Technological Shells in the Processes of Rolling Thin Sheets From Hard-To-Deform Materials

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TECHNOLOGICAL SHELLS IN THE PROCESSES OF ROLLING THIN SHEETS FROM HARD-TO-DEFORM MATERIALS

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Abstract

The present work is devoted to the study of deformability of high-strength and hard-to-deform materials. Today the most promising technology for their forming is a rolling in a ductile shell also known as sandwich rolling. Despite the fact that the use of such technological shells allows to effectively reduce the rolling forces and soften the stress state, they have not got wide application in manufacturing practice due to the accompanying disadvantages.

On the basis of finite element (FE) simulation, we carried out an all-around analysis of the effect of shell material on process parameters of method: rolling force, total reduction of hard-to-deform material, deformation inhomogeneity and thickness variation of rolled sheet, stress state scheme. Analysis of computer models allowed us to highlight the main reason for the low efficiency of the known method and propose a new design of technological shells.

Preliminary FE-simulation of the rolling process of hard-to-deform material in the new technological shells showed an improvement in process parameters and method efficiency. Approbation was carried out via rolling U12 high-carbon tool steel (Russian analogue of DIN C110W2 tool steel), which has low plasticity and high hardness, on the rolling mill Duo 250 under laboratory conditions. Evaluation according to technological criteria – reducing the rolling force, increase of the total reduction and the deformation uniformity of hard-to-deform material, improvement of its deformability – showed the prospects of using proposed technological shells in manufacturing practice.

Key-words: *hard-to-deform materials, high-strength materials, deformability, sandwich rolling, sustainable technology*

1. Introduction

1.1. Hard-to-deform materials and areas of their application

Innovations in many strategically important sectors of the industries (aerospace, automotive, defense, energy industries, etc.) are determined by manufacturing of products from materials with special properties – high strength, heat resistance, high-temperature strength, corrosion resistance in aggressive environments, wear resistance, magnetic, electrical or other properties. Typically, these properties are assigned to steels and alloys by high alloying, the result of which is, as a rule, a simultaneous increase in strain resistance and decrease in ductility. Such a deterioration of the technological properties of high alloys significantly complicates the processes of their forming (by forging, rolling, drawing, etc.) and hence Dzugutov [1] proposed to call such materials “hard-to-deform”.

Examples of such materials and areas of their application are: high strength dual-phase steels in the automotive industry [2, 3]; tool steels, e.g. AISI D2 steel and tool for rolling threads, trimming tools, cutting tools, broaches, etc. [4]; high-speed steels, e.g. AISI M2 steel and twist drills [5]; powder metallurgy tool steel, as well as powder high-speed steels, powder cold and hot work tool steels and various tools [6].

There are metals and alloys which are of great interest for various industries but are seriously limited in their plasticity. Examples of such metals and their applications are: pure magnesium, magnesium alloy AZ31 (Mg–3Al–1Zn) and thin sheets in the automotive industry [7-9]; molybdenum, molybdenum alloys and various parts in aerospace, defense and nuclear industries [10, 11]; alloy of uranium with molybdenum U-10Mo and foil for nuclear reactors [12, 13]; titanium alloys and various parts for the aircraft industry [14].

It is noteworthy to highlight the general tendency in different industries to increase the strength of structural materials, since this allows to reduce the total weight and dimensions of structures, reduce the amount of welding work during their assembly, and also improve aesthetics. In automobile and aircraft

manufacturing, due to the use of lighter materials (subject to ensuring their structural strength and operational reliability), there is a strive towards to reduce the weight of vehicles and, accordingly, reduce fuel consumption and CO₂ emissions into the environment.

In most cases, the main method for manufacturing semi-finished products from hard-to-deform steels and alloys is hot [1, 2, 4, 5, 6, 7, 9, 11, 12, 13] or cold sheet rolling. It provides high productivity of the process with the opportunity of automation, allows to get the required dimensions of the semi-finished product and to improve the microstructure and mechanical properties of the metal. Cold rolling is usually used to deform relatively thin sheets and strips (thickness less than 1.5 - 2 mm), however, in the case of hard-to-deform steels or alloys, its use is difficult due to limited plasticity of these materials.

