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Failure mode of reinforcing steel mesh in aluminum roll bonded composite material

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Характер руйнування армувальної стальної сітки під час зварювання прокаткою композиційного матеріалу на основі алюмінію

Flat roll-bonded aluminum 6060 composite materials with reinforcing steel inlets made of woven wire mesh (AISI 321) and expanded mesh (AISI 304) have been produced at 20 % and 30 % reduction. The roll bonding process has been performed at 400 and 500℃. After the process the composites were peeled and their interfaces were subsequently studied via SEM microscopy. In all cases the fracture of mesh inlets has been observed. The analysis of the failure mode has shown that the fracture of woven wire mesh corresponds to that described by other researchers. At the same time, the failure mode of expanded mesh inlet was presented in this study is characterized by a significant amount of brittle fracture at the region between strands and knuckles of expanded mesh. In order to analyze a stress state in these regions, the simulation using the finite element method (FEM) was set up by means of QForm software. The thermal and deformational conditions corresponded to experimental ones. It was shown that the von Mises stress reaches a significant magnitude up to the strength of austenitic steel. At the same time, a study of initial micro hardness of expanded mesh was conducted. The study revealed a significant work-hardening in the region of knuckles due to manufacturing procedure of expanded mesh and this seems to be the most important cause of destruction. In order to avoid such fracture, the annealing of expanded mesh was proposed. Presented results show a significant decrease of hardness and therefore an opportunity plastic deformation of expanded steel mesh.
Key words: roll bonding, steel mesh, reinforcement, composite material, aluminum,

Були виготовлені композиційні матеріали на основі алюмінію АД31 з армованими сталевими вставками, виготовленими з сітчастої сітки (08Х18Н10Т) і просічно-витяжної сітки (08Х18Н10), степінь деформації склав 20% і 30%. Процес пакетної прокатки був проведений при температурі 400 і 500 ℃. Після експерименту композиційні матеріали були розшаровані з метою подальшого дослідження поверхні сітки за допомогою скануальної електронної мікроскопії. У всіх випадках спостерігалося руйнування сітчастих вставок. Аналіз характеру їх руйнування показав, що у випадку плетеної сітки руйнування відповідає типу, описаному попередніми дослідниками. Водночас, у випадку просічно-витяжної сітки, спостерігається значна міра крихкого руйнування на ділянці початку ниток сітки.

Для аналізу напруженого стану в цих ділянках було проведено моделювання з використанням методу скінчених елементів за допомогою програмного забезпечення QForm. Термічні та деформаційні умови моделювання відповідали експериментальним. Показано, що інтенсивність напружені у цих ділянка досягає величин, більших за міцність аустенітної сталі. При цьому, моделювання показало достатньо точне змінення кута між нитками просічно-витяжної сітки при порівнянні з експериментальними результатами. Також було проведено дослідження мікротвердості просічно-витяжної сітки у початковому стані, та після термічної обробки. Дослідження показало значний наклеп у області кутів сітки, що утворюється під час виготовлення такої сітки. Передбачається, що це є найважливішою причиною руйнування. З метою уникнення такого руйнування, було запропоновано попередню термічну обробку просічно-витяжної сітки. Наведені результати показують значне зниження мікротвердості і, отже, можливість пластичної деформації розширеної сталевої сітки.
Ключові слова: пакетна прокатка, стальна сітка, армування, композиційний матеріал, алюміній

Introduction. Composite materials consisted of lightweight matrix and reinforcing core are widespread in modern in automotive and aerospace manufacturing since decreasing of weight play significant role in decreasing of fuel use and achieving both economic and ecological effect. Composites based on lightweight alloy such as aluminum and reinforced with steel mesh can be applied above-mentioned fields as well.

Purpose of the research. The target of this research is to advance analyze failure mode occurred in reinforcing expanded mesh and wire mesh inlets in aluminum composite during the roll bonding and advance the formability of steel mesh in aluminum matrix.

Analysis of publications. There are several studies in which researchers worked on reinforcing alloys of aluminum or magnesium with steel wires. The twin-roll casting of aluminum with inserted steel wire was performed by Haga et al [1]. Hufenbach et al. applied a gas pressure infiltration method was applied to produce magnesium flat composite reinforced with austenitic and ferritic steels wire mesh [2]. Explosive welding was also used in order to obtain composite material based on aluminum AA1070 matrix and wire woven mesh by Gülenç et al. [3]. Huang et al. in their work [4] produced a composite material based on aluminum AA 1060 matrix and austenitic steel woven mesh AISI 304 by means of twin-roll casting with one solid aluminum substrate (so-called solid–liquid cast-roll bonding (SLRCB)). The roll bonding process was studied by Stolbchenko et al. [5,6] and by Frolov et al.

