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INVESTIGATION OF BIMETAL COMPOUND WITH THE AIM TO INCREASE EQUIPMENT RELIABILITY FOR COMPLEX GAS PREPARATION

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ДОСЛІДЖЕННЯ ВЛАСТИВОСТЕЙ З'ЄДНАННЯ БІМЕТАЛУ З МЕТОЮ ПІДВИЩЕННЯ НАДІЙНОСТІ ОБЛАДНАННЯ ДЛЯ КОМПЛЕКСНОЇ ПІДГОТОВКИ ГАЗУ

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ИССЛЕДОВАНИЕ СВОЙСТВ СОЕДИНЕНИЯ БИМЕТАЛЛОВ С ЦЕЛЬЮ ПОВЫШЕНИЯ НАДЕЖНОСТИ ОБОРУДОВАНИЯ ДЛЯ КОМПЛЕКСНОЙ ПОДГОТОВКИ ГАЗА

Abstract. This article is devoted to the investigation of technical process of reinforcement of aluminum sheets with wire for increasing equipment reliability for complex gas preparation. Reduction of operating coalmines forces to give more attention to gas and gas-condensate deposits.

Before supplying gas to the pipeline, it must be cleaned from various impurities at special plants for complex gas treatment. Separating equipment, absorption or adsorption columns and other equipment used for these purposes, should be wear-resistant and lightweight and withstand high loads. Aluminum sheets with mesh reinforcement possess such properties. Actual task is improving of technology for obtaining such sheets in order to receive higher quality and reduce cost of the products. The article presents results of experimental studies of the strain parameters of rolling an aluminium matrix when wire mesh is inserted between aluminium layers. During the experiment, two types of stainless steel fabric meshes oriented parallel and diagonal to the rolling axis were placed between two aluminium strips and rolled. Rolling processes were performed, at which temperature and pressure on the material were varied to produce bonding of matrix layers. This study focused on measuring strain in areas of longitudinal and cross sections; stretching and ovalization of the wire mesh; measuring changes in the mesh angles of the cell; and testing mechanical properties of composites along the rolling direction. Main contradiction resulting from this experiment was as follows: contact pressure required for the bonding of aluminium layers produces extreme tensile strain on the inserted wire mesh, degrades mechanical properties of the reinforcing mesh and, thus, degrades properties of the entire composite. Optimal results in the longitudinal tension tests were achieved by using strips with diagonally oriented mesh-reinforcement. This study was supported by German Academic Exchange Service (DAAD) in the framework of German-Ukrainian project «Praxispartnershaft Metalurgie».

Key words: aluminium matrix, steel mesh, reinforcing, rolling, delamination, mechanical properties

Introduction

The steady tendency to reduce the number of working mines forces us to pay more attention to the gas and gas condensate fields. After extraction from the deposit before supplying gas to the pipeline, it must be cleaned of various impurities. The presence of water, liquid hydrocarbons, aggressive and mechanical inclusions in the gas reduces the capacity of gas pipelines, increase the consumption of inhibitors, increases the corrosion of equipment, leads to the need to increase the capacity of gas compressor stations, removes the reliability of technological systems, increases the probability of emergency situations at gas compressor stations and the linear part of gas pipelines.Gas preparation for long-distance transportation is carried out in gas complex treatment plants (GCTP) intended for drying natural gas from water, separating impurities, liquid hydrocarbons and cleaning from sulfur compound.

The choice of industrial equipment for GCTP depends on the composition of the gas, the content of moisture and impurities, the direction of the further use of gas and the climatic conditions of the mining and transportation areas. Taking into account the above factors, the GCTP can include separation units, absorption or adsorption columns and other equipment.

To increase the resource and reduce the cost of this type of equipment, it is advisable to use wear-resistant, light materials that are not subject to corrosion, capable of withstanding high loads. Wire-reinforced aluminum sheets have similar properties. Actual is the task of improving the technology for obtaining such sheets in order to improve the quality and reduce the cost of products.

