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Investigation of the influence of kinematic asymmetry on the properties of laminated materials

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Abstract. Trend of simultaneous improvement of such mechanical metal properties as strength, hardness and ductility remains popular. Asymmetric accumulative roll bonding is a method of severe plastic deformation that can create large shear deformations. These deformations in its turn are responsible for increase of mechanical properties. Initially computer modeling was carried out to study the influence of kinematic asymmetry parameters on the stress-strain state of laminated aluminum composites. For the study, such combinations of aluminum alloys as 5083/1070, 5083/2024, 6061/1070, 6061/2024 were considered. As a result of a numerical study, the conditions for obtaining high values of shear deformation, which affects the increase in mechanical properties in laminated aluminum composites, are determined. Experimental confirmation of the simulation results was carried out on a unique asymmetric rolling mill 400 installed in NMSTU. As the final stage of work, the development of rational technological schemes and regimes of cold and warm asymmetric accumulative roll bonding of laminated aluminum composites was carried out. The study showed a simultaneous increase in the strength and technological plasticity of received products, which differ in the ratio of total equivalent deformations and shear angles during at least 2 cycles of asymmetric accumulative roll bonding. It is shown that with an increase in value of the speed rolls ratio at the same inter-roll gap, the relative reduction increases, and the rolling force decreases by a factor of 2 (compared with these parameters at equal speeds of the work rolls). It is supposed to use such composites in space and automotive industries.

Introduction

For a lot of industrial application, including the automotive, aircraft and space industries, there is an acute problem of reducing the weight of the structures while maintaining or increasing the level of mechanical properties. For any metallic material, the fundamental mechanical characteristics include strength and ductility, which have a clearly expressed inversely proportional relationship. Very rarely, such materials simultaneously have high values of these properties. Materials processing technologies are being developed in such countries as Russia, China, Japan, South Korea, India, Germany etc. to solve this problem [1-6]. One of the ways to obtain new materials is asymmetric accumulative roll bonding. This method of rolling consists of several cycles with cutting and joining layers after each processing cycle [7-10]. Kinematic asymmetry is deliberately created; the work rolls speed ratio can be different. In Magnitogorsk (Russia) scientists of the "Zhilyaev Mechanics of Gradient Nanomaterials Laboratory" of Nosov Magnitogorsk State Technical University, investigate new fundamental effects of asymmetric deformation, which provide an increase in strength and plasticity [11-13]. It should be noted that the laboratory has unique scientific facility, an experimental reversible sheet rolling mill with an individual drive of work rolls. This equipment has no analogues in the world, according to such an important indicator as the work rolls speed ratio. This value can vary from 1 to 10 [14]. In the closest analogue, the South Korean mill, the maximum value of V_1/V_2 does not exceed 5.

Materials and Experimental Methods

To determine the technological parameters of the accumulative roll bonding process of laminated materials, samples of aluminum alloys were studied. The variation of laminated composites is presented in the form of the following combinations: 5083/1070, 5083/2024, 6061/1070, 6061/2024. On this issue, first of all, a computer simulation of asymmetric accumulative roll bonding process in the software package "Deform" and "QForm" was installed. Boundary and initial conditions for computer simulation of cold and warm accumulative roll bonding of laminated aluminum composites 5083/1070, 6061/1070, 5083/2024, 6061/2024 were established. The example of layer variations is presented on Fig. 1.

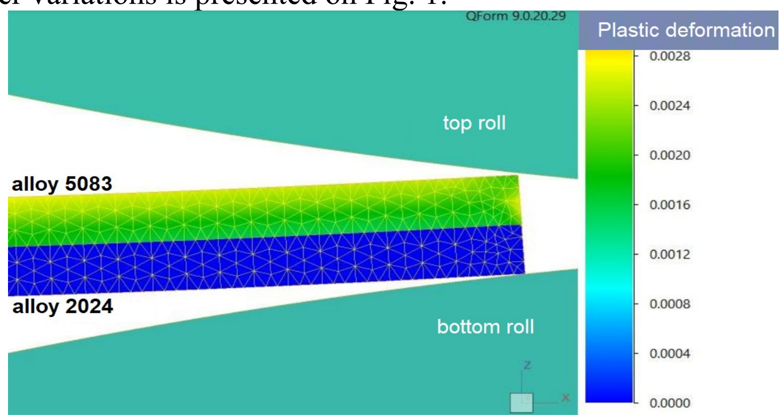

Fig.1. *The example of layers variation in laminated composite.*

It was found that it is rational to take the values of the friction coefficient not lower than 0.2 (for laminated aluminum composites 5083/1070, 6061/1070) and not higher than 0.3 (for laminated aluminum composites 5083/2024, 6061/2024).

