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Experience in obtaining laminated aluminum composites by asymmetric accumulative roll bonding

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The issue of asymmetric processing of long products in the range of speed ratios of work rolls from 2 to 5 has not been widely studied and is of interest from the point of view of increasing both the strength and ductility of metal products. An area of severe plastic deformation was found, showing the relationship between shear strain and shear angle, at which large compressive strains and ultra-high shear strains occur. An analysis was made of the values of equivalent deformations of laminated aluminum composites obtained both after the first and second processing cycles, modeled in the DEFORM and QForm software systems. The paper defines a rational range of the speed ratios of work rolls, which makes it possible to obtain not only the rectilinear movement of the metal at the exit from the deformation zone, but also the maximum elongation, the ratio of tensile strength to the yield strength for laminated aluminum composites. A regularity has been deduced showing that with an increase in the speed ratio of work rolls, the rolling forces decrease, the value of the relative reduction at a constant roll gap increases. At the maximum speed ratio of the rolls (5), melting of the samples occurs.

Keywords: laminated materials, severe plastic deformation, accumulative roll bonding, asymmetry, mechanical properties.

1. Introduction

The paper considers the main features of the processing of laminated aluminum composites. Aluminum products are widely used in a range of industries. It is a unique material that has high ductility and corrosion resistance at room temperature. At significant sub-zero temperatures, plasticity increases, as well as strength. These characteristics make it possible to use aluminum products widely in critical structures.

Products from laminated aluminum composites considered in the article can be distributed in such industries as space and automotive industry. As concerning space industry, it can be used as fuel tanks of carrier rockets and spacecraft for oxidizer and combustible liquefied fuel with a metal thickness of 0.4 – 2.5 mm. This industry has been gaining popularity in recent years both in the USA (Falcon 9, Falcon Heavy, Alpha, Dragon, Starship) and in Russia (Proton-M, Progress MS-12, Soyuz MS-14, Angara). There is a topical problem of technogenic contamination due to explosions of space objects (in this case, it is necessary to increase the strength of metallic materials, trying to reduce their weight in order to save fuel). In addition, the possibility of replacing kerosene fuel with hydrogen is being considered. This replacement faces a number of problems: the complexity of storage, transportation and operation. The explosiveness and low resistance of storage units at the moment do not allow such a replacement, since hydrogen embrittles a number of metals from which fuel tanks are made. The possibility of using hydrogen fuel must be confirmed in accordance with GOST R (Russian Government Standard) 55891-2013. Nowadays one of the metal materials for the body of the fuel tank are aluminum alloys of the 5th series of the Al-Mg system according to GOST 21631-76, GOST 4784-97, EN 515, EN 573-3, EN 485-1,2,4. In reference to automotive industry, laminated materials can be used as overall parts of the car body — hood, fenders, roof, doors, bottom with a metal thickness of 0.6 – 1.3 mm. As in previous case, it is worth touching on the problem of ecology: the formation of greenhouse gases during the operation of a car leads to a slowdown in environmental development. In the countries of the European Union, standards have been set for the amount of possible carbon monoxide emissions, the requirements for which are constantly growing. In 2021, automakers must achieve a 40% reduction in emissions. It is known that with an increase in the weight of the car structure, there is an increase in the level of fuel consumption: for example, a car weighing 1.5 tons (standard sedan) consumes an average of 10 liters of gasoline per 100 km, while the consumption of a car weighing 3 tons (SUV) is more than 20 liters of fuel per 100 km. Reducing the weight of the car while maintaining the strength characteristics will not only improve the environmental situation, but also make the car safer in operation, as well as increase resistance to accidental deformation. Materials are often made from aluminum alloys of the 6th series of the Al-Mg-Si-Cu system according to GOST 21631-76, GOST 4784-97, EN 515, EN 573-3, EN 485-1,2,4 for cars of such brands as Audi, BMW, Porsche, Tesla, Jaguar, Ferrari, etc.