1. Formulation of the problem

The combination of different materials in a single product, known as a composite, usually incorporates the best properties of each material into a single finished product. An example of such a composite is aluminium alloy sheet reinforced with steel netting. The aluminium is lightweight and highly resistant to corrosion whereas the steel netting is strong and ductile. The properties and characteristics of such compositions, including those obtained in the metal forming processes, are described in [1]. In the United States, Patent [2] claims the methods of producing a metallic material composite which involves assembling at least two stacked matrix layers of relatively low-strength metal and one or more reinforcements in the form of wire or net. This method involves a) placing a wire-wrapped aluminum sheet between two additional aluminum sheets and rolling it at 400-450 °C; b) hot rolling a wire mesh sheet placed diagonally between the two sheets of aluminium alloy; c) hot rolling a multilayer composite of interwoven alternate matrix layers, meshes of woven stainless steel and aluminium wires; and d) filling mesh cells with aluminium spraying and rolling between the soft matrix sheets. Aside from production methods, the results of mechanical and fatigue tests of obtained composites are also presented in this patent. They show that all composites had an increased fatigue life, especially with a diagonal net-reinforcement. However, in some experiments, the rolled sandwiches showed a decreased level of strength and ductility in comparison to pure matrix material. Unfortunately from study [2], the strain parameters of rolling and the contraction of cross-sectional wiring remain unclear. Patent [3] describes the elements of longitudinal steel wire reinforcing technology of an aluminium matrix during rolling. The methodology begins with the formation of half-rounded longitudinal grooves on the aluminium matrix surface. Steel wire is then placed in the grooves of both matrices and rolled flat. The implementation of these methods avoids significant strain in both the matrix and wiring. In our opinion however, this technology lacks an additional pre-bonding operation in grooving matrices. In patent [4] is described another way of reinforcing, which consist compounding and subsequent rolling of transversally grooved aluminium matrix, with longitudinal steel wires. This technology with a small rolling reduction provides higher contact pressure between the matrix and the reinforcement, as well as between the matrix layers. Its drawback however, is the high probability of a porous appearance inside the finished sandwich. Authors claim that such porosity can be eliminated following further deformation processes. Both technologies described in [3] and [4] require compliance between the wire diameter and diameter of the groove for each material pairing as well as the determination of strain-temperature conditions of process. Numerous tests were devoted to investigating strain-temperature conditions at roll bonding of flat products.

Experiment [5] analyzes the deformation of the longitudinal and transversal net wires within a flat composite after rolling. Results of the experiment show that the wire cross section changes in two ways during rolling: ovalisation (flattening) and stretching. The set of these deformations depends on the position of wire in the composition as well as on the strain parameters during rolling. The appearance of carbon fibre breakages inside the twin-roll cast composite, presented in [6], also reflect the importance of monitoring strain parameters during the composite’s deformation.

The implementation of the energy-saving twin-roll casting technology for aluminium-steel clad strips allows a thin and uniform layer of intermetallic phases on the materials interface of approximately 3 μm thickness with an adhesive strength of over 70 MPa [7] to be obtained. Moreover, a good cold formability of the twin-roll cast and consequently hot rolled clad strip of pure aluminium and austenitic steel is shown in [8]. The results of the research on the roll bonding of two-layer (Al - Al) and a three-layer (Al - steel - Al) compositions are described in [9]. It is shown that the strain rate during rolling has no significant impact on the composite's mechanical properties. The main parameters are: contact pressure, temperature and strain. A minor number of known studies is devoted to casting technologies, in particular twin-roll casting, for manufacturing aluminium matrix composites reinforced with wires and netting and to the evaluation of their properties. Section [10] describes process parameters and upper limitations of wire diameter by twin-roll casting of net-reinforced aluminium strips. At the same time, the contraction of cross-sectional wiring due to the consequent rolling was not observed considerably. The devices for feeding and positioning of the wires inside the composite during the twin-roll casting are described in [11]. Thus, the current level of research shows that strain-temperature parameters of roll bonding in a certain range can increase composite properties without a preliminary grooving. Establishing this range is necessary in understanding how the rolling parameters impact the contraction of reinforcing phase and how they influence the composite's properties.

