

FEM study of metal rolling in grooved rolls

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Keywords

Finite element method, grooved rolls, deformation hardening, sheet metal rolling

ABSTRACT

LS-DYNA was used to model the rolling process in grooved rolls. One-pass and two-pass (with rotation of the metal sheet at 90° after first pass) rolling in grooved rolls, as well as four-pass rolling in plain rolls and various combinations of these two types of rolling were simulated. With the help of finite-element analysis we estimated the influence of the areas of deformation hardening on the stress-strain state of metal sheet. The developed finite-element model allows analyzing stress-strain state of the system caused by variation of parameters, such as: geometry (design), rolling speed, physical-mechanical properties of materials, temperature and friction coefficient. Process parameters can be fine-tuned to achieve the desired improvement of physical-mechanical properties of the rolled metal .

INTRODUCTION

In the modern world many of devices and designs, created by humans, are being built with help of various products of sheet metal (parts of cars, trains, planes, ships; pressure vessels, etc.). As a consequence of high requirements to durability and safety of these products, the requirements to the strength properties of metal sheet are increased as well. Control of product quality is an important problem at each processing step of sheet-metalworking. While many defects, such as cracks, strings of non-metallic inclusions, porosity etc, appear at the step of roughing down at hot rolling, the important task is to search and develop new approaches to sheet-metalworking, which would help preventing the abovementioned defects during warm rolling of thick and medium plates.

The studied process of sheet metal forming in grooved rolls is presented in the article. This process is considered as an intermediate processing step between hot and cold rolling. The process allows improving the physical-mechanical properties of sheet

metal and reducing the influence of some types of defects that appear during rolling at roughing stands [3]. Improved material properties could extend the application of rolled metal products. Therefore, the research of various rolling patterns, parameters of grooved rolling and its influence on material properties is an important problem nowadays.

The process of metal shaping during the rolling in grooved rolls is a complex non-linear problem due to specific conditions in the contact deformation-zone. Factors, like geometry of grooved roll, depth of penetration, rolling speed, temperature and friction coefficient between rolls and metal plate, influence the rolling process. Experimental investigations are difficult to conduct due to their high costs. However, the research of the rolling process in grooved rolls can be successfully performed with the help of finite-element method.

Finite-element analysis (FEA) helps estimating the influence of characteristic zones of deformation hardening on the stress-strain state of metal plate. The developed finite-element model allows analyzing the stress-strain state of the changing parameters of process, such as: system geometry, rolling speed, physical-mechanical conditions of materials, temperature and friction coefficient. The right combination of parameters leads to the improvement of physical-mechanical properties of the rolled metal.

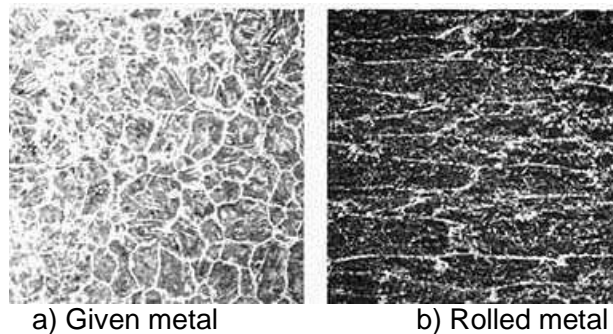
THEORETICAL BASIS

Recrystallization is a process of formation and growth (or only the growth) of certain grains (crystallites) in a polycrystal due to other grains of the same phase. Recrystallization process is enhanced in plastically deformed materials. The initial temperature of recrystallization depends on the accumulated deformation. The more the crystal lattice is distorted and deformed, the easier and at a lower temperature the recrystallization occurs. In areas, in which metal is undergoing the recrystallization process, there are zones with increased hardness and reduction of ductility. A.A.Bochvar [1] showed that there is a simple correlation between the recrystallization temperature and the melting point of alloys. Recrystallization starts at the temperature

$T_{r.t.}$, which is the same fraction of the melting temperature for all metals and alloys: $T_{r.t.} = (0,3\div 0,5)T_{m.t.}$, where $T_{m.t.}$ is the absolute melting temperature for the given metal. For example, the recrystallization threshold for steel St-3 is $T_{r.t.} = (1510+273)0,4-273 = 440,2\text{ }^{\circ}\text{C}$ [2].