This causes a constant increase in the requirements for the quality of aluminum metal products. The main emphasis should be placed on the development and improvement of production technologies for these products to improve the mechanical characteristics: obtaining high strength, hardness and satisfactory ductility values. Methods of severe plastic deformation [1–12] are promising for obtaining an ultrafine-grained structure in aluminum alloys, which makes it possible to achieve the required parameters in terms of mechanical properties.

However, along with the great advantages of these methods, they have one significant drawback, which is the complexity, and often the impossibility of their use for the production of long products. This significantly limits the use of these methods in industry. Based on this, the task is to develop technologies for processing materials using special methods that allow obtaining long products with high values of a complex of mechanical properties. Such methods include asymmetric accumulative roll bonding [13–16]. Also, to improve the quality of metal products, it is necessary to develop methods for processing materials that will not only be profitable from an economic point of view, but will also significantly improve the mechanical properties of metals and alloys. Asymmetric rolling in this case is considered as an economically profitable process that has been developing rapidly in recent years. Asymmetric rolling is a rolling process in which asymmetry is created to obtain certain properties. This is a rolling process in which the process conditions are changed towards asymmetry: geometric, physical, kinematic factors change based on the requirements of the technology. Asymmetric accumulative roll bonding is a special type combining two processes, thanks to which it is possible to obtain long metal products with high mechanical properties.

2. Materials and experimental methods

If we divide the process of asymmetric accumulative roll bonding into its component parts, it becomes clear that each of them has its own advantages. It has been proved that during asymmetric rolling, high compression and shear deformations simultaneously occur in the metal due to oppositely directed contact friction forces acting on the sheet simultaneously from the upper and lower rolls rotating at different circumferential speeds. Shear deformations are characterized by the tangent of the macroscopic slope angle of the metal layers in the vertical plane. Thus, the implementation of high shear deformations is a determining factor in the development of an asymmetric rolling process to obtain an ultrafine-grained structure. Accumulative roll bonding is of great interest as one of the methods of severe plastic deformation. With the help of it, with the required number of cycles, it is possible to obtain an ultrafine-grained structure due to the accumulation of stresses after each processing cycle. A big plus of the process is that it is possible to use dissimilar materials as initial workpiece and obtain properties inherent in both the first and second alloys. All the shortcomings of the accumulative roll bonding can be solved by proper selection of the processing mode. In the manufacture of metal by the accumulative roll bonding, it is important to observe the technology of metal welding, highly hardened layers may the adhesion strength of two dissimilar metals low. This can lead to the formation of a large number of cracks during the rolling process. To form a stronger connection, it is possible to use the process of warm rolling, or to pre-treat the initial workpiece, if the metals are welded by pressure according to the technology.

A significant shear deformation is one of the main factors influencing obtaining high values of the complex of mechanical properties. It can be obtained by simultaneously implementing large compression and shear deformations. Main characteristics are the values of the equivalent strain “e” and the shear angle “φ”. This angle seems like deviation of the vertical section at the entrance to the deformation zone from the section at the exit from the zone.

Analysis of works shows that in order to obtain the required mechanical properties of aluminum sheets, it is necessary to achieve an equivalent deformation “e” of at least 3 and a shear angle “φ” of at least 70 degrees. To obtain high values of strength and technological ductility in laminated aluminum composites, such values of equivalent deformation ($e>3$) and shear angle ($\varphi>70°$) should be as in each individual layer as in the transition layer. In addition, the parameters must meet the criteria of reducing the bending of the strip during processing.

Computer simulation of the process was carried out using the “DEFORM” and “QForm” software packages. When modeling the process of asymmetric accumulative roll bonding in the presented software systems, the influence of the rolls speed ratio V_1/V_2 =1…4 times (in the symmetrical case, the top roll speed was 10 rpm), the friction coefficient $f=0.1…0.4$ and the degree of deformation $\varepsilon=50…70\%$ on the value of the equivalent deformation and the incline angle of the Lagrange grid. This will allow to determine the necessary and sufficient conditions (getting into the boundaries of the areas of the ratio of the total equivalent deformation and the shear angle in combination with the rectilinear movement of the laminated aluminum composite) for obtaining high values of strength and technological plasticity during asymmetric deformation of laminated aluminum composites.

