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Optimization of mechanical properties and hardness of cold-worked plates out of 1565ch aluminium alloy

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In light of ever increasing material requirements for most industrial applications, an ability of a supplier to guarantee a predefined level of aluminium semiproducts' properties in accordance with each customer's needs is currently taking a more prominent role in the material selection decisions. In particular, this is true for such type of a product as cold-worked (strain hardened) aluminium plates, for which certain mechanical properties and hardness distribution over the plate's thickness have to be ensured. The power of modern computing hardware and software allows to accurately resolve the tasks of processing metals by pressure that often imply high level of discretization of a geometric model into finite elements that in their turn determine the number of equations being solved. This paper presents an outcome of a research of the strain hardening process of the plates produced out of 1565ch aluminium alloy that belongs to the 5xxx series high-magnesium group of aluminium alloys. The material has been chosen for the study due to its unique combination of physical and mechanical properties as well as welding and corrosion characteristics that make it possible to use the 1565ch alloy as a structural material for a wide range of applications. The research employed both computer mathematical modeling based on finite-element analysis as well as its in-situ verification on a rolling equipment of Arconic Samara metallurgical plant. Described in the paper are the summarized results of calculation of a considerable number of separate tasks (rolling cases) in the DEFORM software that made it possible to estimate the influence of reduction schedule and other cold rolling process parameters on the final product's properties. Also presented are the results of experimental rolling trials that have proved validity and accuracy of the finite-element analysis.

Key words: finite element method, cold rolling, strain hardening, aluminium plates, 1565ch alloy.

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Introduction

Mechanical properties of pure aluminum can be improved by alloying, followed by either heat treatment (for heat-treatable alloys) or by work hardening (for non-heat-treatable alloys). The 1565ch alloy plates belong to a group of high-magnesium, strain-hardened products. In addition to high strength, the main advantage of the material is a good weldability by all types of welding [1] and high-performance under cryogenic temperatures [2]. The alloy has been successfully employed in construction of large welded structures for ship-building and railway applications [3].

The plates out of 5xxx series high-magnesium aluminum alloys are widely used for manufacturing of various high-duty parts [4]. By additional alloying it is possible to further improve mechanical characteristics of the material. The chemical composition of the 1565ch alloy used in the present study is regulated by the special technical specification [5].

In order to achieve a particularly high strength the work or strain hardening operation by cold rolling is

Table 1

Properties of 1565ch alloy

Temper	Thickness, mm	Mechanical properties, not less than			Brinell hardness (*HB*), not less than	Impact elasticity *KCU*, not less than
		Tensile strength, MPa	Yield stress, MPa	Elongation, %		
F	15–50	335	175	15	85	20
	50–60	330	175	12	85	20
H18	15–40	370	270	8	110	9
H19	15–40	412	314	6	120	8

usually practiced. The advantage of work hardening — an increase of ultimate strength up to 400 MPa and even higher — is crucial for some applications, and therefore the process of cold rolling is usually carried out with overall reductions greater than 20%. Mechanical properties, Brinell hardness and impact elasticity of the 1565ch alloy plates in "as fabricated" (F), full hard (H18) and extra strain-hardened (H19) tempers are shown in the Table 1 [6].

However, there is an attempt to simulate hot deformation behavior of 1565ch alloy [7], individual impact of such factors as total strain, rolling rate, reduction schedule, friction conditions and other process parameters on quality of the cold-working and its pattern over plate's thickness was not thoroughly studied yet. Thus, a research of the work-hardening process is necessary to investigate the influence of the above parameters, also having in view an intent to obtain a material with desired, application-oriented properties. For the purpose of this work, the finite element method (FEM) implemented in the DEFORM software [8] was used as a basic research tool.

The work described in this article was particularly aimed at investigation of the deformation behavior and resulting hardness of relatively thick plates made of 1565ch alloy.

Finite element modeling

The FEM has proved its efficacy in analyzing of various metal forming processes [9]. With respect to the rolling process simulation it allows to study the stress-strain state of work-hardened plates, to determine the rolling force, to foresee the tendency of plates' alligatoring and to investigate other aspects of the process. As for predicting of mechanical properties, the most significant values calculated in the course of the analysis are equivalent strains distributed over the volume of the deformed material. It is assumed that for the most of aluminum alloys equivalent strains are proportional to material's hardness [10]. There are analytical expressions that establish relations between the values of equivalent strain found by numerical methods and Brinell hardness or ultimate strength of the material.