During rolling, the metal undergoes the work hardening, which is a process hardening of metals and alloys due to the change of their structure and phase composition during the plastic deformation at temperatures below the recrystallization temperature. The work hardening has the following effects: the yield strength and tensile strength are increased while ductility decreases. The strength increases especially at the initial stages of deformation (up to 20—30 %). Further deformation does not lead to the increase of hardening. During rolling process, grains are shaped according to the deformation pattern, which means they are elongated in the direction of rolling and are reduced in the transverse directions (Fig. 1). Metal structure becomes fiber-like and as a result the properties in different directions are different [4]. This difference of properties in different directions is called anisotropy and the degree of anisotropy depends on the amount of deformation hardening.

Anisotropy is related to several factors, such as creation of a preferential crystallographic orientation (texturing), alignment of non-metallic inclusions, and chemical segregation [4]. Before the rolling process, the material is a polycrystalline metal comprised of stress-free grains. After rolling, the plastically deformed (strain hardened) material contains highly stressed, elongated grains aligned in the rolling direction (Picture 1).



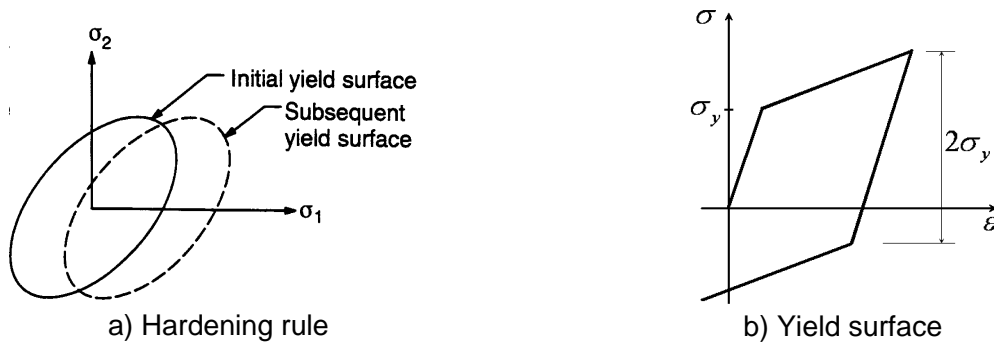
Picture 1. Changes in metal microstructure due to rolling process

If the work-hardened metal is heated to a temperature above the recrystallization

temperature,,it softens back and its ductility is recovered to the pre-hardened state. In the early stages of heating, or at temperatures below the recrystallization temperatures, the concentration of crystallographic defects is reduced without the movement of grain boundaries. This process, known as recovery, has a pronounced effect on the residual stress in the work piece and on certain physical properties, such as electrical conductivity and magnetic permeability. However, at this stage, no change in the microstructure is discernible and no significant change in the mechanical properties is evident.

That is why it seems to be appropriate to roll sheet metal in groove rolls at temperatures below the recrystallization point for conservation of the stressed structure gained during the process. At the same time working temperature should be appropriate for effective plastic forming of the metal blank. The temperature regime of warm rolling meets both requirements. While heating the hardened material to $0,3T_{m,t}$ (250°-400°C for steel) its strength partially reduces and ductility increases, but its internal structure and the mechanical properties stay unchanged. This temperature regime would allow applying efficiently the strain hardened zones which would also remain after the cold rolling and should have positive effect on strength properties of final products.

For the simulation of plastic behavior of the metal we used a bilinear kinematic hardening model. The hardening rule describes the changing of the yield surface with progressive yielding, so that the conditions (i.e. stress states) for subsequent yielding can be established. Kinematic hardening assumes that the yield surface remains constant in size and the surface translates in stress space with progressive yielding, as shown in Picture 2(a). The surface in Picture 2(b) is known as the yield surface and any stress state inside the surface is elastic, that is, they do not cause plastic strains. The Bilinear Kinematic Hardening option assumes the total stress range is equal to twice the yield stress [6].



Picture 2. Kinematic Hardening features

MODEL DESCRIPTION

The processes of metal rolling in plain and grooved rolls were modeled using LS-DYNA. Steel St-3 was selected as rolled material. The mechanical properties were chosen for the metal at temperature 400° that is below the recrystallization temperature (440° for St-3) and is 0,265T_{m.t.}. This temperature allows implementing efficiently the plastic forming being below the recrystallization temperature at the same time. Physical-mechanical properties of simulated material are shown in Table 1. Rolls were modeled as absolutely rigid.

Table 1. Physical-mechanical properties of the steel under consideration

Characteristic	Value
Density, [kg/m ³]	7700
Young's Modulus, [GPa]	187
Poisson's Ratio	0,28
Yield Stress, [MPa]	240
Tangent Modulus, [MPa]	420

The process of grooved rolling is implemented in rolls whose surface has a shape of multiple-thread helicoids with round tips (Picture 3). The helicoid is shaped like Archimedes' screw, but extends infinitely in all directions. It can be described by the following parametric equations in Cartesian coordinates:

$$x = \rho \cos(\alpha\theta), y = \rho \sin(\alpha\theta), z = \theta,$$

where ρ and θ range from negative infinity to positive infinity, while α is a constant.

