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Simulation of the rolling process of a laminated composite AMg3/D16/AMg3

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ABSTRACT

Introduction. Over the past decades, laminated composites based on aluminum alloys have been increasingly used in the aerospace and automotive industries. Laminated composites are usually produced by accumulative roll bonding, which results in the metallurgical bonding of initially prepared sheets. Hence, the main task of accumulative roll bonding is to obtain a reliable bond between materials. However, at present, the process of joining similar or dissimilar materials by plastic deformation is still a poorly understood phenomenon. In this regard, in recent years, methods of finite element modeling of the processes of joining materials have begun to develop intensively. **The purpose of the work** is to establish a relationship between stress-strain state parameters and the formation of a stable bond between aluminum alloys of different compositions. To achieve this goal, the following **tasks** are formulated: 1. Simulation of the laminated composite "*AMg3/D16/AMg3*" rolling process using data corresponding to physical experiments carried out at the Institute of Engineering Science of the Ural Branch of the Russian Academy of Sciences; 2. Selection and analysis of the most important stress-strain state parameters of the laminated composite "*AMg3/D16/AMg3*" rolling process. **Research methods.** Process simulation system *Deform-3D* was chosen as the main research tool. **Results and Discussion.** An analysis of the coordinate grid distortion and velocity vectors of material flow of layers revealed that the deformation is distributed inhomogeneously in the cross section after rolling: the outer layers flow more intensively compared to the middle layer. The maximum scatter of strain intensity e_i in the cross section, observed at a maximum reduction ratio of 75%, is 12%. This allows one to accept for analytical calculations in the first approximation the assumption of deformation uniformity. A relationship is established between the beginning of the formation of a bond between composite layers and the threshold expansion of the contact surface and normal pressure at the interlayer boundary. In the final part of the study, future directions for improving the approaches of simulation the laminated composites rolling processes are proposed.

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Introduction

Over the past decades, laminated composites based on aluminum alloys have been increasingly used in the aerospace and automotive industries [1]. Due to the use of different materials in one part, it is possible to combine such properties as strength, corrosion resistance, specific weight (which is important for aviation), and thermal conductivity, etc.

Laminated composites are usually produced by accumulative roll bonding, during which the metallurgical joining of preliminarily prepared sheets occurs [2]. Accumulative roll bonding technology includes the following main stages: preparation of sheet surfaces to be bonded by chemical and mechanical treatment; sheets packing and fixing by welding or riveting; rolling of the pack according to the specified schedule; heat treatment; and cutting off the fixed edges of the pack. These operations can be followed by sheet stamping operations, such as cutting and drawing [2].

The principal purpose of accumulative roll bonding is to obtain reliable bonding between materials characterized by strength and evaluated through special tests [3]. However, at this moment, the joining processes of similar and dissimilar materials by plastic deformation are still poorly understood. This is confirmed by numerous works devoted to the study of the influence of individual technological factors of accumulative roll bonding on the bond strength between materials' layers [1–10]. Analysis of review [2, 4, 5], experimental [4–10] and theoretical [11, 12] works showed that the most significant factors of accumulative roll bonding are thickness reduction and pressure during rolling, surface preparation technology for joining and the ratio of strength properties of materials to be bonded. Due to the lack of reliable models for predicting the conditions under which the bonding of materials begins, the development of technologies to produce new laminated composites is accompanied by a large amount of preliminary experimental research. As shown in the previous work of the author [3], additional difficulties are caused by the unequal influence of the same factors on the process of joining materials, which depends on the combination of materials in a particular technological process. For example, in some cases, an increase in the roughness of the contact surfaces contributes to bonding; in other cases, on the contrary, it prevents bonding.

To describe the mechanism of bonding of similar and dissimilar materials, there are approximately six theoretical models described in [13]. The most frequently cited model is *Bay's* theoretical model of materials' bonding [14], which describes bonding of materials as a four-stage process: (1) cracking of surface oxide films, (2) extrusion of pure metals into cracks between oxides, (3) interatomic interaction of pure metals, and (4) formation of "bonding bridges". The limitations of *Bay's* theoretical model are the assumptions typical for continuum mechanics: two-dimensional formulation, uniformity of flow of layer materials and pressures in the deformation zone, etc. In addition, *Bay's* model does not allow one to determine analytically the level of deformations and pressures during rolling, which is necessary to initiate bond formation.