1.2. The main issues of rolling hard-to-deform materials

Specialists in the field of metal forming point out several problems associated with sheet rolling of hard-to-deform steels and alloys. One of the main problems is edge cracking of thin sheets during rolling due to the inherent low plasticity of such materials [2, 3, 4, 5, 7, 9, 12, 13, 15, 16, 17, 18, 19]. Among the factors influencing the plasticity of the material, two groups are distinguished: 1) the properties of the material itself: chemical composition, microstructure, type of crystal lattice, number of microstructure phases, structural and chemical heterogeneity, etc. 2) thermo-mechanical conditions of deformation: temperature, strain and strain rate, shape and dimensions of the workpiece, dimensions of the deformation zone.

Specifically, the influence of thermo-mechanical conditions of deformation is expressed in the stress-strain state of the material – cracking begins in areas with the least favorable stress-strain state. In the case of sheet rolling, the stress-strain state on the free lateral surfaces of the rolled sheet is of crucial importance. It is well known that the lateral surfaces of a thin sheet are the most prone to cracking

areas due to the appearance of longitudinal tensile stresses on them during rolling [2, 3, 19].

Authors in [3, 19] have indicated that strip edge cracking directly depends on 1) lateral spreading during rolling – the larger the lateral spreading, the greater the probability of cracking; 2) the shape of the lateral surface – the convex lateral surface, due to barrel formation, accelerates the appearance of cracks; 3) the surface condition of the rolls – rough surface of the rolls facilitates the barrel formation of lateral surface of the rolled strip and its cracking. Hence, in order to avoid cracking, rolling of hard-to-deform material is significantly limited by the value of allowable reductions and by the ratio of initial width to thickness of strip. As a measure of prevention of strip cracking, trimming of its edges between rolling passes [2, 19] is also proposed in order to maintain a rectangular cross-section of the strip, but this solution significantly reduces rolling productivity and increases material loss.

The second problem is associated with the deformation of high-strength steels and alloys. During rolling such materials, significant forces arise, which leads to bending and flattening of the work rolls and, consequently, to significant longitudinal and transverse thickness variation of the strip [20, 21, 22]. In some cases, the high rolling force does not allow to deform the material due to insufficient power of the rolling mill engine and the risk of damaging the work rolls. In such situation, manufacturers are forced to use specialized equipment, for example, a Sendzimir rolling mill or a planetary rolling mill for rolling high-strength materials, which at the same time leads to a rise in the cost of products and the impossibility of expanding the range of products manufactured by available production facilities [20].

1.3. Rolling of hard-to-deform materials in technological shells: application prospects and technological limitations

From the literature [1, 20, 21, 22, 23, 24] the method of rolling high-strength and low-ductility steels and alloys in a shell made of softer material (Fig. 1) – e.g. from aluminum, copper, low-carbon steel, etc – is known. Theoretical calculations and experiments carried out in [20, 21, 23] show that the method allows to reduce the rolling force by 40 – 60 % and thereby reduce roll flattening and the thickness variation of rolled sheet. Huang et al. [22] based on new analytical models estimated the effect of thickness ratio of shell and core, coefficient of friction, reductions, yield stress ratio and dimensions of deformation zone on the rolling force. The studies [1] carried out by Dzugutov show that the method of rolling in a ductile shell is also suitable for deformation of low-ductility materials, since it creates a “softer” stress state. However, despite the obvious advantages of the method, its practical application is difficult due to the following reasons.

a) Since two materials with different properties are rolled together – a high-strength (or hard-to-deform) material and a shell material made of a softer material – the transition of both materials to the plastic state does not occur simultaneously. The softer material deforms more intensively, being squeezed out of the gap between the hard material and the roll and creating additional tensile stresses in the hard material. After the front end of the sheet exits from the roll gap, the conditions for extruding the soft material deteriorate, so forced deformation of the hard material begins. Under this changing rolling conditions, the plastic deformation of the hard material becomes unstable (effect of instability of plastic deformation), which leads to its local thinning (necking formation) and even ruptures.