Main parameters of grooved rolls are:

A – number of starts of helicoids;

R – roll radius;

L – roll length;

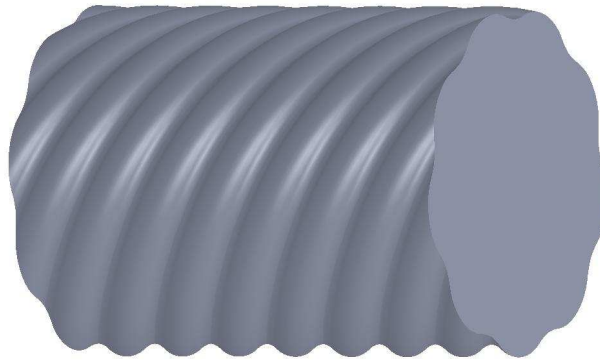
r_1 – fillet radius of groove ridge;

r_2 – fillet radius of groove gash;

h – distance between centers of ridge and gash;

l – distance between centers of 2 turns.

α – Inclination angle of helicoids to roll axes.

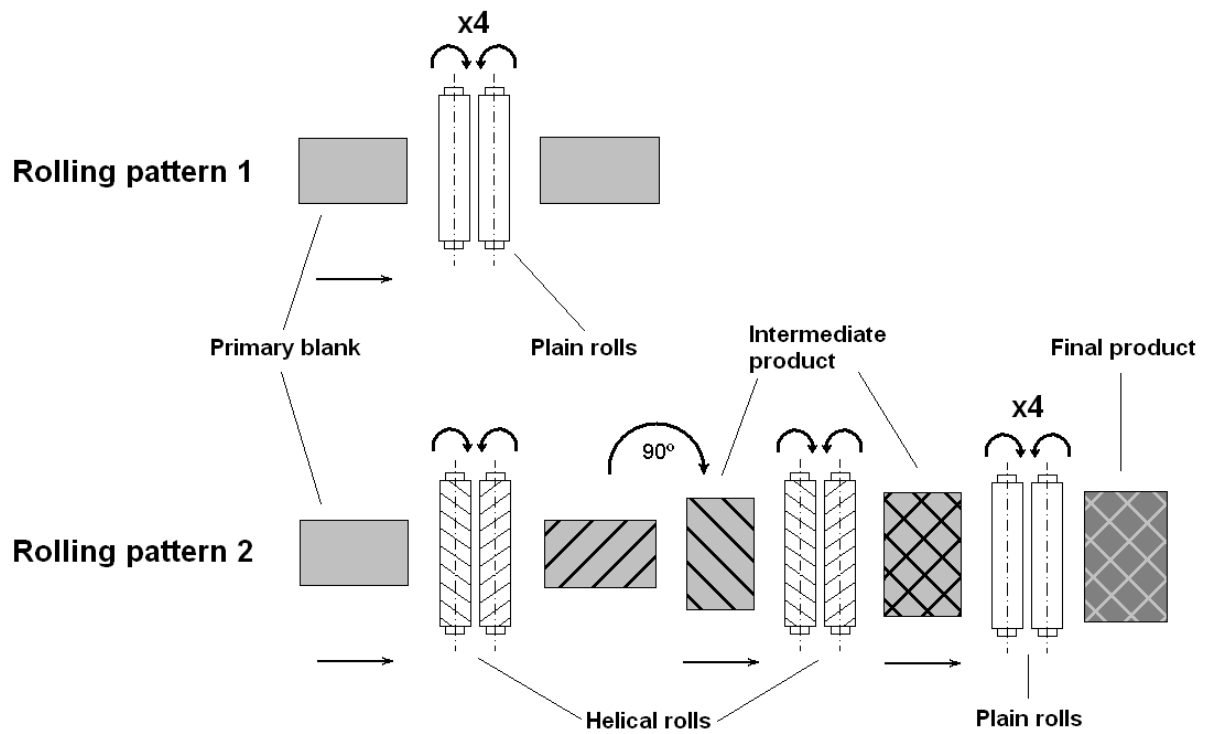


Picture 3. Geometry of a grooved roll under research:

$A = 9$; $R = 54\text{mm}$; $L = 150\text{mm}$; $r_1 = 10\text{mm}$; $r_2 = 5\text{mm}$; $h = 5\text{mm}$; $b = 20\text{mm}$; $\alpha = 60^\circ$.