In this regard, in recent years, methods of finite element (*FE*) simulation of the processes of joining materials have undergone great development [15–19]. Based on full-scale experiments, it is possible to reproduce the conditions under which bond formation between materials occurs. In particular, for the analysis of processes of materials' bonding, such characteristics as normal pressures, shear stresses, relative average normal stresses, and effective strains are of interest. The most detailed *FE* analysis of the rolling process of aluminum composite was provided by *Khaledi et al.* [17–18]; however, they simulated the process of similar aluminum sheets bonding, which was well studied in the experimental works of *Bay* [14]. Study of the mechanism of bonding between dissimilar materials is a more difficult task. Therefore, **the aim** of this work was to establish a relationship between the stress-strain state parameters and the formation of a stable bond between aluminum alloys of different compositions. To achieve this aim, the following **tasks** of the work are formulated: 1. Simulation of the rolling process of the laminated composite "*AMg3/D16/AMg3*" with the initial data corresponding to the physical experiments carried out at *IES Ural Branch of the Russian Academy of Sciences*; 2. Selection and analysis of the most important stress-strain state parameters during rolling of laminated composite "*AMg3/D16/AMg3*".

Research methodology

The subject of research was the rolling process of laminated composite "*AMg3/D16/AMg3*" consisting of aluminum alloys *D16* (alloy of the 2xxx series, strain- and age-hardenable) and *AMg3* (alloy of the 5xxx series, strain-hardenable) [20].

Deform-3D FE modeling package was chosen as the main research tool. The simulation of the rolling process was carried out in accordance with the following conditions. Sheets with dimensions of 2.92 × 50 × 75 mm (thickness × width ×length) were considered as initial workpieces corresponding to the actual dimensions of sheets used for physical modeling. Sheets from *D16* and *AMg3* alloys were supplied in the annealed (soft) state. The hardening curves of these alloys were obtained using a cam plastometer of *IES Ural Branch of the Russian Academy of Sciences* and then integrated into the *Deform 3D* environment. The resulting strain resistance ratio $\frac{\sigma_{D16}}{\sigma_{AMg3}}$ of the alloys was close to 0.8.

Before rolling, the sheets were stacked in a pack, as shown in Fig. 1. The rolls were assumed to be ideally rigid with a linear rolling speed of 150 mm/s, and the roll diameter was 255 mm. The friction conditions corresponded to the *Coulomb* friction law with a friction coefficient μ equal to 0.12 between the rolls and the outer layers of the pack and a friction coefficient μ equal to 0.5 between the layers in the pack. The temperature of the pack corresponded to room one.

