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M. Nosko,
orcid.org/0000-0002-8792-4016,
D. Konovodov*,
orcid.org/0000-0001-8282-4991,
A. Samsonenko,
orcid.org/0000-0001-6992-2327,
O. Bobukh,
orcid.org/0000-0001-7254-3854

Ukrainian State University of Science and Technology, Dnipro, Ukraine
* Corresponding author e-mail: konovodov@metal-forming.org

DETERMINATION OF THE DEFORMATION PARAMETERS OF THE STEEL REINFORCING PHASE INSIDE THE ALUMINUM MATRIX DURING HOT ROLLING

Purpose. Comparison of deformation parameters during rolling of reinforced composites based on aluminum alloy using braided and expanded steel meshes as a reinforcing phase.

Methodology. An experimental study on the effect of pressure on the deformation of the reinforcing phase during rolling of aluminum composites is carried out. A wire mesh and expanded mesh made of stainless steel was used as a reinforcing phase. The effect of deformation on the change in the lattice angle of the reinforcing phase is investigated.

Findings. In this work, experimental data on the parameters of deformation of the wire mesh and expanded mesh are obtained. A comparison is made of the shape change in such grids under hot rolling conditions between two aluminum plates, which play the role of a matrix. It is found that the elongation coefficients of the lattice for the experiment with a wire mesh μ_c is equal to 1.68–2.3, which is greater than the coefficient of elongation of the lattice in the expanded mesh of 1.55–2.2. Therefore, expanded sheets make the best reinforcing layer for aluminum-based composites produced by the roll-bonding process. Expanded mesh also reduces the risk of rupture at the intersection of wires.

Originality. In the work, for the first time, a comparison of the deformation parameters during roll bonding of composites based on an aluminum alloy, reinforced with a braided and expanded steel mesh, has been given. Obtaining composite materials by means of hot roll bonding requires an understanding of the flow of composite components during deformation and their influence on each other. These peculiarities have not been studied sufficiently. Currently, there is no reliable method for predicting the behavior of the material of a solid reinforcing phase of various shapes inside a composite.

Practical value. Advantages of using an expanded steel mesh for reinforcing aluminum-based composites have been confirmed. Scientific results can be used to refine calculating methods for metal flow at high hydrostatic pressure with variable components of the stress tensor and the major stresses.

Keywords: *roll bonding, aluminum matrix, steel mesh inlay, flat rolling, composite, deformation parameters*

Introduction. The article is aimed at research and development of effective technology of hot rolling of sheet aluminum composite reinforced with steel mesh. The development of technologies to produce composite materials by means of hot rolling requires detailed research, given that at present there is no reliable method for predicting the deformation of the solid inserts from the mesh within the package. In addition, an important condition determining the quality of the resulting material is that the pressure welding of the two layers of the aluminum matrix between each other must be ensured during rolling. The object of the research is the behavior of different types of grids in aluminum composite, considering the degree of deformation during roll-bonding of the product. A certain combination of these parameters during rolling provides an increase in the properties of the product, in particular a decrease in specific gravity, an increase in impact energy that can be absorbed, as well as fire resistance. The composites obtained in this way can be used as protective barriers, finishing elements, as well as a blank for further production of structural elements.

Literature review. The properties and characteristics of aluminum materials, including those obtained in metal forming processes, were first described in [1]. The characteristics of metal flow under the action of temperature and strain in this work are described using the dependencies given in [2].

The paper [3], which describes the roll-bonding process, defines the key process parameters and provides a detailed discussion of the scientific and technical aspects that influence the relationship between the microstructure and the mechanical behavior of the processed materials. In addition, the application, and advantages of the process in heterogeneous material joining technologies by hot rolling to produce titanium, stainless steel and carbon steel sheets are discussed. The paper concludes with a discussion of the mechanisms and engineering principles of roll-bonding and suggests possible applications for future research.