This is evidenced by numerous experimental and theoretical results of the studies of rolling a hard material in a soft shell [12, 13, 25 – 39]. In the literature, such a scheme is also known as sandwich rolling or rolling “soft-hard-soft” package.

In particular, Souلامي et al. [12] note that during rolling the foil made of U-10Mo uranium alloy in the low-carbon steel shell, due to the difference in their

strength properties, defects are appeared – local thickening at the end sections of foil (so-called “dog boning”) and thinning of the shell material. Local thickening does not allow to use a semi-finished product from U-10Mo in responsible manufacturing, for this reason the method is ineffective. The authors point out that with a decrease in the strength of the shell material, these defects become more and more pronounced.

Utsunomiya et al. [25, 26] studied local thinning periodically repeated along the entire length of core (so-called “waviness”) by FE-simulation of rolling virtual materials in a soft shell. Local thinning (waviness, periodical necking) was also investigated by Nowicke et al. [27] on the example of sandwich rolling of corrosion-resistant steel and aluminum according to “Al-SS-Al” scheme, sandwich rolling of low-carbon steel and aluminum “Al-St-Al” was studied by Clerico et al. [28], sandwich rolling of copper and titanium “Cu-Ti-Cu” – by Yu et al. [29] through FE simulation and full-scale experiments.

Moreover, local thinning of a hard material during rolling in a soft shell was noted and discussed by Luo and Acoff [30] in the study of sandwich rolling of aluminum and titanium “Al-Ti-Al”; by Mahdavian et al. [31] – in the study of sandwich rolling of copper, zinc and aluminum Cu/Zn/Al; by Mozaffari et al. [32] and Min et al. [33] – in the study of sandwich rolling of nickel and aluminum “Al-Ni-Al”; by Su et al. [34] – in the study of sandwich rolling of AA1050 aluminum and AA606 aluminum alloy; by Cui et al. [35] – in the study of sandwich rolling of titanium Ti and composite TiB₂/Al; by Eizadjou et al. [36] – in the study of sandwich rolling of copper and aluminum “Al-Cu-Al”; by Zhang and Acoff [37] – in the study of sandwich rolling “Ti-Al-Nb”; by Yasuna et al. [38] – in the study of sandwich rolling “Fe-Ag”; by Chen et al. [39] – in the study of sandwich rolling “Al-Mg”; by Semiatin and Piehler [40] – in the study of sandwich rolling of corrosion-resistant steel and aluminum “Al-SS-Al”. As we can see this problem is widespread.

It is worth noting separately the mathematical models that allow to predict the conditions under which local necking of a hard material during rolling in a

ductile shell begins [40, 41]. Semiatin and Piehler [40] proposed frictionless, homogeneous plane-strain compression model for analysis of stresses in sandwich “Al-SS-Al”. Based on the simplified model, the authors explained the mechanism of onset of unstable deformation in a hard material. Hwang et al. [41] also proposed homogeneous plane-strain model of sandwich rolling and defined the critical conditions (material properties, thickness ratio, reductions) under which necking of the hard layer occurs. Together with the results of FE simulation made by Souلامي et al. [12] and Utsunomiya et al. [25], the following factors which reduce the local necking of a hard material can be pointed out:

- increase of yield stress of the shell material (i.e. decrease of the difference in strength properties between the hard material and the shell);
- higher work hardening exponent n of the shell material ($Y \text{ (stress)} = K \text{ (material constant)} \cdot \epsilon \text{ (true strain)}^n$);
- decrease of rolling reductions;
- decrease of the radius of the work rolls;
- decrease of the relative thickness of the shell.

b) Sandwich rolling of a package with large difference in strain resistance between hard-to-deform material and shell material causes shear stresses at the interlayer boundary [21, 22, 42, 43, 44]. Along with a large difference in the flow rates of materials and weak adhesion between them, shear stresses lead to delamination of the shell which makes further rolling impossible [23, 45]. This is especially noticeable during cold and warm rolling of steels in an aluminum shell “Al-St-Al”, as aluminum and its alloys tend to stick to the roll. These circumstances significantly reduce the effectiveness of the method and limits of applicability.