The value of the work rolls speed ratio for the rectilinear movement of the metal must be increased with an increase in the thickness of the initial workpiece, reduction and strength of processed the material (in the range from 1 to 4). The distribution of layers in laminated aluminum composites along the length of the deformation zone depended on the value of the work rolls speed ratio (from 1 to 4), reductions (50–70%), as well as on the grades of aluminum alloys used (1070, 2024, 5083, 6061) and original total workpiece thicknesses (2 - 4 mm).

The most rational ratio of layer thicknesses in the initial workpiece is 2 to 1 (3 mm), at which the maximum values of the equivalent deformation and shear angle are achieved ($e > 2…4$, $\varphi > 65…70^\circ$). With an increase in the value of the work rolls speed ratio and equivalent deformation, the rolling force decreases (compared to the symmetrical case).

The next step was to verify technological regimes of asymmetric accumulative roll bonding of laminated aluminum composites 5083/1070, 6061/1070, 5083/2024, 6061/2024. The experimental plan included regimes with varying the type of laminated composite, the work rolls speed ratio (from 1 to 5), the position of the layers in the second rolling cycle, the type of heat treatment, and the value of the relative reduction (from 50 to 70%). Accumulative roll bonding regimes have been identified that made it possible to obtain high values of strength and technological plasticity, a high level of welding of composite layers, and a satisfactory surface quality. These regimes included cold and warm accumulative roll bonding, with two cycles of asymmetric deformation. Regimes including the value of the work rolls speed ratio 5 were excluded from the studies due to the melting of the metal in the deformation zone.

Cold asymmetric accumulative roll bonding was carried out:

1) without heat treatment;

2) using heat treatment (annealing at a temperature of 420˚ C for 90 - 120 minutes, followed by cooling in air).

Version 1 can be used when processing laminated aluminum composites 5083/1070 and 6061/1070, which consists of carrying out the initial stage of the first cycle with alloy 5083 or 6061 and the second stage of the first cycle with alloy 1070. The surface of the connection of the layers must be prepared (cleaning, degreasing). However, the second cycle of asymmetric accumulative roll bonding is not recommended to be carried out without heat treatment, because this can lead to delamination, as shown in Fig. 2.

According to version 2, annealing of alloys 1070, 2024, 5083 and 6061 was carried out at a temperature of 420˚C for 90–120 minutes, followed by cooling in air. In this case, the appearance of irreversible defects, similar to the one shown in Fig. 2 is possible.

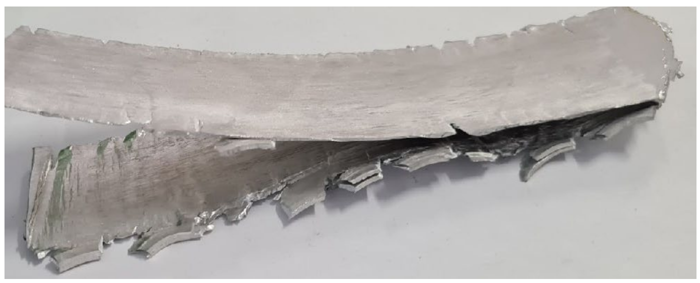

Fig.2. *Laminated aluminum composite 5083/2024 after cold accumulative roll bonding (cycle 2)*

Warm asymmetric accumulative roll bonding was carried out:

1) using preheating before rolling at a temperature of 420˚C for 15 - 30 minutes;

2) using preheating before rolling at a temperature of 380˚C for 5 to 30 minutes.

In both cases, the cooling of the metal occurred during the transport of the samples from the furnace to the rolling mill.

Version 1 was used in the processing of the laminated aluminum composites 5083/1070, 6061/1070 in the second cycle of asymmetric accumulative roll bonding, 5083/2024 and 6061/2024 in all processing cycles and was characterized by the formation of such defects as "transferring" and "wave" in all cases, as shown in Fig. 3.

Fig.3. *Laminated aluminum composite 5083/2024 after warm accumulative roll bonding (cycle 2)*

Version 2 can be used for processing the laminated aluminum composites 5083/1070 and 6061/1070 in 1 and 2 cycles (depending on the arrangement of the layers); 5083/2024 and 6061/2024 in all processing cycles. The main results are presented in Fig. 4 (a – c).