A new study [4] presents numerical and experimental studies on the change in the shape of the reinforcing insert in the aluminum-steel mesh-aluminum package during roll-bonding. The diameters of the rolls used during rolling, pressure and temperature affect the resulting mechanical properties, i. e., the energy absorbed. As a rule, reinforced products exhibit up to 20 % higher impact energy compared to unreinforced composites [4].

The research aimed at studying the rolling process of composite products described in [5]. The authors investigated composites based on alloys EN AW 6063 and EN AW 5056 with different orientation of the mesh fibers. It was found that aluminum plates reinforced with steel mesh at an angle of 45° to the rolling direction show the best mechanical properties compared to products with the arrangement of the reinforcing phase at a different angle to the rolling direction. In a study [6], the authors concluded that the wire mesh insert increases the tensile strength of the entire product if there is sufficient connection between the matrix and wire layers. A similar conclusion was obtained in [7], where a solid aluminum substrate (a compound of solid and liquid casting and rolling) was processed into a composite material by two-roll casting. In this case, the hardness of AA1060 aluminum was increased by almost 30 % by using an AISI 304 austenitic steel mesh.

The assumption of complete connection between the two layers of aluminum matrix was made based on a previous study [7], which found that diffusion adhesion between steel mesh and alu-

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minum matrix in rolled composites is almost absent, and the connection of two layers of aluminum matrix – almost complete.

The authors of [6] determined that the improvement of the quality of the composite element's connection and, consequently, its properties is limited by the ability of the mesh to plastic deformation without fracture. In combination with additional localized intense compression in the mesh nodes, this effect leads to wire fracture. Thus, there is a contradiction between the strain required to properly bond the matrix layers (under given strain conditions) and the strain that causes the mesh elements to fracture. Good results in longitudinal tensile tests were obtained on rolled specimens with 45 % compression. Having mechanical properties insignificantly higher than those of unreinforced bilayer plate, the reinforced composites showed much higher bonding ability at lower rolling pressure [6].

Three types of composite fracture were also found in [6]. Each of them depends on a combination of the following factors: specific part of the wire in the cross section of the product, matrix material properties, strength of the connection on the mesh-aluminum and aluminum-aluminum interface line.

The parameters of the deformation zone during rolling play a significant role in the deformation of the wire within the composite [8]. On the other hand, a better idea of the influence of the process characteristics is given by the results of impact energy and mechanical characteristics of the composite. As a rule, an increase in rolling pressure causes the following chain of deformation of the mesh:

- grid deformation;
- wire stretching;
- ovalization of the wire.

The roll-bonding studies on an aluminum composite described in [8] were aimed at finding the optimal crimping during rolling and developing elements of the technology for obtaining aluminum bars with a mesh inside with predictable mechanical properties. The authors analyzed the deformation of both the mesh geometry and the wire, considering three parameters: grid deformation, wire thinning (stretching) and wire ovalization. These parameters increase in proportion to the rolling pressure. The authors concluded that the best ratio between impact energy and mechanical properties of the material was achieved when rolling with a reduction of 35 to 45 % and a process start temperature of 500 °C.

The authors [9] investigated the microstructure and mechanical properties of composites based on aluminum alloy $AlSi_9Cu$, with an insert of wire steel mesh (AISI 304) obtained by gravity casting. The structure formed in this way made it possible to achieve a slight improvement in the relative elongation at rupture of the product as compared to the aluminum alloy.

In [10], a stainless-steel sheet clad with aluminum was successfully obtained by horizontal two-roll casting. It has been studied that subsequent heat treatment can significantly improve the joint quality at the interface. Cold-rolling treatment also improves the joint strength of the clad sheets. The average peel strength of sheets annealed at 510 °C increases as the pressure during cold rolling increases from 23 N/mm for 25 % crimping to 28 N/mm for 40 % crimping.

Gülenç et al. investigated the reinforcement of an aluminum plate with a steel mesh using an explosion welding process [11]. In addition, Hufenbach, et al. [12] observed a significant increase (up to 400 %) in impact toughness for AM50 alloy when using austenitic steel mesh inserts. In the present study, an injection molding method was used to produce the composite material. Although different methods can be used to produce flat aluminum matrix composites and austenitic steel reinforcements, the rolling process seems to be the most promising solution because it is much easier to control than other processes in industrial production. In addition, it ensures a continuous production process.