The first stage of the research implied creation of a two-dimensional finite element model consisted of a work roll, an aluminum plate and a pusher (Fig. 1). The large number of separate tasks ought to be resolved required well-founded assumptions and simplifications of the mathematical model: the geometrical model was halved with a symmetry boundary condition, the thermal problem was not calculated, the modeled work roll and the pusher were assumed to be made of rigid, non-deformable material. The assumptions made it possible to resolve a significant number of FEM tasks in appropriate time with both high accuracy and computing performance.

Based on the results of tensile tests of the new aluminium alloy, a stress-strain curve was plotted and used for the material properties designation in the concerned mathematical model: the tensile tests data were approximated by the power law of flow stress [11], the functional relation applicable to the models in DEFORM:

$$\sigma = K \cdot \varepsilon^n \qquad (1)$$

where $K = 505$ MPa is a material-related constant stress, $n = 0.16$ is a strain-hardening exponent.

The mathematical model was then validated by comparing the FEM results with theoretical and experimental values. The discrepancy in the total rolling

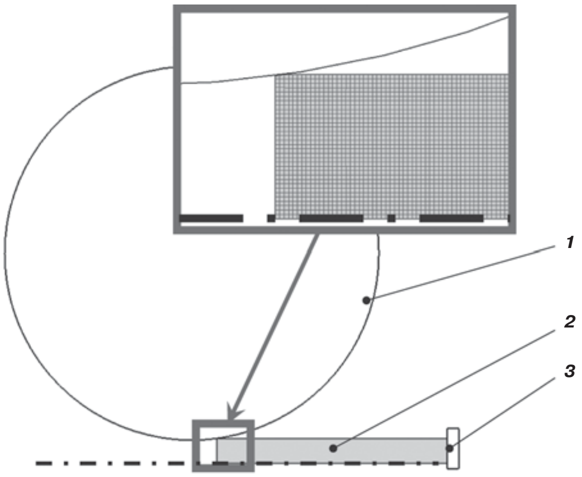

Fig. 1. 2D model for the analysis of cold rolling process in the Deform software:
1 — work roll; *2* — aluminum plate (FE-meshed model is shown on a separate view); *3* — pusher

force determined by FEM, by theoretical evaluation and by actual experiment did not exceed 5% on each rolling pass. Also verified were the roll bite condition and a position of neutral (no-slip) point.

Experimental cold rolling of the plates was performed on a laboratory rolling mill with work rolls of 300 mm in diameter. High level of correspondence between the mathematical model and the real physical conditions of the laboratory trial allowed to ascertain correlation between the achieved FEM results and the actual material properties.

Each separate solved FEM task gave a distribution of equivalent strain over the thickness of a rolled plate for a given reduction schedule. Collation of this data with the results of mechanical properties and hardness tests resulted in the following relationship between hardness and equivalent strain:

$$HB = 146(0.1 + \varepsilon_{eqv})^{0.2}, \qquad (2)$$

wherein ε_{eqv} – equivalent strains calculated by the finite element method.

The ultimate strength of the alloy most closely approximates to a linear equation:

$$\sigma_u = 3.63HB, \qquad (3)$$

where σ_u — ultimate tensile strength, MPa.

The two equations above have an important practical value, as they allow to accurately predict the unknown material's properties based on either the values that can be calculated by the FEM (the first equation), or derived from the FEM results (the second equation).

Further research was conducted to determine the factors that affect strength and hardness over the thickness of the cold-worked material. This resulted in solving multiple FEM tasks that differed in variable reduction schedules and technological parameters of the rolling process:

Parameter	Value
Work roll diameter, mm	550; 650; 900
Workpiece temperature (isothermal conditions), °C	20
Initial plate thickness, mm	40; 50; 60; 80
Number of rolling passes (depends on a reduction schedule)	from 1 to 20
Overall reduction, %	25; 30; 35
Rolling speed, m/s	0.5
Friction coefficient	0.08; 0.1; 0.15

To gather necessary amount of data of the FEM results, based on which any conclusions can be made, there have been solved more than a hundred FEM tasks simulating cold rolling process with various initial conditions. By means of modern software and hardware the tasks with a relatively high level of discretization of geometric models were solved in a reasonable time period.