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[7]. In all above-mentioned papers authors reported about significant rise of mechanical properties of composites due to application of wire mesh such as fracture toughness [2-3] and tensile strength [3-7].

Among all mentioned processes, for aluminum matrix, roll bonding seems to be the most perspective, since it allows much higher rate of manufacturing, it is simple to control the technology and there is no constrains in length of the product. Yet, the manufacturing technology is challenging. Application of strong inner core inside the soft metal matrix leads to sufficient rise of stress concentration in this hard material as a result of relatively high deformation plastic deformation magnitude of soft matrix [5-8]. Application of woven wire mesh as an internal core during roll bonding leads to appearance of zones with significantly intensified stress and strain at the location of wires intersection, this leads to possible fracture of wires during the manufacturing process [4-7]. In order to solve this problem, in this research it is decided to use expanded mesh instead of the woven one. At the same time, it should be noted that the inlet made of austenitic steel experiences hardening during the plastic deformation at the temperature of higher 200℃, which reduced its plasticity [7,9].

Experimental procedure. Two types of flat composite materials based on aluminum matrix 6060 with inlets made of wire steel mesh AISI 321 and expanded mesh AISI 304 located between two aluminum layers (see fig. 1) were produced by means of hot roll bonding process with reduction magnitude 20 and 30% at the temperature 400 and 500 ℃. Each component of specimens was degreased with ethanol solution, then layered packages were fastened the corners via rivets and exposed roll bonding with one pass. The parameters of the process are presented in the table 1.

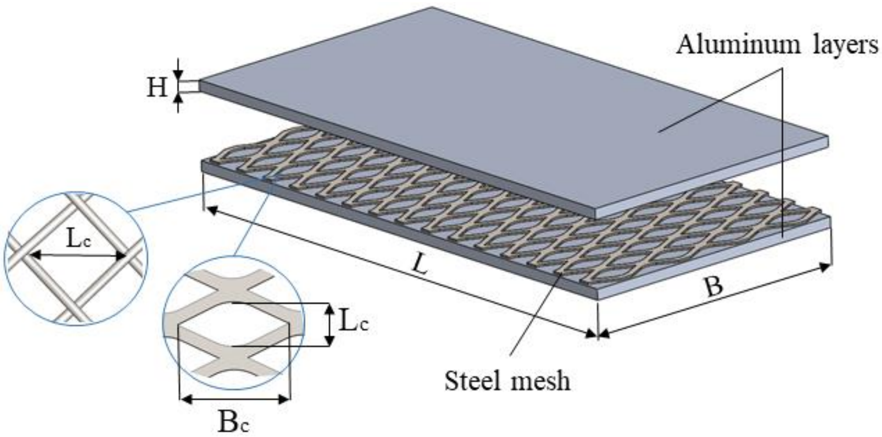


Figure 1 – Scheme of workpiece with steel meshed inlets (expanded sheet and wire mesh)

After the all experimental procedures the composites were peeled and a studying of bonding interfaces was conducted by means of electron microscope “Zeiss Ultra Plus”.

In addition, due to obtained fracture on expanded mesh inlets, the studying of their micro hardness of in as received state as well as after heat treatment was conducted in order to clarify the occurring destruction mode of inlets. Heat treatment of steel mesh inlets consisted of annealing at 1050℃ with holding time 5 minutes and subsequent quenching with water. The target was to remove the work hardening occurred at the stage of expanded mesh manufacturing and to improve the ductility to of expanded mesh.