In the scientific literature, there are data on the influence of the plastic deformation process on the strength of the connection of the components of a composite material. For example, it is known about an increase in the tensile strength of a material with an increase in pressure during rolling [13, 14].

It was shown in [15] that a reduction of 45 % is favorable for joining aluminum layers with a steel reinforcing phase. Tensile tests of such a composite showed an improvement in mechanical properties. At the same time, in [16], during cold rolling with a reduction of 10 % of aluminum composites reinforced with a steel core, values of tear resistance were obtained that are commensurate with the values characteristic of specimens obtained by hot rolling with a reduction of 30 % [13] and 35 % [17].

In a study [8], a bonding mechanism called "zip-bonding" was described. In this connection, the matrix metal surrounds the rigid wire due to its constant ovalization and rotation. This ensures the mechanical strength of the connection even with only 25 % reduction.

Increasing the process temperature can improve the adhesion of most metals. This fact was established in [16] for various combinations of the main matrix and the reinforcing layer. Subsequent heat treatment promotes diffusion between the layers. The formation of intermetallic phases at the interface can either increase or decrease the strength of the joint. It depends on the chemical composition of the joined metals and alloys [13, 16].

The use of reinforcement with high-strength materials makes it possible to achieve an increase in the mechanical properties of the composite, but its partial collapse in the production process can significantly degrade the properties of the finished product [18]. This also substantiates the importance of controlling the parameters of deformation under rolling reduction.

Although the parameters affecting the connection during rolling of flat products and their range are sufficiently covered in the literature, quantitative data on the roll-bonding of mesh-reinforced packages are not very numerous. The deformation of the mesh within the composite may determine the feasibility of the roll-bonding process in the production of reinforced composites and influence the set of final performance parameters of such composites. In addition, there is no comparison of the behavior of different types of mesh during rolling of reinforced materials. The comparison of mesh deformation parameters will allow more reasonable choice of mesh type in the production of specific composites.

Purpose. The aim of the work is to investigate the deformation parameters during roll-bonding of composites based on aluminum alloy, reinforced by braided and expanded steel mesh.

Methodology of experimental research. The flat composite material consisting of two outer layers of aluminum alloy and inner layer of stainless-steel mesh is manufactured by a rolling process. As the matrix of the composite material, the following aluminum alloys are used in sheet form:

1. EN AW-5083 (Al-Mg system) in annealed condition, sample dimensions ($h \times b \times l$) – 3 × 70 × 120 mm.

2. AA1050, sample dimensions ($h \times b \times l$) – 3 × 70 × 200 mm (Table 1).

Table 1

Chemical composition of aluminum alloy

Alloy	Chemical composition, %						
AA1050	Fe	Si	Ti	Al	Cu	Mg	Zn
	to 0.5	0.3–0.7	to 0.15	97.25–99.3	to 0.1	0.4–0.9	to 0.2

The reinforcing material used included:

1. Braided wire mesh made of stainless steel EN 1.4301, wire diameter – 0.5 mm; square cell size – 3 × 3 mm. Mechanical properties of mesh material EN 1.4301: tensile strength $\sigma_B = 500$ MPa; yield strength $\sigma_t = 0.2 = 195$ MPa; relative elongation $\delta_5 = 40$ % (Table 2).

2. AISI 304 expanded stainless-steel mesh, square cell size ($L_c \times B_c$) – 2 × 4 mm. Mechanical properties of the AISI 304 mesh material: tensile strength $\sigma_B = 510$ MPa; yield strength $\sigma_t = 0.2 = 205$ MPa; relative elongation $\delta_5 = 45$ % (Table 2) [19].

Braided and expanded mesh of stainless steel EN 1.4301 with a mesh size of 3 × 3 mm and AISI 304 with a mesh size of 2 × 4 mm were used as reinforcement material (Fig. 1).