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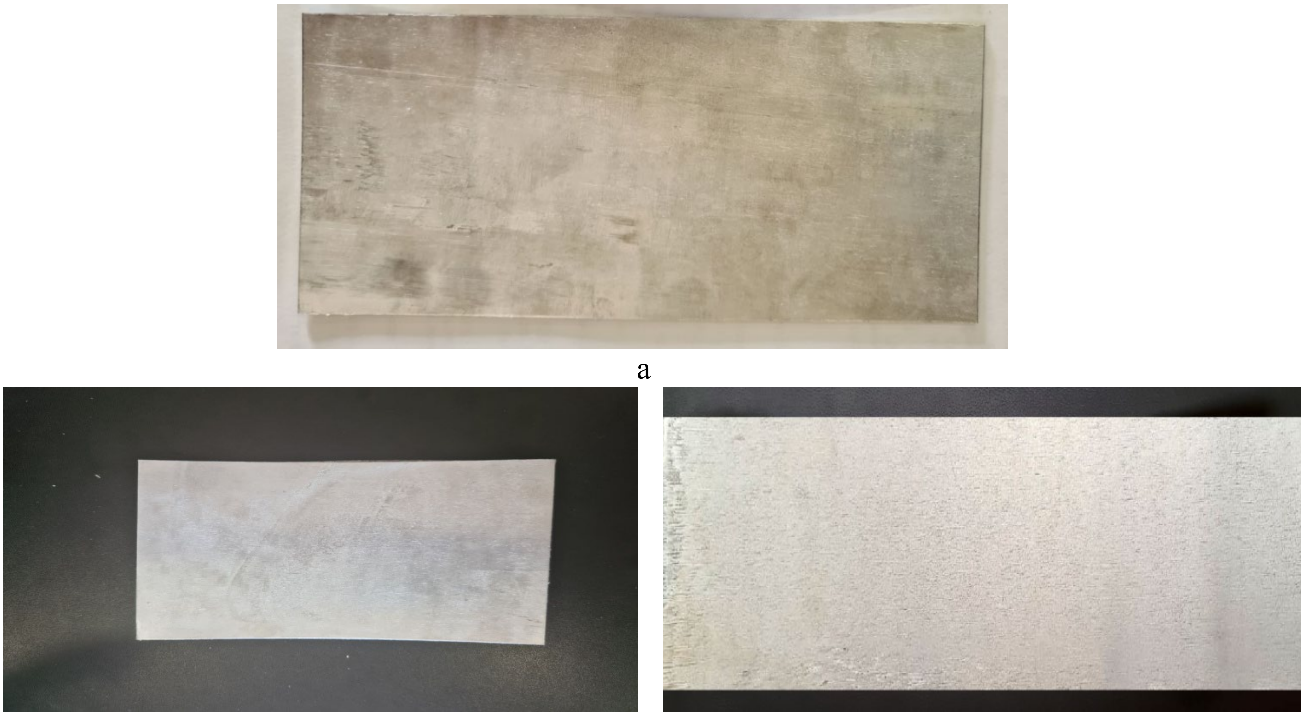

a

b c

Fig.4. *Laminated aluminum composite 5083/2024 (a), 6061/1070 (b), 6061/2024 (c) after warm accumulative roll bonding (cycle 2)*

The required flatness and surface quality can be obtained at the work rolls speed ratio of 10 rpm for the bottom roll and 2–6 rpm for the top roll. The reduction value ranged from 50% to 67%.

The results and discussion

In a number of cases, the displacement of the layers to each other in the deformation zone was observed. This led either to the absence of a connection between the alloys, or to partial welding and inversion of the front part of the workpiece according to such type of defect as "crescent". The reasons for the formation of these defects can be insufficient degrees of deformation, insufficient temperature in the deformation zone, incorrectly selected friction conditions and values of the work rolls speed ratio. One of the solutions of this problem can be the preliminary compounding of the laminated material surface in the first rolling cycle with the formation of a relief on the surface of the workpiece using relief rolls and subsequent smoothing of the workpiece in the next processing cycle.

An assessment was made of the influence of the work rolls speed ratio on the technological plasticity and rolling forces. The results for laminated aluminum composite 5083/2024 with an initial layer thickness of 1 mm (5083) and 2 mm (2024) and an established roll gap of 1.2 mm are presented in Table 1; for laminated aluminum composite 5083/1070 with an initial layer thickness of 1 mm (1070) and 2 mm (5083) and an established roll gap of 1.2 mm are presented in Table 2.