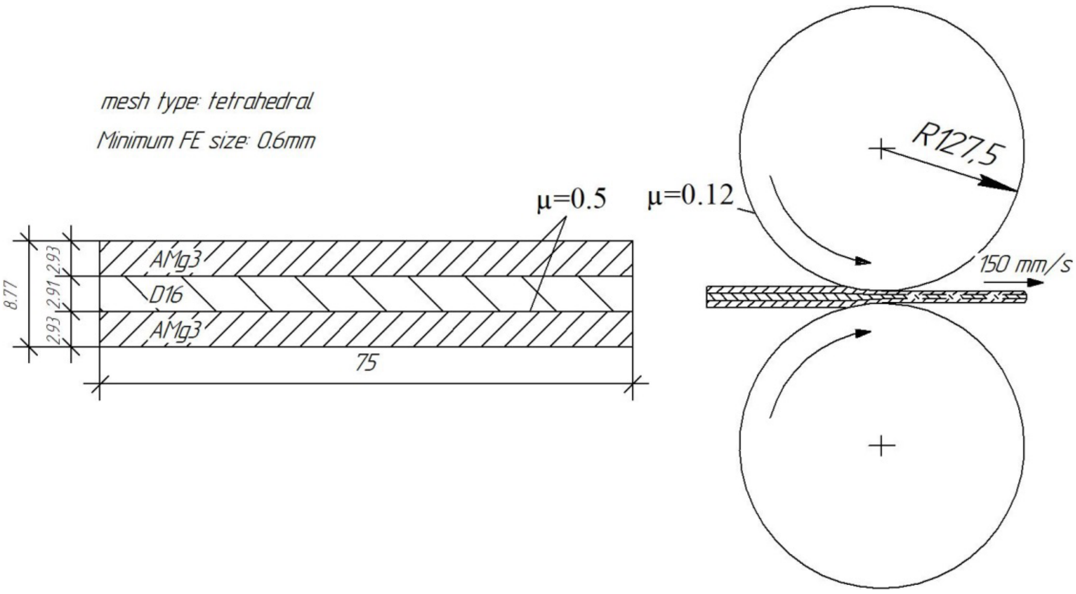


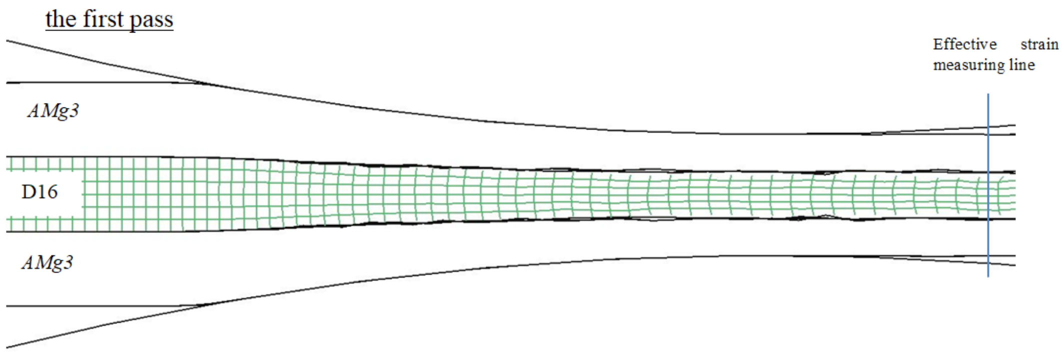
Fig. 1. Setting of the problem of *3D FE*-simulation of the laminated composites"AMg3/D16/AMg3" rolling processes

To simulate the fixation of sheets in a pack during rolling, the condition of the possibility of its mutual slipping without separation from each other is taken. The minimum size of *FE* for sheet workpieces, which allows one to find the convergence of the problem at iteration steps, was experimentally established: the minimum size of *FE* in the density window was 0.6 mm, the minimum size of *FE* outside the deformation zone was 1.3 mm, and the total number of *FE* was ~50,000 for each sheet. Thus, there were three *FE* per sheet thickness in the deformation zone, which can be considered satisfactory in terms of accuracy and solution time.

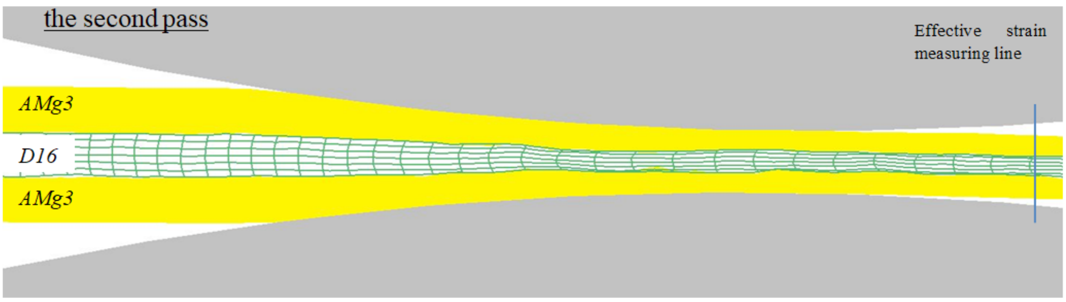
During simulation, the thickness reduction of the pack $\varepsilon = \frac{h_0 - h_1}{h_0} \cdot 100\%$ was varied, where h_0 and h_1 are the initial and final thicknesses of the pack, respectively. The reduction ε specified in the simulation corresponded to the real ones: 30, 45, 55, 65 and 75 %. At the same time, reduction of more than 45 % were performed in two passes, where the first pass was equal to 45 %, and the second one corresponded to the target final reduction (from 55 to 75 %). The authors experimentally determined that bonding between aluminum alloys occurs when the thickness reduction ε is not less than 45 %. This observation is consistent with the literature. For example, in [6], it was established that a thickness reduction of at least 40 % is required for joining sheets from commercially pure aluminum.