Table 1 – Roll bonding conditions

Aluminum layer thickness: H, mm	3
Aluminum layer width: B, mm	70
Aluminum layer/steel inlet length: L, mm	200
Steel inlet thickness (exp. sheet/wire), mm	0,5
Expanded sheet cell parameters: L_c×B_c, mm	2×4
Wire mesh cell parameters: L_c×B_c, mm	2×2
Angle between strands, exp. sheet, °	60
Angle between strands, wire mesh, °	90
Diameter of rolls, mm	135
Temperature, ℃	400; 500
Reduction, %	20; 30
Rolling speed, mm/sec	300

Simulation procedure. The FEM simulation the roll bonding aluminum/ expanded steel mesh/aluminum composite materials was conducted by means of QForm software. Conditions of the simulation corresponded to experimental ones. However, in order to optimize the simulation, the initial length of the workpiece was 20 mm and width was 40 mm. As a condition of friction between parts of workpiece "Full sticking". This admission suggests an existence of initial bonding between aluminum layers and mesh inlets, in other words, there is no sliding of elements relatively to one another. The presence of curvatures in expanded sheet was neglected.

As a frictional condition between tools and worpiece the Zilberg's model was applied.

Due to the plane of symmetry, only half of the process was simulated as it can be seen in the figure 2.

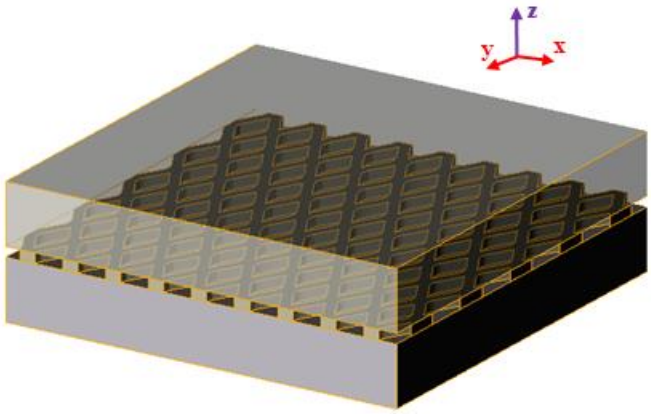


Figure 2 – Finite element model of the initial workpiece in QForm cut off in the plane of symmetry

The flow stress curves of aluminum alloy 6060 was taken from the study [10]. The flow stress of steel inlets was set by means of Hansel-Spittel model [11]. With corresponding coefficients that consider initial strain resistance, temperature, strain and strain rate. These coefficients are presented in the table 2.

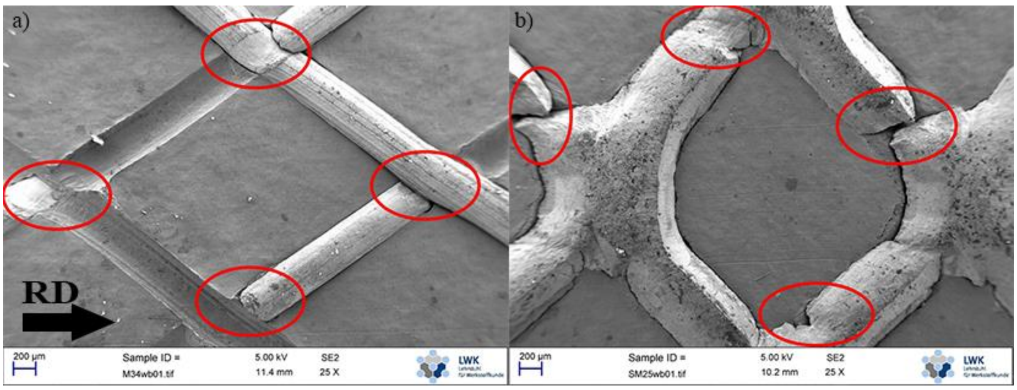
$$\sigma = A_1 \cdot e^{-m_1 T} \cdot \varepsilon^{m_2} \cdot e^{-m_4 \varepsilon} \cdot \dot{\varepsilon}^{m_3} \quad (1)$$

Where A is a constant, m_1 to m_8 are exponents containing the influence of the deformation conditions on the flow stress.

Table 2 – Coefficients of Hansel-Spittel model for steel AISI 304

A_1	m_1	m_2	m_3	m_4
1335,332	- 0.00148	0,36219	0,01014	0,003372

Results and discussion. In all cases regardless to reduction magnitude the destruction of mesh inlets was observed. The failure mode of wire mesh inlets observed in this research corresponds to that one described by previous authors [4-7]. The fracture is located at the zones of wires intersection as presented in the figure 3 (a). Excessive stress at these zones caused by the mutual reduction of overlayed wires and elongation of the whole composite leads to the crack appearance and destruction in this zone [5-7]. At the same time, the failure mode of expanded sheet inlet is presented in figure 3 (b). As it can be seen, in this case, fracture appears at the zone of where strands are connected to knuckles.



a) Wire mesh inlet; b) expanded sheet inlet

Figure 3 – Failure mode of steel meshed inlets

The possible reason of such failure mode of expanded mesh lies in the features of its manufacturing technology. Metal is exposed to cold plastic deformation during the process of obtaining of cells and as well as during the subsequent flattening by meats of cold rolling. Thus, steel in the regions of knuckles becomes hardened and therefore, fragile.