Three types of blanks were prepared (Fig. 2):

- *type a*: composite with braided mesh oriented at an angle of 45 (diagonally) to the rolling direction;
- *type b*: the composite with expanded steel mesh;
- *type c*: without mesh.

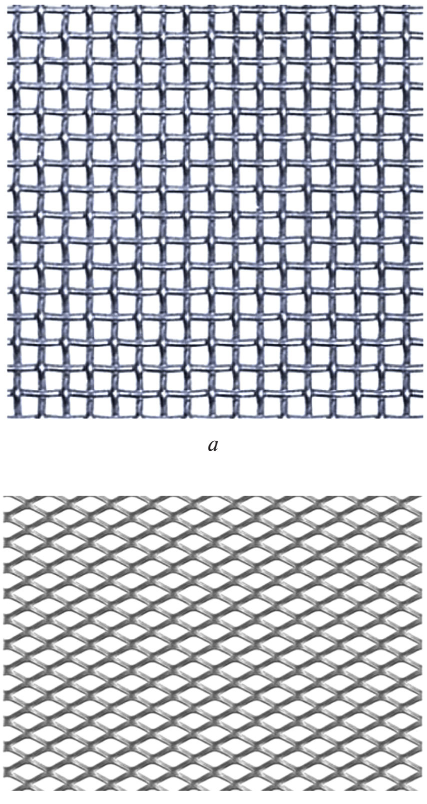
To make the rolling process more stable, the workpieces were held together at the corners with aluminum rivets.

The effective temperature range for the hot roll bonding process is 450–550 °C. However, at these temperatures, the stainless-steel mesh becomes less ductile. To increase the ductility of stainless steel, the mesh was preliminarily annealed in a furnace at a temperature of 750 °C. After being held there for 10 minutes, the samples were cooled to ambient temperature to obtain an austenitic microstructure. In addition, heat treatment made it possible to eliminate the hardening of the steel obtained during the manufacture of the mesh by the plastic deformation method. The blanks from the base material and the grid were degreased with an ethanol solution and put into a bag. To prevent displacement of the layers relative to each other during deformation, the components of the package related to an aluminum rivet in front.