Results and discussion

Fig. 2a, b shows the shape change of the coordinate grid, which characterizes the flow of the middle layer during rolling with a reduction of 45 and 75 %, respectively. The coordinate grid was built in the central longitudinal section with a cell size of 0.5 × 0.5 mm. From the shape change of the grid, one can note that the near-surface layers of the *D16* alloy flow in the longitudinal direction more intensively than the central layers of the alloy during rolling. At higher reduction ratio, as shown in fig. 2*b*, there is a more intensive elongation of the near-surface layers of the *D16* alloy compared to the central ones.



a



b

Fig. 2. Shape change of the central layer grid under rolling with thickness reduction ratio of 45 % (*a*) and 75 % (*b*)

Fig. 3 shows the flow of metal to the exit from the deformation zone. One can note that there is a curvature of the flow velocity vectors surface of the metal layers with a lag in the flow of the central layer of *D16* alloy compared to the outer layers from *AMg3* alloy. In other words, the metal of the central layer is displaced toward the entrance to the deformation zone due to its lower deformation resistance. Based on this, it is obvious that the law of constancy of second volumes is not fulfilled with the corresponding distortion of the coordinate grid.

To evaluate the strain inhomogeneity in the cross section of the rolled composites, the effective strain e_i was measured along the line shown schematically in fig. 2. The effective strain e_i was calculated as per the equation $e_i = \frac{\sqrt{2}}{3}\sqrt{(e_1 - e_2)^2 + (e_2 - e_3)^2 + (e_3 - e_1)^2}$, where e_1–e_3 are the principal strains. The measurement results are presented as a graph in fig. 4, where the relative thickness of the laminated

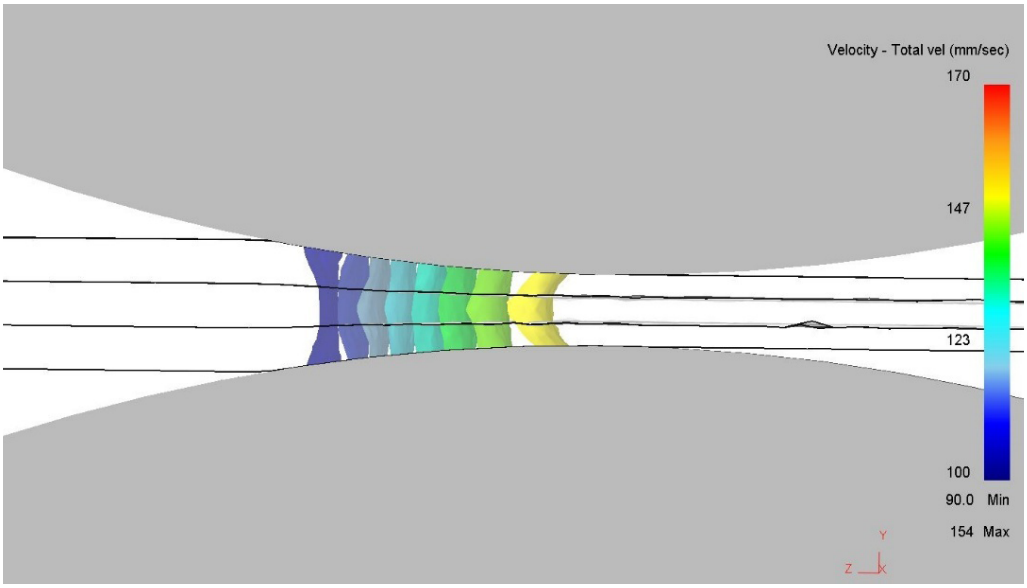


Fig. 3. Surfaces of metal flow velocity vectors of layers during accumulative roll bonding with thickness reduction ratio of 45 %

composite is plotted along the abscissa (**0** is the lower surface of the composite, and **1** is the upper surface of the composite).

In fig. 4, attention should be given to the increase in the inhomogeneity of the effective strain e_i with an increase in reductions during rolling. At a low reduction ratio of 30 %, the deformation inhomogeneity across the layers is practically indiscernible, and the difference between the maximum and minimum values is 0.02. With an increase in reductions, the inhomogeneity of effective strain e_i becomes more pronounced and reaches a maximum at the highest reduction of 75 %, with a difference between the maximum and minimum value equal to 0.17. It should be noted that at reductions up to 65 %, the middle layer of the composite from *D16* alloy is characterized by lower values of the effective strain e_i. This is consistent with the distribution pattern of the layer flow velocity vectors and the conclusion about the lag of the flow velocity of the central layer from those of the outer layers.