Table 1 - Influence of the values of the work rolls speed ratio on the technological plasticity and rolling forces of the laminated aluminum composite 5083/2024

The work rolls speed ratio, $\frac{\text{rpm}}{\text{rpm}}$	Final thickness of laminated aluminum composite 5083/2024, mm	Relative reduction, %	Rolling force, kN
10/10 (1)	1.90	37	1330
10/6 (1.7)	1.60	47	1080
10/5 (2)	1.53	49	990
10/4.5 (2.2)	1.47	51	940
10/4 (2.5)	1.35	55	900
10/3.5 (2.8)	1.25	58	790
10/3 (3.3)	1.20	60	700
10/2.5 (4)	1.00	67	600
10/2 (5)	melted		

Table 2 - Influence of the values of the work rolls speed ratio on the technological plasticity and rolling forces of the laminated aluminum composite 5083/1070

The work rolls speed ratio, $\frac{\text{rpm}}{\text{rpm}}$	Final thickness of laminated aluminum composite 5083/1070, mm	Relative reduction, %	Rolling force, kN
10/10 (1)	not welded		
10/8 (1.25)			
10/7 (1.4)	1.8	40	860
10/6 (1.7)	1.7	43	710
10/5 (2)	1.45	52	630
10/4 (2.5)	1.3	57	520
10/3 (3.3)	1.2	60	300
10/2 (5)	melted		

It is shown that with an increase in the work rolls speed ratio from 1 to 4 for laminated aluminum composite 5083/2024, the rolling force decreases with a simultaneous increase in the relative reduction. For laminated aluminum composite 5083/1070, the rolling force is also reduced and the reduction ratio increases with an increase in the rolls speed ratio from 1.4 to 3.3. Moreover some of samples or didn't weld either melted.

All samples after two processing cycles were tested on hardness, tensile strength, yield strength and relative elongation. The obtained characteristics were compared with the properties of materials currently used in the automotive and space industries. The values of plastic characteristics were approximately on the same level with the existing materials, and the strength values exceeded it by 15 - 20%, the hardness was 2 times higher.

From the obtained data it’s obvious that in the first cycle of asymmetric accumulative roll bonding, a significant gradient is observed in laminated aluminum composites, which is characterized by hardness values in different layers (for example, HB = 109 units on the 5083 side and HB = 89 units on the 2024 side at the rolls speed ratio of 4 etc.). In the second cycle of deformation, in most cases, not only the hardness values decrease, but also the values of the first and second sides equalize relative to each other (for example, HB = 76 units on the 5083 side and

HB = 75 units on the 2024 side at a speed ratio of 4 and etc.). This is explained by the fact that during the deformation of the metal in the second cycle of asymmetric accumulative roll bonding, the characteristics of the laminated composite are averaged due to the sequential arrangement of the layers.

Both in the first and in the second cycle of asymmetric accumulative roll bonding, the values of yield strength and tensile strength decrease with an increase in the rolls speed ratio. The value of the relative elongation in the first cycle has low values (from 3% to 7%), in the second cycle with the rolls speed ratio of 2.5 - 4 it increases on average almost 2 times (up to 12% maximum), and with the rolls speed ratio 1 - 2.22 almost does not change. This is explained by the fact that with an increase in the rolls speed ratio, the temperature of the deformation heating of the sample in the deformation zone increases. Due to this, the technological plasticity of the metal also increases, which is expressed in a greater elongation (increase in drawing) of the finished laminated aluminum composite (in each subsequent experiment by 10–20% with an increase in the rolls speed ratio in the range of 1–4).

After mechanical testing of laminated aluminum composites, alloy 6061 was excluded from possible alloy for composite combination, because the values of strength and plastic characteristics did not meet the requirements of regulatory documentation. The value of the relative elongation in the second cycle has low values (from 1% to 3%), the yield strength varies from 184 to 192 MPa, and the tensile strength changes from 212 to 240 MPa. To obtain simultaneously high plastic and strength characteristics in these composites, it is necessary to use other regimes of asymmetric accumulative roll bonding.

Conclusion

Asymmetric accumulative roll bonding of laminated aluminum composites 5083/1070, 5083/2024, 6061/1070 and 6061/2024 was carried out on the asymmetric rolling mill 400 of the "Zhilyaev Mechanics of Gradient Nanomaterials Laboratory" of Nosov Magnitogorsk State Technical University. The regimes of the laminated aluminum composites processing are revealed, including such parameters as: type of material, total thickness of the sample and thickness of each layer, type of heat treatment, value of the rolls speed ratio, reductions, friction conditions, number of required cycles. For laminated aluminum composites 5083/1070, 6061/1070 and 5083/2024, 6061/2024, preheating is required before the asymmetric deformation process (rolling process must be warm). But laminated aluminum composites 6061/1070 and 6061/2024 should be excluded from the experiments due to the low mechanical properties.

The necessity of control of deformation heating in the deformation zone during rolling was revealed in order to avoid melting of the material or its sticking to the rolls (the rolls speed ratio should not exceed 4). It is important to observe the temperature limits for heating samples before rolling (in the case of warm rolling).

An increase in strength and ductility in the processing of laminated aluminum composites 5083/1070 and 5083/204 by the asymmetric accumulative roll bonding method was shown.

Acknowledgment

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