c) At the moment, the method of rolling high-strength and hard-to-deform materials in a ductile shell is still poorly studied from the point of view of manufacturability. In the most works devoted to the theoretical and experimental study of this method, attention is focused on the assessment of only one or two parameters: rolling force and torque [20, 21, 22]; conditions of local necking of

hard material, distortion of sheet geometry (“waviness” or “dog boning”) [12, 13, 25, 26, 41]; rolling force and layer reductions [43, 44, 46].

As mentioned above, the choice of the shell material can have a positive effect on some process parameters of the rolling process and negative on others. For example, the choice of a softer shell material provides: a decrease in rolling force and “softening” of stress state, but at the same time a decrease in total reduction of the hard material and the process performance, an increase of the depth of local thinning and the length of “dog boning” of the rolled material. The lack of comprehensive studies on the influence of the shell material on the mentioned process parameters complicates the rational design of the technological process. It should be noted separately that no assessment of the effect of the shell material on the stress-strain state of hard-to-deform materials at the edges was found in the literature. This is directly related to the fact that mathematical and FE-simulation in the mentioned works is carried out mainly in a two-dimensional formulation.

Thus, based on practical importance, several tasks were set in this research work:

- to study with the use of FE-simulation the rolling process of hard-to-deform materials in technological shells from the point of view of the effect of shell material on the most important process parameters;
- to optimize the structure of the technological shell for rolling hard-to-deform materials on the basis of results of FE-simulation;
- to carry out approbation of the developed technological shell on the example of rolling hard-to-deform tool steel.

2. Finite element model

FE-simulation package Deform-2D/3D was chosen for the first part of the work. Deform-2D was used for carrying out the main volume of works; Deform-3D was used for evaluating stresses at strip edges in individual cases.

In order to study the influence of properties of shell material on the deformability of the hard material without taking into account other technological factors (heating temperature of materials, rolling speed, friction conditions, etc.), model (virtual) materials with a linear hardening law were set: $\sigma = Y + H \cdot e$, where σ – flow stress, Y – yield stress, H – work hardening rate, e – true strain.

For hard-to-deform material $Y_h = 1000$ MPa, $H_h = 100$ MPa was taken. The shell material was chosen as a variable value, four levels of yield stress were taken: $Y_s = 100, 250, 330, 500$ MPa, work hardening rate was set at one level $H_s = 100$ MPa. The choice of material models is conditioned by the absence of periodical local necking according to the results of the analysis of works [25, 26, 41].

Initial thickness of the hard-to-deform material h_{h0} was taken equal to 1.5 mm, shell thickness h_{s0} was 1.5 mm, respectively, thickness of the whole package h_0 was 4.5 mm. Length of the layers l_0 was taken equal to 100 mm, the width b_0 was 40 mm (for three-dimensional tasks). The choice of initial layer thicknesses h_{h0} and h_{s0} is conditioned by satisfaction of the expression $h_{s0}/h_0 = 0.5 \dots 0.66$, since according to the results of mathematical modeling in [20, 21], the maximum reduction in rolling force is achieved at these ratios of layer thicknesses.

The package was deformed in one rolling pass with a reduction in thickness ε equal to 30 %, the linear rolling speed was 150 mm/s, the work roll diameter – 225 mm, roll material was set ideal rigid. Coulomb friction coefficient μ between the rolls and the shell material was taken equal to 0.1, and between the core and the shell 0.3. The conditions of contact between the materials of the core and the shell allow their mutual sliding without separation from each other. The package temperature was taken equal to 20 ° C.

Simulation of conventional rolling (without shells) of hard-to-deform material was also carried out under the same conditions for comparison.

3. Results of simulation and its discussion

Simulation results of the rolling of the hard-to-deform material in ductile shells with different strength levels and also conventional bare rolling are summarized in Table 1.