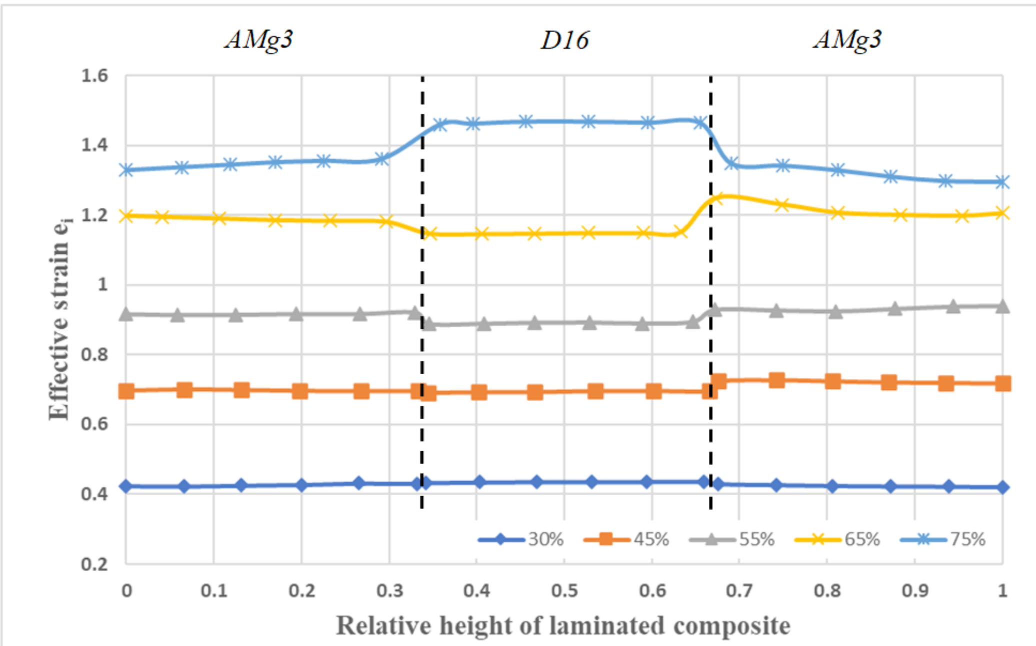


Fig. 4. Distribution of effective strain in the cross section of composites depending on thickness reduction during rolling

At a reduction ratio of 75 %, the reverse pattern is observed: the central layer of the composite is characterized by large values of the effective strain e_i. This phenomenon is most likely caused by the small thickness of the sheet (2.2 mm) at this reduction ratio, which leads to a more intense propagation of the deformation into the depth of the composite. In general, the maximum scatter of the effective strain $\frac{e_{i(\max)} - e_{i(\min)}}{e_{i(\max)}} 100\,\%$ is 12 %, which was observed at a thickness reduction ratio of 75 %. Therefore, it is possible to make an assumption about the uniformity of the strain distribution in the cross section of the composite "*AMg3*/*D16*/*AMg3*" in the first approximation for analytical calculations of the manufacturing technology.

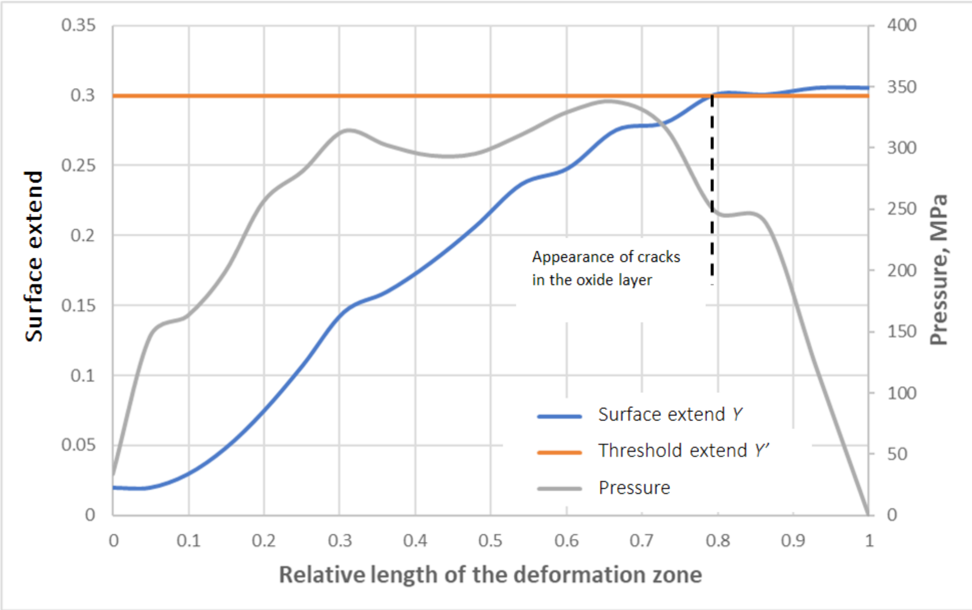
To study the conditions of the bond formation between layers from different materials, the degree of surface extend $Y = \frac{A_1 - A_0}{A_1}$ was calculated for different rolling options, where A_0 and A_1 are the initial and final surface areas [14, 21]. To determine the beginning of the bond formation in the deformation zone, the boundary criterion Y' was set, which means the contact surface extend, at which cracks appear in the oxide layer. According to the literature sources [6, 14, 16, 17, 18, 22] devoted to the production of aluminum composites by rolling, Y' criterion can vary from 0.3 to 0.4 for commercially pure aluminum, which is equivalent to an approximate rolling reduction ratio ε of 30–40 %. In our case, Y' criterion was taken equal to 0.3, considering the lower ductility of the studied alloys compared to commercially pure aluminum.