3. Results and discussion

In the course of the study, the technological parameters of the process of asymmetric accumulative roll bonding were found, in which the metal came out of the deformation zone in a straight line. The required minimum values of the speed rolls ratio at a friction coefficient of 0.3, depends on the thickness of the initial workpiece (with a reduction of 50–70%). Obviously at any ratio of the roll speeds, the value of the equivalent strain obtained after the first cycle is not enough (the minimum obtained value is 0.5), therefore, a second cycle is required to achieve equivalent strain values in the range of 2…4.

Also it is shown that with an increase in the total thickness of the workpiece, as well as in the reduction and strength of the material, it is necessary to increase the rolls speed ratio of the rectilinear exit of the laminated composite from the deformation zone, as shown in Table 1.

The state of the boundaries of two joined metals in laminated aluminum composites was also analyzed. It seems possible to evaluate the change in the behavior of the curvilinearity of the layers of the composite with respect to the influence of one on the other. Since the speed of the

Table 1. Values of the required rolls speed ratios depending on the workpiece thickness with a friction coefficient of 0.3.

Material	Initial workpiece thickness	Rolls speed ratio with reduction of 50%	Rolls speed ratio with reduction of 60%	Rolls speed ratio with reduction of 70%
5083/1070 6061/1070	1 mm (5083; 6061) + 1 mm (1070)	1.25	1.7	2
	2 mm (5083; 6061) + 1 mm (1070)	1.7	2	2.5
5083/2024 6061/2024	1 mm (5083; 6061) + 1 mm (2024)	1.7	2	2.5
	2 mm (2024) + 1 mm (5083; 6061)	2	2.5	3.3

upper roll in the asymmetric case will be higher than the speed of the lower roll, the arrangement of the composite layers will correspond to this fact — the upper metal layer is alloy 5083 and the lower layer is represented by alloy 2024 or 1070. The position of the metal layers relative to each other is represented by a zero mark in the form of a straight line. With an increase in the thickness of the original workpiece, the deviation increases imperceptibly.

Next step of the present research consisted, on the one hand, of verification of the adequacy of the computer model of asymmetric accumulative roll bonding of laminated aluminum composites 5083/1070, 5083/2024, 6061/1070, 6061/2024, and, on the other hand, of an experimental study of the influence of various process parameters on the stress-strain state, geometric characteristics, power parameters of asymmetric accumulative roll bonding, mechanical properties and material structure. To confirm the adequacy of computer models, laboratory studies of the process of asymmetric accumulative roll bonding for laminated aluminum composites 5083/1070, 5083/2024, 6061/1070, 6061/2024 were carried out on an asymmetric rolling mill 400 in NMSTU (Magnitogorsk, Russia). Rolling of laminated aluminum composites 5083/1070, 5083/2024, 6061/1070 and 6061/2024 held on in accordance with the accumulative roll bonding technology. Process deformation carried out in symmetrical and asymmetrical modes. For each of the samples, from 1 to 8 processing cycles were done. The value of the rolls speed ratio varied from 1.25 to 5. The total thickness of the initial samples ranged from 2 to 4 mm, each layer separately had a thickness of 1 and 2 mm. Some alloys were subjected to preliminary heat treatment or immediate heating before rolling, carried out after each cycle. The immediate heating time before rolling was differed and depended on the type, size and technological parameters (rolls speed ratio, friction coefficient), but was within 350 – 420°C, holding time was from 5 to 30 minutes.

Before cold rolling, the surface of the aluminum alloy joint was processed: the samples were cleaned to remove oxide films in some cases with an abrasive (grinding paper with a grain size of P40, P180 and P240), in others — with grinding brushes. Degreasing was carried out to remove contaminants with solvent. Transportation of the material to the stand was carried out immediately after grinding to reduce the time of interaction of aluminum alloys with atmospheric oxygen and the rapid formation of a large layer of oxide film. The layers were welded in the deformation zone during deformation. Rolling was carried out without the use of coolant and other methods that cause a change in the friction coefficient. To increase the friction coefficient, at least 5 aluminum sheets were rolled before experimental studies.