Further studying of expanded metal has revealed that its initial hardness reaches approximately 300-320 HV at the strands (dots 3-7 on the figure 4), while the hardness at corners of the knuckles is even higher and reaches approximately 370 HV (dots 1,2,8-10 on the figure 4).

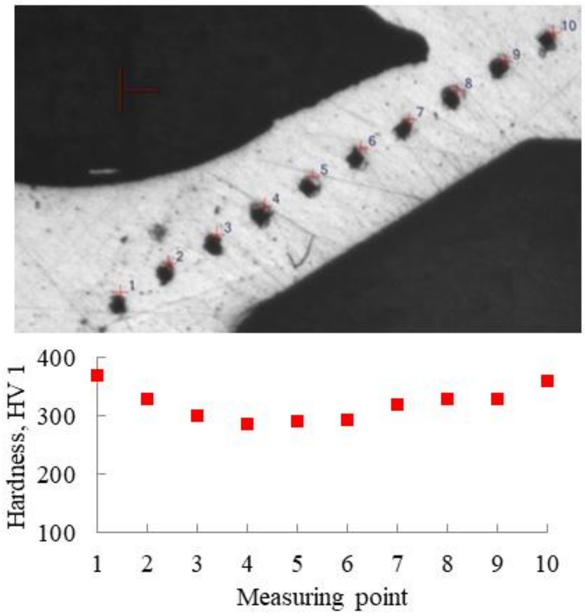


Figure 4 – Hardness of expanded metal elements before the heat treatment

It can be seen on the figure 5 that the heat treatment removed hardening sufficiently, the hardness dropped to approximately 120-150 HV and has become even in all parts of a cell. Therefore, a technology of manufacturing of such composites should include a pre heat treatment of expanded sheet.

Considering the facts described above, it is assumed that pre-heat treatment of expanded sheet inlet might assist to avoid destruction in these zones.

Furthermore, the analysis of stress state in the simulation presented a significant stress intensity (von Mises stress) in mesh strands, and it reaches the magnitude beyond that of austenitic steel strength (see figure 6).

Von Misess stress in the simulation rises as the distance from knuckles increases, and its pick magnitude located at centers of strands length. In addition, it can be seen that von Mises strain raises as temperature decreases from 500℃ to 400℃ and reduction magnitude increases from 20% to 30%. This indicates imprecision of the simulation. In spite of localization of maximal magnitude of von Mises stress at centers if strands, the fracture that observed experimentally, is located at zones of connection of strands and knuckles where the steel is hardened. This indicates that in this case the main factor contributed to fracture appearance is pre-strain-hardening of expanded mesh. In order to clarify plastic deformation behavior of the composite structural parts, further studying with annealed expanded mesh will be conducted in the future.