Fig. 5 shows the dependence of the extend of the contact surface Y at the interlayer boundary on the relative length of the deformation zone, where "**0**" is the entrance to the deformation zone, "**1**" is the exit from the deformation zone. Additionally, the same figure shows normal pressure. Analysis of the surface extend values Y at the exit from the deformation zone in fig. 5 reveals that these values practically coincide with the reduction ε values. This suggests that the influence of the lateral broadening of sheets on the contact surface extend Y is negligible and can be neglected for analytical calculations under these conditions.

Fig. 5*a* presents the case of rolling of the three-layer pack "*AMg3*/*D16*/*AMg3*" with a rate of reduction equal to 30 %. As can be seen, the contact surface extend Y crosses the threshold exposure Y' at a relative length of 0.8 of the deformation zone, which corresponds to the onset of cracking of the oxide layer and the possibility of contact between pure metals. However, at a relative length (0.8–1) of the deformation zone, normal pressures are intensively reduced from 250 to 0 MPa. Thus, the maximum relative pressure $\frac{p}{\sigma_{D16}}$ is 1.5, which is not enough to create contact between the materials. Under real conditions of rolling with a reduction of 30 %, bonding between aluminum alloys does not occur, which is consistent with the computer simulation data of the presented case.

Fig. 5b shows a dependence of the contact surface extend and normal pressure on the relative length of the deformation zone during rolling with a reduction of 45 %. In this variant, the achievement of the threshold value of the contact surface exposure Y' occurs at a relative length of the deformation zone equal to 0.42. After reaching the threshold value, the contact surface continued to extend and Y reached a value of 0.45. At the relative length of the deformation zone (0.42–1), corresponding to rolling with cracks in the oxide layer, the pressure continued to increase from 320 MPa to a maximum value of 394 MPa. The relative pressures $\frac{p}{\sigma_{D16}}$ in the area of the deformation zone range from 1.6 to 1.97. Since the primary bonding of materials is formed during rolling with a reduction of 45 % under laboratory conditions, it can be assumed that relative pressures from 1.6 to 1.97 are sufficient to extrude pure metals between cracks in the oxide layer and bring it to the distance of action of interatomic forces.

To confirm the results of the computer simulation, the data of the microstructural study of laminated composite "*AMg3*/*D16*/*AMg3*" after rolling with a reduction of 45 % are shown in fig. 6. Fig. 6a presents the cross section of the composite in the area of material bonding. The bonding boundary is a visible line, with no signs of cracking or fracture of structural elements. After rolling, the laminated composite was



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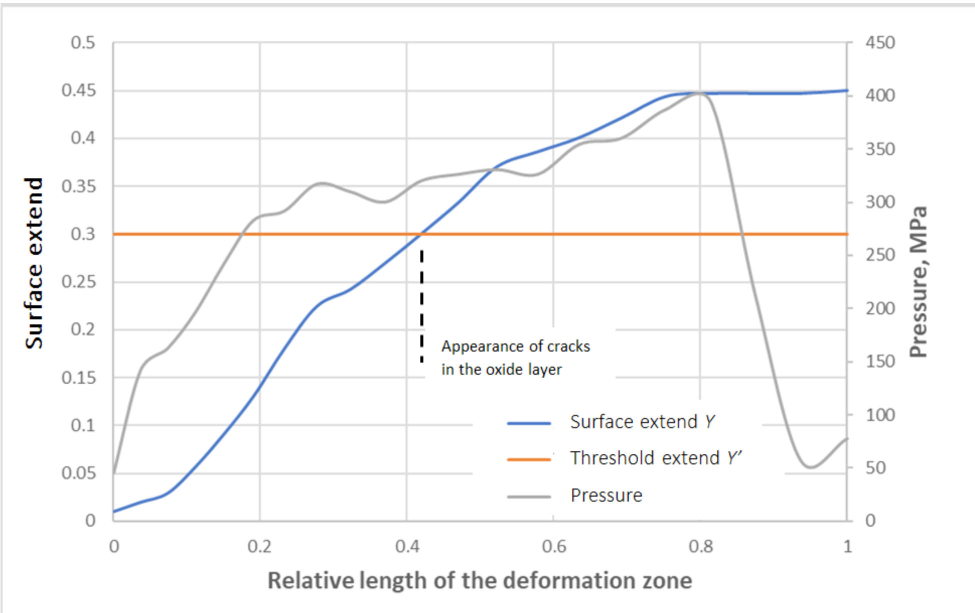