For preliminary testing of technological solutions, samples were obtained from laminated aluminum composite 5083/5083 and 6061/6061 by symmetrical and asymmetric deformation. As a result, workpieces in symmetrical cases were destroyed during processing, the metal layers did not weld together, and a rupture formed in the middle of the workpieces. When processing samples in asymmetric cases compared to symmetrical cases, the rolling force decreased on average by 50% (from 912 to 490 kN for 5083/5083 and from 980 to 540 kN for 6061/6061). The reduction varied from 50% to 57% per pass, and the total reduction ratio was 77.5% for the 5th series (for 2 cycles) and 95% for the 6th series (for 4 cycles). The roll speed ratio varied from 1.8 to 2 depending on the pass.

Experiments have proven that asymmetric rolling is characterized by a decrease in the formation of defects (all samples showed good pressure weldability). Technological plasticity has increased significantly — it became possible to process samples with a reduction of 77.5% (as for 5083/5083) and 95% (as for 6061/6061). Moreover, in the asymmetric case, such reduction values are not limiting.

Cold asymmetric accumulative roll bonding was carried out according to two modes. First mode carried out without the use of heat treatment. Second mode held on with the use of heat treatment (annealing at a temperature of 420°C for 90 – 120 minutes, followed by cooling in air). Mode 1 can be used when processing laminated aluminum composites 5083/1070 and 6061/1070, which consists in carrying out the first 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 2nd cycle of asymmetric accumulative roll bonding is not recommended to be carried out without heat treatment, because this can lead to delamination. According to mode 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 is possible.

Warm asymmetric accumulative roll bonding also carried out in accordance with two main regimes. First regime had a distinction consisted in preheating before rolling at a temperature of 420°C for 15 – 30 minutes. Second regime defined 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 stand. Mode 1 was used in the processing of laminated aluminum composites 5083/1070, 6061/1070 in the 2nd cycle of asymmetric accumulative roll bonding, 5083/2024 and 6061/2024 in all processing cycles and was characterized by the formation of "transferring" and "wave" defects in all cases. Mode 2 can be used for processing 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 required flatness and surface quality can be obtained at roll speeds of 10 rpm for the lower roll and 3 – 6 rpm for the upper roll. The reduction value ranged from 50% to 67%.

In a number of cases, the displacement of the layers relative to each other in the deformation zone was observed, which 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 the "crescent" type of defect. 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 rolls speed ratio. One of the solutions of this problem can be the preliminary machining of the surface of the laminated material 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 rolls speed ratio on the technological plasticity and rolling forces. It is shown that with an increase of the work rolls speed ratio from 1 to 4 for laminated aluminum composite 5083/2024, the rolling force decreases from 1330 to 600 kN with a simultaneous increase in the relative reduction from 37% to 67%. For laminated aluminum composite 5083/1070, the rolling force is reduced from 600 to 300 kN, the reduction ratio increases from 40% to 60% with an increase in the rolls speed ratio from 1.4 to 3.3. With a rolls speed ratio of 1 and 1.25, samples of 5083 and 1070 alloys were not welded. The rolls speed ratio of 5 is characterized by the melting of laminated aluminum composites in the deformation zone in both cases.

All samples that underwent two cycles of processing by the accumulative roll bonding method were tested to determine the values of tensile strength, yield strength and relative elongation. Then, the obtained characteristics were compared with the properties of materials currently used in the automotive and space industries. The results for samples with an initial total thickness of 3 mm are shown in Table 2.

In this case, the necessary boundaries of the ratios of the total equivalent deformations areas and shear angles for layered sheet composites made of aluminum alloys (5083/1070, 5083/2024) are determined. The value of the equivalent strain "e" must be at least 3, and the shear angle "φ" at least 70° for these laminated aluminum composites.

Table 2. The results of mechanical tests of laminated aluminum composites 5083/2024, 5083/1070, 6061/2024, 6061/1070.

