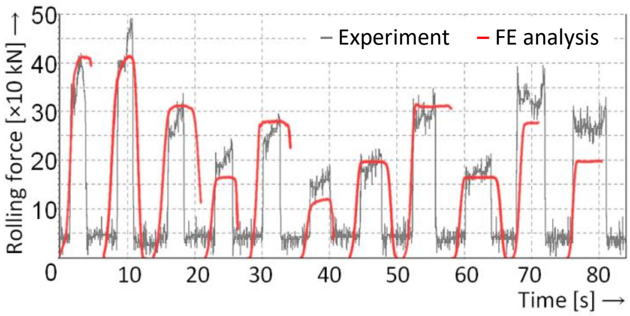


Figure 7. The comparison of rolling forces

When comparing the size of the rolling forces with the simulation, differences are evident. As a part of the simulation settings, the program has a limitation of a temperature input. In a practice, it means that the temperature of the semi-finished product is constant throughout the cross-section and length, which does not simulate the real state. In fact, the rolled stock has different temperatures in the middle and on the surface. Therefore, the temperature setting was conducted on the basis of the approximation curves of cooling for similarly sized rolled sections, which was created from long-term measurements in VÚHŽ. Even so, it is the surface temperature, which was measured by a pyrometer. The comparison of all results is summarized in tab. 3.

Pass	Measured rolling force [kN]	Rolling force by simulation [kN]	Difference of forces [%]
1	400	411	2.8
2	475	414	12.8
3	300	312	5
4	230	166	27.8
5	280	280	0
6	180	121	32.8
7	210	200	4.8
8	310	311	0.3
9	185	165	10.8
10	350	278	20.6
11	280	200	28.6

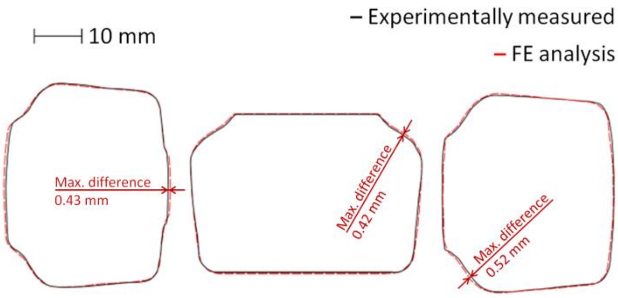
Table 3. The comparison of rolling forces [Sigmund 2018]

In order to verify the predicted profile shape by the numerical simulation, rolling stocks for all passes were cut and geometrically analyzed using a profile projector at 10x magnification. Fig. 8 shows rolled sections and their geometry measurements on a profile projector.

a) rolled profiles b) the profile projector

Figure 8. Experimental rolled profiles evaluation [Sigmund 2018]

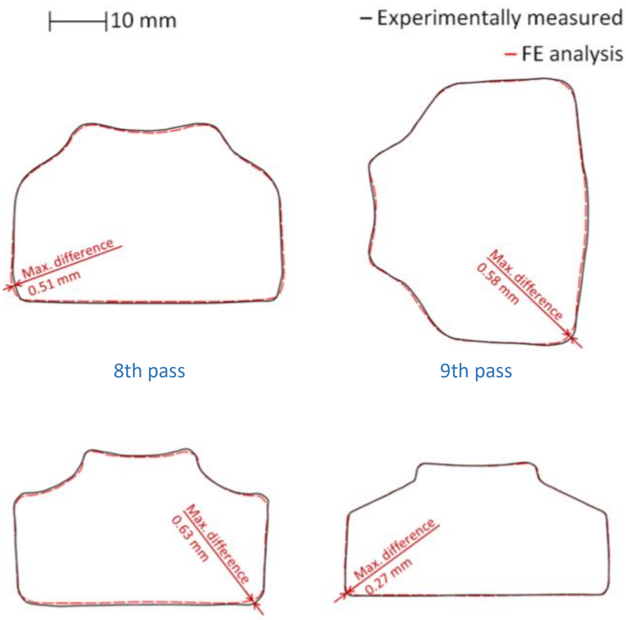
In the fig. 9, a visual comparison of the passes no. 5, 6 and 7 can be seen, in which the height of the cross section of the rolled stock for the entry into the 3rd groove is gradually reduced. The comparison shows that the simulation determined the filling of the section almost exactly as it was in reality.



5th pass 6th pass 7th pass

Figure 9. Comparison of rolled profiles for 5th, 6th and 7th pass

The same conclusions can be observed also for other results, i.e. comparison of sections from passes no. 8, 9, 10 and 11, see Fig. 10. Overall, the simulation shows a fairly good level of agreement with the practical solution.



8th pass 9th pass

10th pass 11th pass

Figure 10. Comparison of rolled profiles for 8th, 9th, 10th and 11th pass

4 CONCLUSIONS

The rolling mill design, which contains 6 different grooves, was made to make required shape of the rolled section. The rolling system is designed for 11 passes.

In order to verify the accuracy of the design, finite element simulations of individual passes was performed by using Simufact Forming software, which confirmed the proposed and expected behaviour and the material flow in all passes through the rolling rolls.

In the next, rolling forces were measured during the rolling process, which were also compared with the predicted values from the numerical simulation. There are differences of up to about 30 %. However, due to the size of the actual forces up to 500 kN and the machine limit of 2 000 kN, it can be considered as acceptable since the rolling machine will not be overloaded.

Furthermore, according to the tool design, the trial rolling was performed to achieve the required shape of the rolled section in certain dimensional tolerances. Subsequently, samples of rolled sections from several individual passes were taken to assess the accuracy of simulation results.

The utilization of the numerical simulation by using Simufact Forming software is therefore verified and it can be used for development of other rolled profiles types.

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