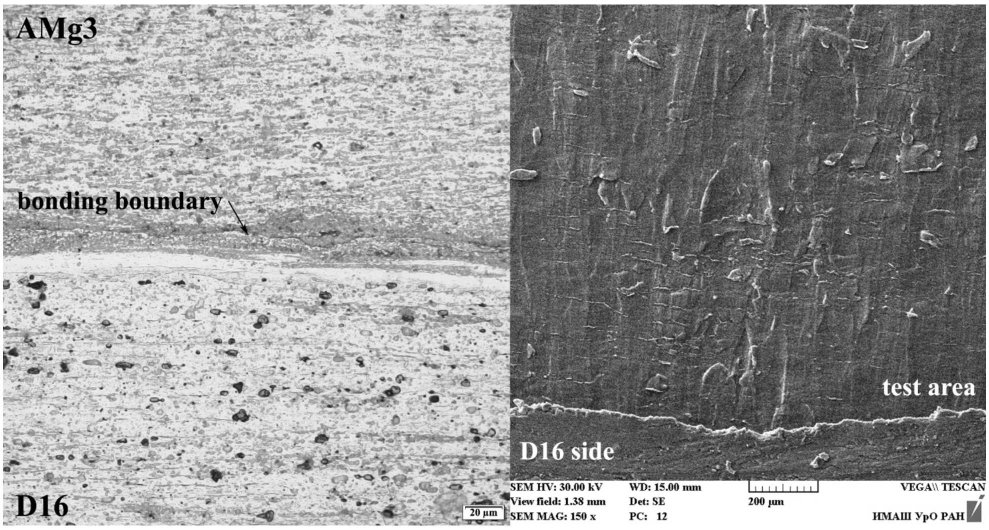
b

Fig. 5. Surface expansion and pressure at the interlayer boundary during rolling of composite with reduction ratio of 30 % (*a*) and 45 % (*b*)

subjected to a mechanical shear test to determine the bond strength, which was 43 MPa. The results of mechanical testing of the composite are presented in Table 1.

The shear zone on the side of *D16* alloy after testing is shown in fig. 6b, which shows characteristic "*stretch lips*", indicating the cracking of oxide films, the extrusion of pure metals into cracks, and the formation of primary bonding. Similar "*stretch lips*" are also found in works [6, 10] devoted to the study of the bond strength between sheets from aluminum and aluminum alloys. Fig. 6b demonstrates that the "*stretch lips*" are located perpendicular to the rolling direction. Therefore, the cause of its appearance should be considered tensile stresses acting along the rolling direction. There are also individual particles of *AMg3* alloy, which peeled off during the shear test and remained in the bond zone on the side of *D16* alloy. This indicates the bonding between materials in these areas.

Based on the results of computer and physical simulation, it can be seen that the primary bonding between the layer materials is achieved during rolling with a reduction of 45 %. To assess the effect of a



a *b*

Fig. 6. Cross-section of the “*AMg3/D16/AMg3”* composite in the bond zone (*a*); shear zone from *D16* side after shear test (*b*)

Table 1

Mechanical properties of “*AMg3/D16/AMg3*” composite after rolling with thickness reduction of 45 %

Yield stress, MPa	Ultimate strength, MPa	Elongation, %	Shear bond strength, MPa
279	292	7.2	43

further increase in the rolling reduction ratio on the bond strength, the dependences of the surface extend Y and the maximum pressure in the deformation zone p_{max} on reduction ratios were studied (fig. 7). It should be noted that at reduction ratio ε equal to 0.55 or more, the surface extend Y is less than reduction ratios ε, which means an increasing inhomogeneity of deformation over the thickness of composites.