Composite	σ_t, MPa	σ_v, MPa	δ, %	HB, units
5083/1070	210	304	10	132/65
5083/2024	215	333	12	130/106
6061/1070	192	212	2	115/45
6061/2024	184	240	2	113/97

After mechanical testing of laminated aluminum composites, alloy 6061 was excluded from possible use cases as a second layer, because with the studied parameters, the values of strength and plastic characteristics do not meet the requirements of regulatory documentation (EN 485-2:1993 and GOST 21631-76). The boundaries of the areas of guaranteed simultaneous increase in strength and technological plasticity of rolled products, which differ in the ratio of the total equivalent strains ($e > 3$) and shear angles ($\varphi > 70°$) in this case are not rational, and it is necessary to establish other boundaries at which the values of the total equivalent strains "e" will be exceed 4.8, and the shear angle "φ" will be more than 80°. The use of these alloys for the manufacture of fuel tanks for launch vehicles (6061/1070) and overall parts of the car body (6061/2024) requires more costs. Obviously, to obtain the required properties, it is necessary to carry out the third cycle of asymmetric accumulative roll bonding.

Also an analysis of the influence of the rolls speed ratio on the change in the mechanical properties of the sheet laminated aluminum composite 5083/2024 was made. It can be seen from the obtained data that in the first cycle of asymmetric accumulative roll bonding, a significant gradient is observed in layered 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 a 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 σ_t and tensile strength σ_v decreased with an increase in the rolls speed ratio. The value of the relative elongation δ in the first cycle has low values (from 3% to 7%), in the second cycle with a rolls speed ratio of 2.5 – 4 it increases on average almost 2 times (up to 12% maximum), and with a rolls speed ratio of 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 workpiece 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 layered aluminum composite (in each subsequent experiment by 10 – 20% with an increase in the rolls speed ratio in the range of 1 – 4).

Figure 1 shows the dependence of the yield strength σ_t, tensile strength σ_v and relative elongation δ on the rolls speed ratio of (V_1/V_2=1…4).

The development of the accumulative roll bonding process was carried out by such scientists as: Beausir B. [17], Kamikawa N. [18], Sato Y.S. [19], Liu X. [20], Yu H. [11],

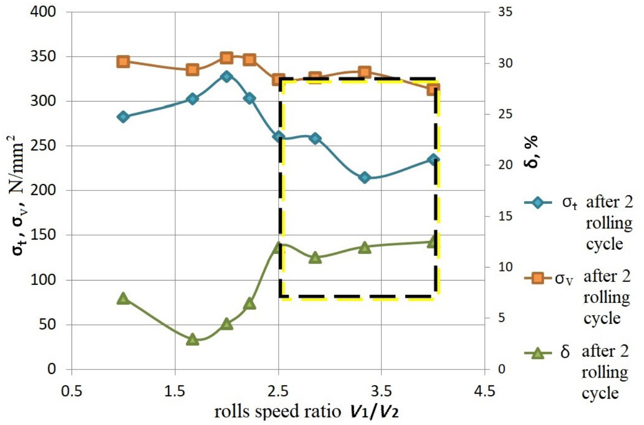

Fig. 1. (Color online) The dependence of the values of σ_t, σ_v and δ in the second cycle of asymmetric accumulative roll bonding on the rolls speed ratio.

Kim Y.S. [21] and others. It was found that the process of accumulative roll bonding can be used, for example, both to increase the strength of aluminum and to produce new multilayer materials by combining aluminum with other strong materials to obtain composites with improved properties and structure. At the same time, the initial thickness of the sheet is maintained and there are no geometric changes in shape, which is another advantage of the process. It was previously mentioned that it is important to observe the technology of metal welding, because of the circumstances of the adhesion in composite. The fact is that during welding and diffusion interactions, transition layer acquires a special structure, which will have unique properties. Such a layer will have both the characteristics of the first and the second metal from which this layer was formed. It should be noted that in order to determine the properties of the transition layer, it is necessary to take into account the alloys of the base metal, that is, the chemical composition, method and conditions for preliminary preparation of the metal before welding, as well as the interaction of rolls and rolled metal. The occurrence of "crocodile" defects, sickle shape in the processing of aluminum alloys with different strengths was found in researches of Farahat A. [22], Bogucka, J. [23]. Also, in the description of this defect, it is indicated that a common cause of occurrence is incorrectly selected reductions and temperature conditions of rolling. Due to the imposition of asymmetry on the accumulative roll bonding process, it was possible to avoid the formation of such defects. However, in the main publications, only processes with a roll speed ratio (V_1/V_2) of no more than 2 are considered. The effect of asymmetry in the range of roll speed ratio (V_1/V_2) from 2 to 5 is practically not studied. Therefore, the presented work is undoubtedly relevant.