Results of the FEM solutions with the above parameters have helped to analyze the factors that basically affect the pattern of distribution of equivalent strains over the thickness of a cold rolled plate, therefore making it possible to predict final properties of strain-hardened products.

FEM results and approbation

Reduction schedule, among all other factors, impacts the pattern of distribution of equivalent strains over plate's thickness at the utmost. This fact creates prerequisites for producing plates with desired pattern of properties over the thickness based on final application of the plates. This can be accomplished by choosing a proper reduction schedule.

FEM results (Fig. 2) show that overall reduction rate determines the minimum value of hardness located in the center of a cold-worked plate, and thus sets the general level of plate's hardness, while this is also substantially influenced by the number of rolling passes.

It was found that to obtain the desired level of hardness and strength a certain minimal rate of overall reduction should be provided at each rolling pass. Whereas the maximum possible reduction at each pass ensures the highest uniformity of hardness over the thickness of a cold rolled plate.

The influence of other parameters of cold rolling process was taken into account as well and is described below.

In particular, it was determined that during cold rolling of relatively thick plates a friction coefficient has little effect both on the rolling force and on the distribution of equivalent strain over the thickness: as a rule, equivalent strain near plate's surface grows slightly with increase of frictional forces. Consequently, hardness and strength

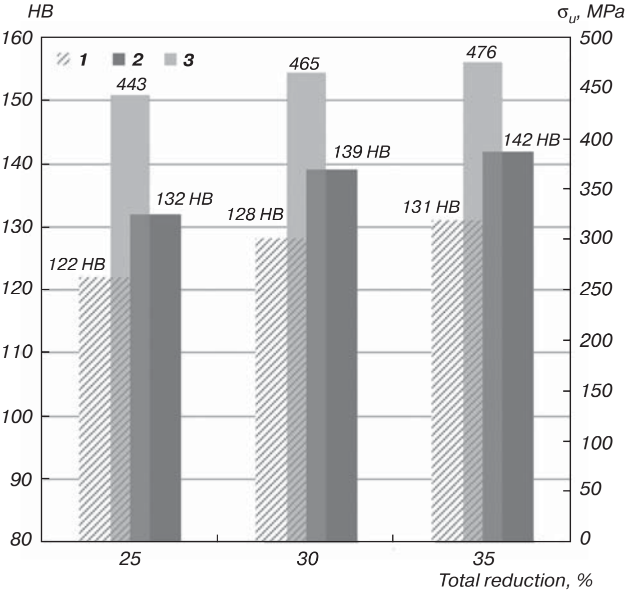

Fig. 2. Estimated hardness and strength of the plates per finite element analysis of the cold rolling process with different overall reduction rates

Table 2

Comparison of FEM results versus trial rolling (average values)

Reduction schedule	Total reduction, %	FEM predicted (see Eqs. 2 and 3)		Experimental values		Deviation, %	
		Brinell hardness, *HB*	Ultimate strength σ_u, MPa	Brinell hardness, *HB*	Ultimate strength σ_u, MPa	Brinell hardness, *HB*	Ultimate strength σ_u, MPa
14 roll. passes	23	119	432	121	430	2	1
19 roll. passes	26	123	446	124	444	1	1

of the final product is not substantially affected by the conditions of friction (lubrication, emulsion etc.).

Well-known is that the bigger is the circumference of a work roll's radius the longer is the arc of contact with the metal and hence the more rolling force is required [12], yet it was found that by using work rolls of a larger radius a more uniform distribution of equivalent strains over plate's thickness can be achieved.

The properties of plates predicted by the FEM analysis were verified by trial rolling of 1565ch alloy plates at Arconic Samara plant.

Mechanical and hardness tests of the samples taken from the cold rolled plates have substantiated good reliability of the study. The calculated error (maximum discrepancy) was less than 5% for the ultimate tensile strength values and ca. 3% for Brinell hardness (Table 2).

Summary

The FEM analysis implemented in the research made it possible to trace the impact of several parameters of cold rolling process on the properties of work-hardened plates. Further investigation of the work-hardening operation allowed to establish a number of important functional relations between the FEM-calculated equivalent strains and the material's hardness and ultimate strength. As part of the research various reduction schedules were studied under several overall reduction rates — this has helped to understand the forming factors for different patterns of hardness distribution over the thickness of the plates. As a result, the preferred technological parameters of the cold rolling process have been determined and can be selected to achieve desired, application-oriented properties of the 1565ch alloy plates.

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