Table 2

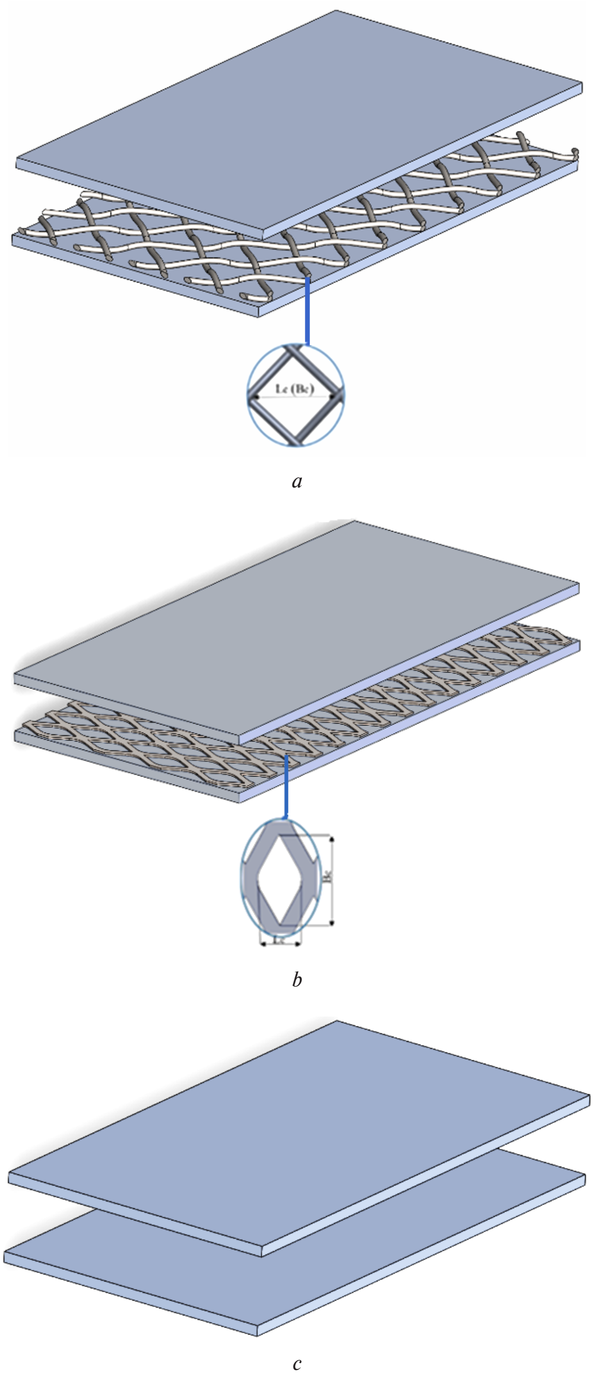
Chemical composition of steel meshes

Alloy	Chemical composition, %						
EN 1.4301	C	Si	Mn	Cr	Ni	N	Fe
	<0.07	<1.00	<2.00	17.5–19.5	8.0–10.5	<0.10	other
AISI 304	to 0.8	to 0.8	to 0.2	17–19	9–11	to 0.2	~69


a

b

Fig. 1. Mesh which was used in the study:
a – steel EN 1.4301; b – steel AISI 304



a

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c

Fig. 2. Scheme of composite preparation for experiments of roll-bonding process:
B_c – width of the cell; L_c – thickness of the cell; a – composite with braided mesh; b – composite with expanded mesh; c – composite without reinforcement

Rolling of the composites was carried out on a two-roll mill. The diameter of the working rolls was 250 mm. The rolling process was carried out in one pass with 20–50 % rolling reduction. Before rolling, the samples were heated to a temperature of 500 °C. The rolling speed was 0.4 m/s. To ensure the repeatability of the experimental results, three samples were rolled for each set of parameters. The rolled composite is shown in Fig. 3.

The aluminum and steel mesh layers were 6 and 0.5 mm thick.

To study the mesh deformation after rolling, the aluminum matrix layer was removed from the package. To dissolve it, the samples were immersed in a sodium hydroxide solution.

Discussion of research results. ***Composite with braided mesh.*** The cell elongation (μc) was chosen as the main parameter of the mesh cell shape change. The cell elongation is calculated as the ratio of the length (diagonal) of the mesh cell after rolling and the length (diagonal) of the mesh cell before rolling, using the example of braided mesh (Fig. 4).

The cell length d1 can be calculated using the length b1 and the cell opening angle α, which is measured before and after rolling. The mesh cell elongation μc is equal to the ratio d_1/d_0. The resulting μc ratio and composite elongation ratio are shown in Table 3 for braided mesh and Table 4 for expanded mesh.

The shape changes in the composite elements during rolling reduction by 50 % corresponds to the shape change observed by the authors of the papers [5, 6] during the deformation of aluminum composites reinforced with a braided mesh.

The peculiarity of a mesh-reinforced composite can be observed when it fractures. It is formed in the fracture of the sample in the areas between the nodes of the mesh. Due to the strong adhesion between the matrix and the reinforcing wire, these wires prevent the development of deformation. When rolling composites without mesh (type C), slight delamination was observed in two composites, whereas no delamination was observed in reinforced composites (type A).

The composite with the expanded mesh. To calculate the cell deformation parameters of expanded mesh as part of the composite, the above methodology was used (Fig. 5).

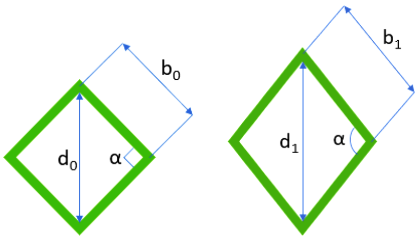
The geometrical parameters of the grid cell elements were determined using a microscope. The calculation results are presented in Table 4.