The rolling is implemented according to one of the rolling patterns shown in Picture 4. The rolling due to the pattern 1 is 4-pass rolling in plain cylindrical rolls. Under the initial speed the metal blank approaches the roll space where it is engaged under friction forces. During 4 passes the metal plate has a thickness reduction of 40%.

Pattern 2 is 2-pass rolling in grooved rolls (with rotation of the blank at 90° between two passes) followed by 4-pass rolling in plain rolls (repetition of the pattern 1). Grooved rolls rotate with a permanent angular speed of 1.25 rad/s. The depth of indentation of the grooved roll tips in the blank body is 1 mm.



Picture 4. Rolling patterns

RESULTS

Table 2 shows the results of FE research of two metal blanks: the first one was rolled in plain rolls only (Plate 1) while the second one was rolled in grooved rolls at first step and then repeated the path of the first blank (Plate 2). There are several parameters that were taken under consideration for both blanks. After each pass in plain rolls plate geometry (length l , width b , thickness h) and maximum von Mises Stress intensity (σ_{\max}) were measured. Also Plastic Strain intensity was described by images.

Analyzing stress-strain state of Plate 1, it is possible to observe the reduction of strain intensity at plate edges. During 3rd - 4th passes the horizontal deflection of the plate on the exit of rolls place was observed.

During the rolling of Plate 2 the depth of grooved roll tips indentation was 1 mm (percent reduction - 24%) and ratio of expansion was 6,5%, while during the rolling Plate 1 the ratio of expansion was 0,52% even with percent reduction - 40%. After rolling in grooved rolls the rhombic supporting net is easily visible at plate surface. This net is

formed by plastic strain hardened zones that penetrate through the whole plate thickness. Supporting net stays clearly visible after 3-4 passes in plain rolls, when plate surface is already absolutely flat. While during first two passes Strain intensity regularly distributed at plate surface, it is possible to observe reduction of intensity at plate edges during 3rd - 4th passes. It allows drawing a conclusion: rhombic structure of supporting net stays saved mostly in the middle part of plate. At the exit of rolls place the plate doesn't deflect of it horizontal axes.

In general, it is obvious that saved plastic strain is significantly higher in the case of rolling according to pattern 2 (Plate 2) than the rolling according to pattern 1 (Plate 1).