In Table 1: Y_s/Y_h – ratio of yield stresses of shell material (“soft”) and hard-to-deform (“hard”) material; mean normal stress $\sigma_m = \sigma_2 = \frac{\sigma_1 + \sigma_3}{2}$; effective stress $\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$; where σ_1 , σ_2 and σ_3 – principal stresses; $\frac{\sigma_m}{\bar{\sigma}}$ – stress triaxiality as stress state indicator; degree of local necking $\alpha = 1 - \frac{h_{h1min}}{h_{h1max}}$, where h_{h1min} , h_{h1max} – minimum and maximum final thickness of hard-to-deform material. Length of deformation instability area is summed up from the length of the thickened and thinned sections (see Fig. 1) and characterizes the loss of hard-to-deform metal. General view of the rolling process of hard-to-deform material in the shells with different strength levels is shown in Fig. 1. General view of the bare rolling process of hard-to-deform material is also shown.

According to the results of FE-simulation in Table 1, the softer the shell material (expressed in terms of Y_s/Y_h ratio), the lower the rolling force (Fig. 2). In comparison with the bare rolling, the rolling of hard-to-deform material in the shell with $Y_s = 100$ MPa provides the decrease in the rolling force by 2.3 times (or by 55%). However, at the same time, the decrease in the total reduction of the hard-to-deform layer from $\varepsilon = 30$ % for bare rolling to $\varepsilon = 20$ % for rolling in the shell with $Y_s = 100$ MPa occurs. These results were expected and are qualitatively consistent with the known mathematical models [43, 44].

Local thinning at the end sections (“dog boning”) of the hard material appeared in all cases of rolling in the shell, which is consistent with the results of the works [12, 13]. As Y_s/Y_h ratio decreases (i.e. when a softer shell material was selected), the degree of local necking α also decreases, which corresponds to a smaller variation in thickness at the end sections. However, at the same time, the length of deformation instability area L_{inst} increases.

From the point of view of the theory of plasticity, this is explained as follows. In the initial, unsteady rolling stage (when the package is bitten by the rolls), the softer shell material flows preferably in the direction of free surfaces, while there are practically no conditions for compression of the hard material. This can be seen from the front ends of packages in Fig. 1. Further, after the front end of the package comes out, the increased friction forces at the contact with the hard material begins to restrain the longitudinal flow of the shell material in the deformation zone – the support is created. In the deformation zone from the side of the shells, normal pressures arise in relation to the hard material. Moreover, intensive flow of the shell material at the exit from the deformation zone creates longitudinal tensile stresses in the hard material. Together, these conditions facilitate the appearance of local necking. Depending on the yield stress of the shell material, the pattern of the formed local necking differs: more elongated and with a lower degree of necking α for $Y_s/Y_h = 0.1$, less elongated and with a greater degree of necking α for $Y_s/Y_h = 0.5$.

The stress state in the main volume of the hard-to-deform material was assessed through the stress triaxiality $\frac{\sigma_m}{\bar{\sigma}}$ which characterizes the sum of stresses along all three axes relative to the stress intensity $\bar{\sigma}$. From the point of view of metal plasticity, the lower this indicator, the better [47]. The results of FE-simulation indicate that the softer the shell material, the greater the stress triaxiality $\frac{\sigma_m}{\bar{\sigma}}$ (Fig. 2) in the hard material which negatively affects its deformability. This is caused by the more intense flow of the soft shell material which, due to the frictional forces, creates additional tensile stresses in the hard material. The softer the shell material, the higher the velocity of its longitudinal flow in comparison with the central layer and the greater the resulting tensile stresses.