Currently, single-layer aluminum alloys of 5xxx and 6xxx series are used as a structural material for the automotive industry (for example, 5182, 6016, etc., manufactured in accordance with GOST 21631-76, GOST 4784-97, EN 515, EN 573-3, EN 485-1,2,4, etc.), which are gradually replacing steel materials. However, aluminum alloys used in the automotive industry do not have high strength characteristics. The main goal of replacing existing aluminum products with 5083/2024 laminated aluminum composite is primarily to increase the level of strength characteristics. Based on this, operational safety will increase, in addition, with a high level of strength characteristics, the probability of minor damage after insignificant accidents will decrease. The combination of 5xxx and 2xxx series will allow to obtain a satisfactory surface quality due to alloy 5083, alloy 2024 can be used in structures that require a high value of the coefficient of ductile fracture, moreover, together they better withstand operating loads. The thickness of the manufactured products will be 0.7–1.5 mm.

Laminated aluminum composites 5083/1070 are intended for use in the space industry, namely for the production of fuel tanks for launch vehicles and spacecraft for oxidizer and combustible liquefied hydrogen fuel. Now, aluminum alloys doped with either magnesium or lithium are used as the main materials for the production of carrier rocket fuel tank bodies (for example, most often AMg5, AMg6 or 1201, 1421, 1469, 8090 in some designs, etc.). These products are manufactured in accordance with GOST 21631-76, GOST 4784-97, EN 515, EN 573-3, EN 485-1,2,4. The thickness of the fuel tanks, depending on the type of carrier rocket or spacecraft, can vary from 0.4 to 2.5 mm, the width of the supplied products depends on the formed tank diameter and does not exceed 2000 mm. It is known that Russia is developing engines for launch vehicles and spacecraft powered by hydrogen fuel. However, the existing materials from which the tank body is made are quite strongly exposed to hydrogen corrosion. This is reflected in the stability of storage units, the explosiveness of objects due to their embrittlement by hydrogen. The combination of 5xxx and 1xxx series will allow, on the one hand, to obtain a sufficient level of strength (corresponding to the established regulatory documentation), on the other hand, it will allow the use of hydrogen fuel as a fuel, since aluminum alloys of the 1xxx series (in this case, alloy 1070) practically do not corrode during interaction with hydrogen.

However, aluminum alloys used in the automotive industry do not have high strength characteristics. The main goal of replacing existing aluminum products with 5083/2024 laminated aluminum composite is primarily to increase the level of strength characteristics. Based on this, operational safety will increase, in addition, with a high level of strength characteristics, the damage after minor accidents may decrease. The combination of 5xxx and 2xxx series will allow to obtain a satisfactory surface quality due to alloy 5083, alloy 2024 can be used in structures that require a high value of the coefficient of ductile fracture, moreover, together they better withstand operating loads.

The obtained results indicate that the proposed technological schemes of asymmetric accumulative roll bonding of laminated aluminum composites 5083/2024 and 5083/1070 make it possible to achieve simultaneously high strength and technological plasticity of laminated aluminum composites due to the creation of large shear deformations [24–28]. The thickness of the manufactured products will be 0.7–1.5 mm.

4. Conclusions

According to the results of numerical and experimental studies, the expediency of obtaining laminated aluminum composites 5083/1070 and 5083/2024 is shown. At the same time, the use of laminated aluminum composites 6061/1070, 6061/2024 is impractical. Technological schemes were developed both for the production of rolled and sheet laminated aluminum composites. For rolled products, it is proposed to use laminated aluminum composites 5083/1070, and for sheet products, both 5083/2024 and 5083/1070, which will depend on the purpose and requirements of the consumer.

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