Experimental data confirmed that the threshold for effective rolling reduction during roll-bonding in terms of the strength of the connection of the layers is above 30 %. Lower values of rolling reduction do not always ensure reliable connection of the layers, because under these conditions the mesh is deformed only by elongation and compression of its lattice.

The angle between the lattice fibers increases linearly by 10 degrees for every 10 % rolling reduction as the composite is rolled, as shown in Fig. 6.

With above 40 % of rolling reduction, the increase in angle becomes smaller.

Fig. 3. View of the composite after rolling



a *b*

Fig. 4. Scheme of cell elongation of braided mesh:
a — cell elongation before rolling; b — cell elongation after rolling

Table 3

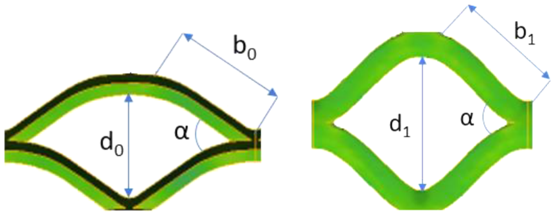
Geometric parameters of braided mesh elements

No.	Rolling reduction, %	Cell elongation coefficient	Elongation coefficient of the whole composite
1	20	1.68	1.28
2	30	1.89	1.37
3	40	1.98	1.35
4	50	2.30	1.37

Table 4

Geometric parameters of the elements of the expanded mesh

No.	Rolling reduction, %	Angle between the wire mesh, °	Cell elongation coefficient	Elongation coefficient of the whole composite
1	20	82	1.55	1.25
2	30	90	1.75	1.4
3	40	105	1.85	1.65
4	50	110	2.20	1.83



a *b*

Fig. 5. Scheme of cell elongation of expanded mesh:
a — cell elongation before rolling; b — cell elongation after rolling

The dependence of the grid angle on the rolling reduction makes it possible to determine the deformation parameters to obtain the optimal cell angle, which is 90°. This angle value makes it possible to obtain such a grid orientation, which will lead to a decrease in the anisotropy of the properties of the finished composite. As can be seen from Fig. 6, for these conditions, the amount of compression required to obtain a cell angle of 90° is about 30 %.

An important parameter in rolling is the ratio of the length of the deformation zone to the average thickness of the composite. This ratio is called the deformation zone shape factor and divides all cases of rolling into thick, medium, and thin plates. Each case is characterized by certain patterns of deformation distribution over the height of the composite. When rolling composite materials, this is a very important factor in terms of deformation of the various components of the package. Analysis of the value of the shape factor of the deforma-

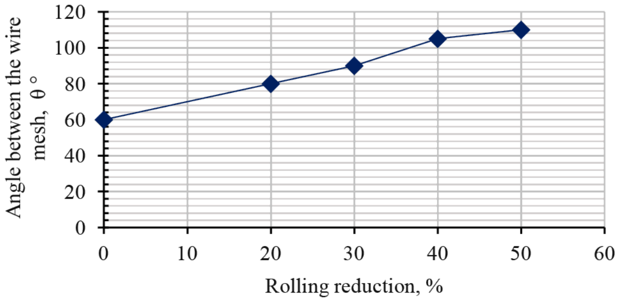


Fig. 6. Change in the angle between the wire mesh (θ) of the expanded mesh

tion zone for the range of crimping used in these studies showed that the values of the shape factor correspond to the case of rolling medium and thin plates.

At 20 and 30 % rolling reduction, the form factor values are 2.2 and 2.8, which corresponds to the rolling of medium plates. At 40 and 50 % rolling reduction, the form factor values are 3.5 and 4.1, which corresponds to rolling thin plates.

The grid elongation coefficient for the experiment with braided mesh μc was 1.68–2.3, which is higher than the elongation coefficient of the grid made of expanded mesh 1.55–2.2. This difference is due to the way the wires are connected in the mesh elements. While the braided mesh has overlapping wires in the knots and no rigid connection, the expanded mesh is solid in the knots. As a result, braided mesh has moving parts at the nodes and a higher elongation coefficient compared to expanded mesh.