In contrast to the main volume of the strip material, the stress triaxiality $\frac{\sigma_m}{\bar{\sigma}}$ at the edges is much higher (+0.49 during bare rolling) which characterizes the prevailing proportion of tensile stresses. As known, their appearance is associated with lateral spreading of the material near the free lateral surfaces during rolling

and explains edge cracking under unfavorable conditions of the process. In table 1, in order to assess the probability of edge cracking of a strip made of hard-to-deform material under different rolling conditions, the worst $\frac{\sigma_m}{\bar{\sigma}}$ indicator was selected for each option. Fig. 3 shows the points of measurement of $\frac{\sigma_m}{\bar{\sigma}}$. It has been found that when rolling hard-to-deform material in the shell, $\frac{\sigma_m}{\bar{\sigma}}$ indicator at the edges is much higher than in the main volume of the material and is only slightly less than in conventional bare rolling (+0.32...+0.35). It follows from this that the critical area during rolling in the shells is also the edges.

A more important observation was the fact that when rolling a hard-to-deform material in a shell, strain rate ξ_b in the lateral spreading direction has negative values in the edge zone (Fig. 3). This corresponds to a narrowing of the strip and a transition to a biaxial compression state which favorably affects the material plasticity. The revealed effect is explained by intensive flow of the shell material which changes the friction forces from reactive to active at the contact surface with the hard material in the edge zone.

Summarizing the results of FE-simulation from the point of view of the manufacturability, we highlight the main obstacles to the widespread use of the method:

- decrease in the total reduction of hard-to-deform material and, consequently, in the method productivity;
- high risk of shell delamination;
- insufficiently effective reduction of $\frac{\sigma_m}{\bar{\sigma}}$ at the edges;
- local necking at the end sections of hard-to-deform material which increases material loss.

These phenomena become more pronounced with a decrease in yield stress Y_s of the shell material.

In our opinion, one of the reasons for the described phenomena is the presence of free surfaces of the shell material in front of and behind the deformation zone which enhance the deformation inhomogeneity of the strip. In

order to eliminate this factor and expand the technological capabilities of rolling method, we have developed new technological shells. Their difference is a two-layer construction: the inner layer of the shell is a soft material with low yield stress (“soft material”) which is responsible for reducing the rolling force; the outer layer of the shell - a material with “medium” yield stress (“medium material”) which increases the rigidity of whole package and restricts the flow of soft material in the direction of free surfaces. Medium material of the outer layer of the shell is chosen close in homological temperature to the hard-to-deform material, therefore the risks of sticking to the rolls and delamination of the shell during rolling are significantly reduced.

Initial approbation of the proposed technological shells was carried out through FE-simulation of three options of assembling “medium-soft-hard-soft-medium” package (“m-s-h-s-m”) with the following values of yield stresses of idealized (virtual) materials: *a*) “500-100-1000-100-500”; *b*) “500-250-1000-250-500”; *c*) “500-330-1000-330-500”. Work hardening rate H was taken 100 MPa for all materials, thickness of all layers – 1.5 mm, other rolling conditions were taken the same as in Section 2. The simulation results are presented in Table 2.

According to the results of FE simulation of the rolling process in the technological shell “m-s-h-s-m”, an improvement in process parameters (except for reducing the rolling force) in comparison with the rolling in the shells “s-h-s” was observed. The most promising packages with a large difference in yield stresses between hard and soft materials ($Y_s/Y_h = 0.1$ in Tables 1 and 2) were chosen for comparison.

It turned out that with a higher rolling force of 11.5 kN versus 8.3 kN, new technological shells provide: reduction of tensile stresses ($\frac{\sigma_m}{\bar{\sigma}}$ decreases from -0.17 to -0.22); increase in total reduction (ε of hard material increases from 20 % to 30.7 %), reduction of local necking (α decreases from 0.35 to 0.18) and length of deformation instability area (L_{inst} decreases from 20.1 mm to 7.94 mm). Slight improvement in rolling conditions at the edges was also observed ($\frac{\sigma_m}{\bar{\sigma}}$ decreases

from +0.35 to +0.17). A general view of the rolling process of hard-to-deform material in the new technological shells is shown in Fig. 4.

Comparison of the options of packages “m-s-h-s-m” $Y_s/Y_h = 0.1$ (Table 2) and “s-h-s” $Y_s/Y_h = 0.33$ (Table 1) with practically the same level of rolling force $P = 11.5 - 11.9$ kN shows that rolling according to the scheme “m-s-h-s-m” provides an increase in the total reduction ε , a decrease in the thickness variation α and the length of deformation instability area L_{inst} .