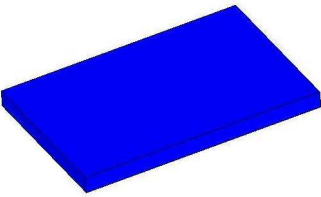
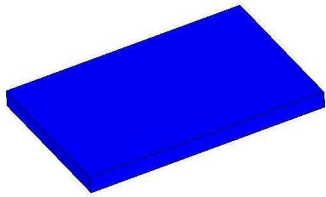
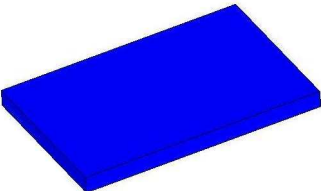
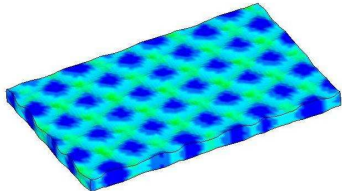
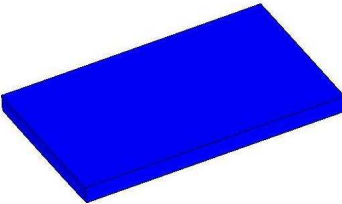
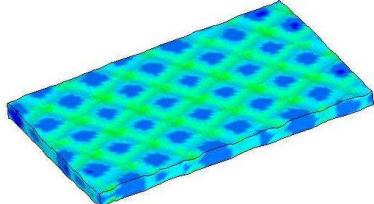
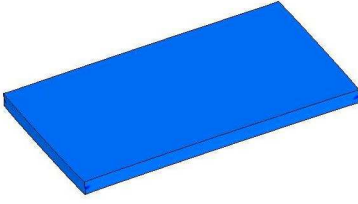
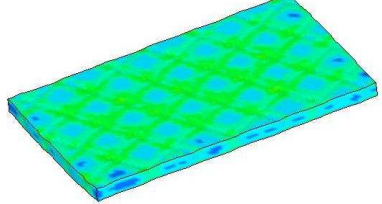
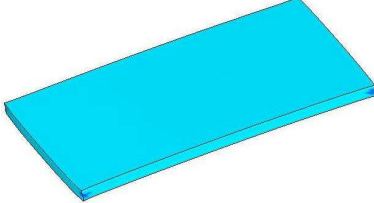
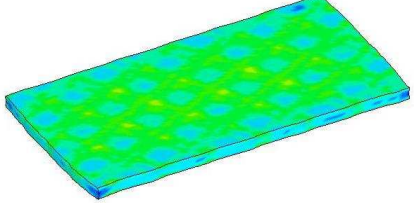
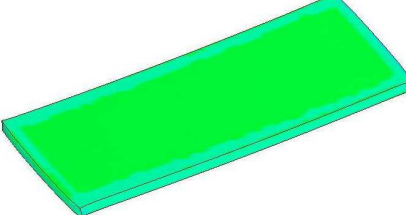
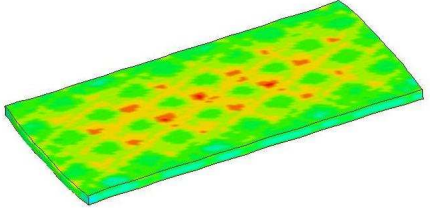
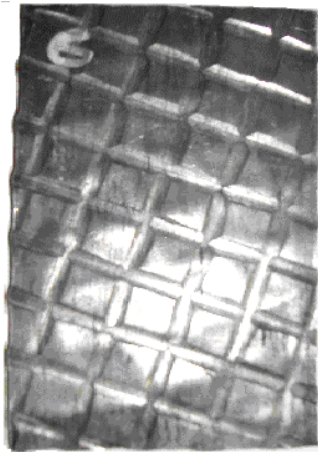
State	Parameters	Rolling pattern 1		Rolling pattern 2	
Initial	$l_0, [mm]$ $b_0, [mm]$ $h_0, [mm]$	118 77 8,3		118 77 8,3	
2-pass grooved rolling	$l_0, [mm]$ $b_0, [mm]$ $h_0, [mm]$ $\sigma_{max}, [MPa]$	- - - -		130 82 6-8,2 254	
1 pass	$l_1, [mm]$ $b_1, [mm]$ $h_1, [mm]$ $\sigma_{max}, [MPa]$	124 77 7,9 208		131,5 82,2 6-7,5 242	
2 pass	$l_2, [mm]$ $b_2, [mm]$ $h_2, [mm]$ $\sigma_{max}, [MPa]$	137 77 7 164		139 82,7 6,1-6,6 202	
3 pass	$l_3, [mm]$ $b_3, [mm]$ $h_3, [mm]$ $\sigma_{max}, [MPa]$	154 77,2 6,2 155		156 82,5 5,8 153	
4 pass	$l_4, [mm]$ $b_4, [mm]$ $h_4, [mm]$ $\sigma_{max}, [MPa]$	176 77,4 5,4 135		177 82,5 5,1 84	

Table 2. Results of FEA

Comparison between natural experiment and FEM demonstrates its qualitative agreement (Picture 5). Natural experiment that took place in Moscow Institute of Metallurgy and Material Science demonstrated improvement of strength properties (yield stress, ultimate strength) of metal after rolling in grooved rolls. As the research showed, the surface layer is better treated in the case of grooved rolling.



a) Nature experiment



b) FE modeling

Picture 5. Qualitative comparison between nature experiment and FE modeling

CONCLUSION

The processes of metal rolling in plain and grooved rolls were successfully modeled using commercial software LS-DYNA.

Analysis of results, obtained during the modeling the process of sheet metal rolling in grooved rolls, allowed to study the stress-strain state in plastically worked zones. In these zones metal was worked deeper that led to grain refinement. Hardened areas with fine grain structure act as barriers for crack growth and work similar to reinforcements in composites. Sheet metal rolled in grooved rolls has higher mechanical properties (yield stress, ultimate strain) than sheet metal rolled in plain rolls only.

Further research in this field using the developed FE model will allow selecting the optimal regimes of sheet metal rolling in grooved rolls. The final product – sheet metal with improved mechanical properties – could be used in automotive industry, machine building, large pressure vessels etc.

REFERENCES

1. A.A. Bochvar Physical metallurgy, 5 edition, Russia, 1956
2. B.B. Diomidov, N.V. Litovchenko. Technology of rolling production. – Moscow, 1979.
3. Atlas of steel defects. Translation from German language. – Moscow, 1979.

4. Dr. Racz Pal. Material Science, Collection of lectures. Budapest. 2011.
5. Parametric Study of Hot Rolling Process by the Finite Element Method/ A.R. Shahani, S.A. Nodamaie and I. Salehinia. - Sharif University of Technology, 2009.
6. LS-DYNA Theory Manual, John O. Hallquist, Livermore Software Technology Corporation, 2005.