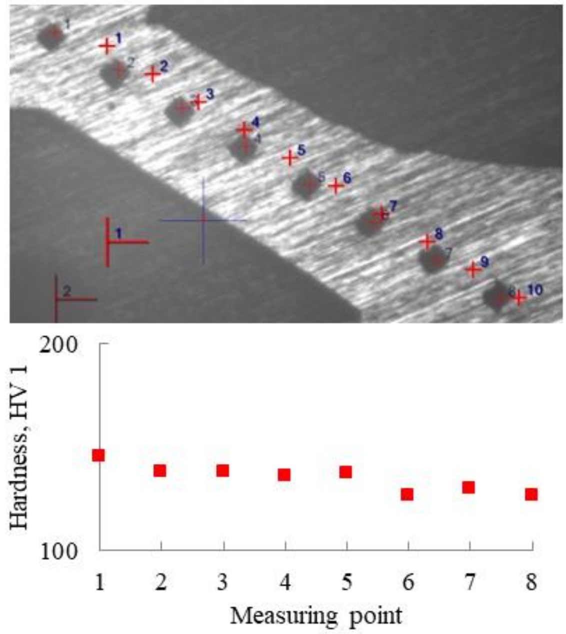
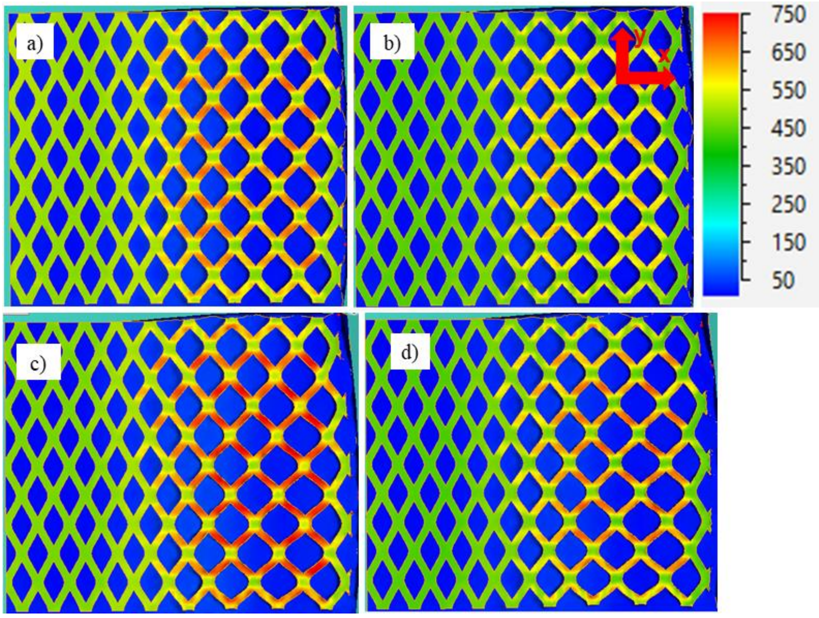


Figure 5 – Hardness of expanded metal elements after the heat treatment

Despite the inaccuracy presented in von Mises stress, a comparison of angles between strands before and after the plastic deformation shows sufficient correspondence of simulation to the experiment (table 3).

Conclusions. Failure mode of wire mesh inlet observed in this paper corresponds to that described in previous works by authors [5-7]. Mesh is fractured at zones of wires intersection as a result of intensified deformation of wires in these zones.

Failure mode of expanded sheet inlet is characterized by cracking appearance at the connections of strands and knuckles as it is shown in the paper. Such failure mode occurs due to the combination of such factors as previous cold work hardening of metal in this zones during the obtaining of splits and their subsequent stretching. This is supposed to be the main reason. Another one is a high stress concentration in in expanded mesh strands during the roll bonding process, which is shown by the analysis of von Mises stress obtained in FEM simulation. However, when it comes to stress intensity magnitude it should be noticed than in simulation it significantly overcomes the ultimate tensile strength of AISI 304 steel at peaks at the centers of strands, which indicates certain inaccuracy of the simulation. However, when it comes to expanded mesh opening during the roll bonding, which presented by the comparison of angles between its strands, the FEM simulation presented developed via QForm software has shown an agreement with experimental results.



Reduction magnitude/temperature: a) 20%, 400℃; b) 20%, 500℃; c) 30%, 400℃; d) 30%, 500℃.
Figure 6 – Von Mises stress (σ_i) in the elements of the composite during roll bonding, MPa

Table 3 – Angles between expanded mesh strands

Reduction	Initial angle between strands, °	Angle between strands, ° (exp. sheet)
Simulation		
20%	60	80
30%	60	90
Experiment		
20%	60	86
30%	60	90

In the experimental procedure, the fracture of expanded mesh occurred not at the centers of strands, but at the connection of strands and knuckles. The measurement of microhardness indicates that the initial hardness of expanded mesh in these zones reaches 370 HV.

As a result of the previous cold deformation during the manufacturing of expanded mesh, steel becomes hardened and fragile. In order to provide sufficient ductility to such type of inlet the annealing treatment of expanded metal is proposed in this study. It is shown that annealing of expanded metal made of steel AISI 304 allows that consists of its heating up to 1050℃, holding for 5 minutes and subsequent quenching in water allows decreasing of hardness from 370 HV up to 120 HV and corresponding rising of the ductility. Thus, it is shown that pre heat treatment of expanded sheet inlet should be applied in manufacturing of such composites.

Further studying will be conducted with pre annealed expanded metal inlet in order to avoid explained above disadvantages and preventing any fracture in expanded mesh.

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