Improvement of important process parameters of rolling a hard-to-deform material with the use of new technological shells allowed us to conclude that their use in a real manufacturing process is promising.

4. Experimental procedure and materials

In order to test the proposed technological shells for rolling hard-to-deform materials, we carried out experimental rolling of model material. U12 high-carbon tool steel (Russian analogue of DIN C110W2 steel) was chosen as the model material. The chemical composition of the steel is presented in Table 3.

Strip from U12 tool steel was used as a workpiece with the following initial dimensions: thickness $h_0 = 6.5$ mm, width $b_0 = 23.2$ mm, length $l_0 = 50$ mm. Rolling was carried out on the rolling mill “Duo” with a roll diameter of 250 mm (Fig. 5), equipped with a load cell to record the rolling force. The rolling speed was 0.15 m/s; U12 tool steel was heated up to a temperature of 600 °C before rolling.

The choice of heating temperature is motivated by two factors: a) there is a risk of damage of the work rolls during rolling at room temperature due to the high hardness of U12 steel; b) there is the plasticity drop of U12 high-carbon tool steel at temperature of 600 °C (Fig. 6, *a*) which allows us to characterize steel as hard-to-deform material under the given rolling condition.

The model conditions created by us reflect the real rolling process of hard-to-deform materials (for example, those listed in Section 1.1), since heating is not applied for rolling thin sheets due to decarburization of the outer layer, the formation of scale and undesirable changes in the microstructure, i.e. rolling is

carried out under conditions of low plasticity of materials. The planned experiments will make it possible to evaluate the efficiency of using technological shells for rolling thin sheets from hard-to-deform materials.

The technological shell was constructed from an inner and outer layer. Aluminum alloy AMg3 (analogue of DIN AlMg3 alloy) with a thickness of 3 mm was chosen as the inner “soft” layer, and low-carbon steel 08ps (analogue of DIN DC01 steel) with a thickness of 1 mm was chosen as the outer “medium” layer. The total thickness of the assembled package was 14.5 mm. The flow stresses of U12 high-carbon tool steel and shell materials under these rolling conditions are shown in Fig. 6, *b*. The ratio of flow stresses of AMg3 aluminum alloy and U12 tool steel is close to the ratio $Y_s/Y_h = 0.1$ realized in FE-simulation.

Rolling was carried out in two ways:

1) conventional bare rolling of U12 tool steel according to the schedule 6.5 → 5.1 → 4.3 → 4 with intermediate heating of the strip up to 600 °C between passes;

2) rolling of U12 tool steel in the technological shell according to the schedule 14.5 → 10.5 → 9 → 8 → 7 with intermediate heating of the package up to 600 °C between passes.

It should be noted that rolling of U12 tool steel according to “s-h-s” scheme in the shell made of aluminum only under these conditions is impossible, because the aluminum layer instantly adheres to the steel rolls.

5. Results of experimental rolling and its discussion

The results of rolling U12 tool steel were evaluated according to several criteria: plasticity, rolling force, total reduction ε and thickness variation α . During bare rolling of U12 steel strip, in the first pass (during reduction from 6.5 to 5.1 mm, $\varepsilon = 21.5\%$), several cracks appeared at the edges. In the second pass (5.1 → 4.3 mm, $\varepsilon = 15.7\%$), the growth of one of the cracks continued, in the third pass (4.3 → 4 mm, $\varepsilon = 7\%$), the crack passed through the entire strip (Fig. 7, *a*). Fracture of the strip clearly illustrates the low plasticity of U12 tool steel.

When rolling the strip from U12 tool steel in the technological shell, the wholeness of the strip was assessed after four rolling passes and cooling down of the package together with the furnace. The cooled package was cut with a band saw in near-edge zones – across and along the rolling direction.