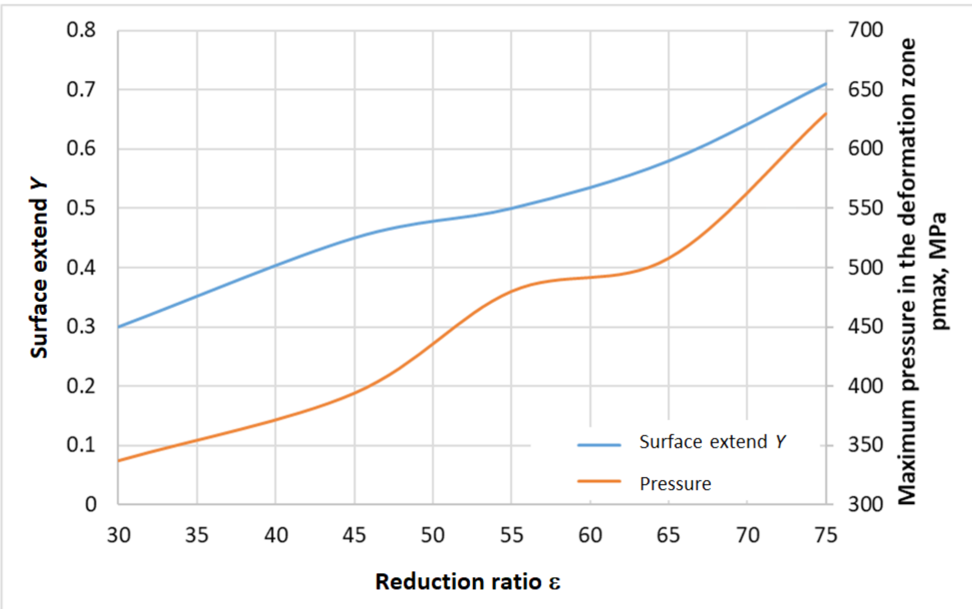


Fig. 7. Dependence of the surface extend Y and the maximum pressure in the deformation zone p_{max} on rolling reduction ratios

In general, fig. 7 shows a monotonous increase in both parameters (surface extend *Y* and maximum pressure *p*), which will increase the bond strength. This conclusion is consistent with the results of experimental studies of the rolling process of aluminum and aluminum alloys [4, 6, 7, 10], where an increase in reductions led to an increase in the bond strength between materials.

Based on the obtained computer simulation data, it follows that the maximum bond strength will be provided by the technological rolling route: reduction ratio in the 1st pass – 45 %; reduction ratio in the 2nd pass – 50 % (the total reduction ratio reaches 75 %). This conclusion is verified by shear tests of the composite obtained through the suggested route. The bond strength reached 67 MPa, which is 1.5 times higher than the primary bond strength obtained by the first pass of rolling.

Thus, the proposed approach reflects the qualitative dependence of the bond strength on the technological factors of rolling. The problem with the proposed approach for investigating the bond formation between dissimilar materials lies in the great difficulty in establishing the threshold surface extend Y', which should be determined for each newly developed composite. In this regard, the direction of future research should be related to the development of new models of the rolling processes of laminated composites and the development of more reliable criteria for the bond formation between dissimilar materials.

Conclusions

In this work, simulation of the rolling process of the laminated composite “*AMg3*/*D16*/*AMg3*” was performed, and stress-strain state parameters affecting the bond formation between layers were estimated.

It was found that the deformation is distributed nonuniformly over the thickness of the layers during rolling: the outer layers flow more intensively than the middle layer. However, the maximum effective strain scatter of 12 % in the cross section was observed after the highest rolling reduction of 75 %. This allows us to make an assumption about deformation uniformity in the first approximation for analytical calculations.

Additionally, a relationship has been established between the onset of bond formation and the contact surface extend and pressure. In the case of rolling at a reduction of 30 %, the contact surface extend reaches a threshold value close to the exit from the deformation zone, while the normal pressures drop sharply, which results in a lack of bonding. In the case of rolling with a reduction of 45 %, the contact surface extend reaches the threshold value at a relative length of the deformation zone of 0.42. In the remaining area of the deformation zone, a relative normal pressure increases from 1.6 to 1.97, which is sufficient to form primary bonding between *AMg3* and *D16* alloys.

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Conflicts of Interest

The authors declare no conflict of interest.