The composite with braided mesh shows more uneven deformation than the deformation of the whole package, which makes it difficult to obtain the specified mesh parameters. In addition, the uneven deformation can cause the mesh within the composite to fracture. In turn, a composite with an expanded mesh shows a lower lattice elongation coefficient and more uniform deformation, which can be a significant advantage when choosing the type of mesh as a reinforcing element for aluminum composites.

Conclusions. It has been established that the rational rolling reduction at roll-bonding is more than 30 %. Lower rolling reduction almost does not cause changes in the mesh size, and the deformation of reinforced mesh is carried out only due to elongation and compression of wires.

The dependence of the grid angle on the rolling reduction makes it possible to determine the deformation parameters to obtain the optimal cell angle, which is 90°. This angle value makes it possible to obtain such a grid orientation, which will lead to a decrease in the anisotropy of the properties of the finished composite. As can be seen from Fig. 6, for these conditions, the amount of compression required to obtain a cell angle of 90° is about 30 %.

The shortcomings of braided meshes when reinforcing composites are established. It is shown that the expanded mesh has a lower coefficient of mesh cell elongation than the braided mesh, since there are no interwoven wires, as it is obtained by extending the steel sheets. This reduces the risk of the mesh breaking at the points where the wires cross. Therefore, the use of expanded mesh for reinforcing aluminum matrix composites is preferable compared to braided mesh.

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Визначення параметрів деформації сталевої армуючої фази всередині алюмінієвої матриці при гарячій прокатці

*М. І. Носко, Д. В. Коноводов**, *А. А. Самсоненко,*
О. С. Бобух

Український державний університет науки і технологій,
м. Дніпро, Україна
* Автор-кореспондент e-mail: konovodov@metal-forming.org

Мета. Порівняння параметрів деформації при прокатці армованих композитів на основі алюмінієвого сплаву з використанням в якості армуючої фази плетеної та просічно-витяжної сталевої сітки.

Методика. Виконано експериментальне дослідження впливу обтиснення на деформацію армуючої фази при прокатці алюмінієвих композитів. В якості армуючої фази використана плетена та просічно-витяжна сітка з нержавіючої сталі. Досліджено вплив деформації на зміну кута гратки армуючої фази.

Результати. У роботі отримані експериментальні дані стосовно параметрів деформації плетеної та просічно-витяжної сітки. Проведене порівняння формозміни таких сіток в умовах гарячої прокатки між двох алюмінієвих пластин, що відіграють роль матриці. Встановлено, що коефіцієнти видовження ґратки для експерименту із плетеною сіткою μc дорівнював 1,68–2,3 що більше, ніж коефіцієнт видовження ґратки із просічно-витяжної сітки – 1,55–2,20. Тому, просічно-витяжна сітка є кращою в якості армуючого шару для композитів на основі алюмінію, отриманих процесом прокатки–з'єднання. Також просічно-витяжна сітка дозволяє зменшити ризик розриву в місцях перехрещення дротів.

Наукова новизна. У роботі вперше наведене порівняння параметрів деформації під час прокатки–з'єднання композитів на основі алюмінієвого сплаву, армованих плетеною та просічно-витяжною сіткою. Технологія виготовлення композиційних матеріалів із різними видами армуючого елемента за допомогою гарячого з›єднання прокаткою вимагає розуміння властивостей кожного елементу композиту в зоні деформації та їх впливу один на одного. Такі особливості ще не були достатньо досліджені. Тому, наразі, не існує надійного методу прогнозування поведінки жорсткої армуючої фази всередині м'якої алюмінієвої матриці.

Практична значимість. Підтверджені переваги використання просічно-витяжної сітки для армування композитів на основі алюмінію. Результати роботи можуть бути використані для уточнення методів розрахунку течії металу в умовах високого гідростатичного тиску зі змінними компонентами тензора напружень і головними напруженнями.

Ключові слова: *прокатка–з'єднання, алюмінієва матриця, сталева сітка, плоский прокат, композит, параметри деформації*

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