Tool-room microscope examination of the longitudinal and transverse sections of U12 tool steel did not reveal the presence of cracks (Fig. 7, *b, c*). Based on this, it was concluded that the deformability of U12 tool steel under these conditions was satisfactory.

For both rolling schemes, reduction of U12 steel strip in the passes and the corresponding rolling force were recorded. When rolling in the technological shell, reduction of U12 tool steel was measured only after the last pass. For each pass, reduction of U12 steel was recalculated in proportion to the ratio of reduction of U12 steel to reduction of whole package in the last pass: the total reduction of the package after all passes $\varepsilon_{\text{pack}} = 0.53$, the total reduction of U12 steel after all passes $\varepsilon_{\text{U12}} = 0.40$, the ratio $\varepsilon_{\text{U12}}/\varepsilon_{\text{pack}} = 0.76$. The reductions of package in each pass $\varepsilon_{\text{pack}}$ were multiplied by the resulting ratio 0.76 to roughly estimate ε_{U12} . Obtained data were processed and presented in the form of graph in Fig. 8.

From the graph in Fig. 8, it can be seen that during rolling U12 steel in the technological shell, the rolling forces decrease by 20 - 30% while the reductions of U12 steel in passes 1 and 3 is even higher than during bare rolling. The total reduction of U12 steel during rolling in the technological shell after all passes also turned out to be higher – 44.9 % versus 38.5 % for bare rolling. Taking into account the requirement of absence of cracks, the total reduction increased from at least 21.5% (bare rolling, 1st pass, cracks have appeared) to 44.9 % (rolling in the technological shell, no cracks).

Degree of local necking α of U12 steel is 0.18 ($h_{\text{hlmax}} = 4.84$ mm, $h_{\text{hlmin}} = 3.98$ mm) which is a consequence of non-uniformity of deformation during rolling in the technological shell. The resulting value is very close to FE-simulation result.

6. Summary

In the present work, for the first time, the method of rolling hard-to-deform materials in a ductile shell (“soft-hard-soft” scheme) is analyzed from the point of view of manufacturability: rolling forces, achieved reductions of material, thickness variation, deformability. By means of FE-simulation, it was shown that the choice of a ductile shell material is limited by the necessity of search for a compromise between a decrease in the rolling force and a decrease in the total reduction of a hard-to-deform material, an increase in non-uniformity of its deformation. Besides, in practice certain materials (aluminum, stainless steels) cannot be used as a shell material due to the high risk of delamination and sticking to the rolls.

Based on the analysis of flow of the shell material during simultaneous deformation with a hard-to-deform material, the main reason of low efficiency of the method of rolling in a ductile shell was formulated and a new shell design was proposed (“medium-soft-hard-soft-medium” scheme).

Efficiency of the new technological shell was preliminarily assessed by means of FE-simulation. For the investigated options of rolling in the technological shells, an improvement in process parameters was achieved – a decrease in rolling force, an increase in the total reduction of a hard-to-deform material, an increase in the uniformity of its deformation, an improvement of the stress state at the edges.

The approbation was carried out under laboratory conditions on the example of rolling U12 high-carbon tool steel which has low plasticity and high hardness. The proposed technological shell consisting of low-carbon steel and aluminum alloy allows to deform U12 tool steel without cracking, reduce rolling forces by 20 – 30 % and increase the total reduction by 23.4%.

Declarations

Authors' contributions Not applicable

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Data availability Not applicable

Compliance with ethical standards

Competing interests The authors declare that they have no conflict of interest.

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Figure 2

. Dependence of the rolling force and stress state of the model hard-to-deform material on the ratio of yield stresses Y_s/Y_h

Figure 3

Due to technical limitations, the caption for this figure can only be found in the manuscript.

Figure 4

Strain state of the hard-to-deform material during rolling in the technological shells with a different ratio of yield stresses (a) $Y_s/Y_h = 0.1$ ("500-100-1000-100-500"); (b) $Y_s/Y_h = 0.25$ ("500-250-1000-250-500"); (c) $Y_s/Y_h = 0.33$ ("500-330-1000-330-500")

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