The purpose of this work is to obtain quantitative data on the contraction of cross-sectional wiring during the roll bonding of net-reinforced aluminium matrix composites. Moreover, the study serves to evaluate the influence of changes in cross-sectional wiring on the composite's tensile strength.

2 Experimental

The flat composite consisting of two outer layers of aluminium alloy and a stainless steel net in the core was manufactured by means of roll bonding. The following aluminium alloys in the form of thin strips were used as a matrix material of the composite:

- EN AW-5056 (Al-Mg system) in the annealed condition; the samples' dimensions for the experimental roll bonding (h × b × l): 4 × 36 × 120 mm.
- EN AW-6063 (Al-Mg-Si system) in the annealed condition; the samples' dimensions: (h × b × l) 3 × 36 × 120 mm.

The two types of the 90° fabric wire nets of stainless steel EN 1.4301 were used as a reinforcement material:

- "A" – diameter of the net wire: 0.5 mm; size of square cell 3 × 3 mm;
- "B" – diameter of the net wire: 0.25 mm; size of square cell 1 × 1 mm.

For each of 4 materials pairs, three types of billets, preliminarily fastened in the corners with aluminium rivets and forming so-called sandwiches, were prepared for the subsequent roll bonding (See Fig. 1):

- Type 90 – the net wires oriented along and across the rolling direction.
- Type 45 – the net wires oriented at an angle of 45° (diagonally) to the rolling direction.

- Type 0 – without reinforcing net.

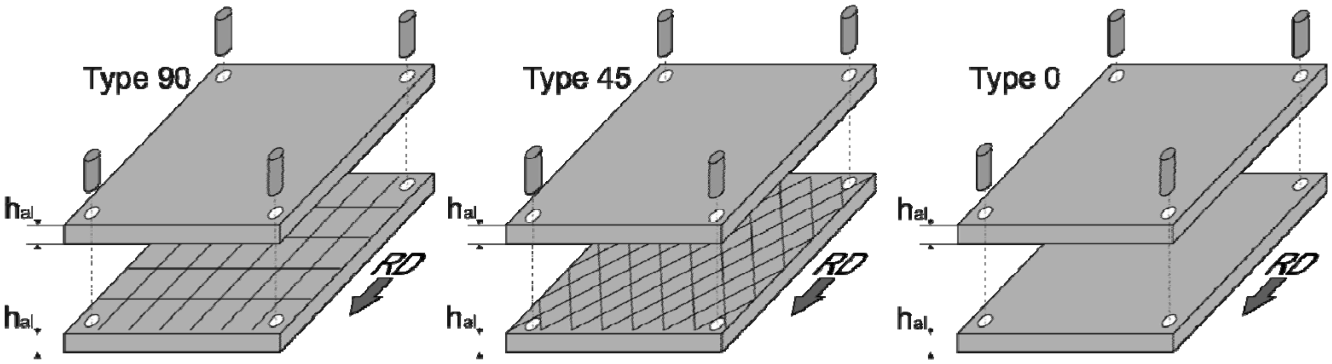

Figure 1 – Sandwich preparation scheme for the experiments on roll-bonding: RD – rolling direction, h_{al}- initial thickness of the aluminium strips

The rolling was carried out in one or two passes with a nominal reduction of 30% in every pass with a preheating to the rolling temperature (see. Table 1) in a two-high rolling stand with 250 mm diameter rolls. Rolling speed was 23.5 m/min.

The general experimental plan and parameters for the hot roll bonding of aluminium strips reinforced with a steel net is presented in the Table 1.

Table 1 – The experiments on the hot roll bonding of net-reinforced aluminium composites

Features			Matrix alloy	
			AW-5056	AW-6063
Samples	Net type A		●	●
	Net type B		●	●
	Sandwich type 90		●	●
	Sandwich type 45		●	●
	Sandwich type 0		●	●
Processing	Nominal reduction 30% in a single pass	Rolling temperature 200 °C	-	●
		Rolling temperature 500 °C	●	-
	Nominal reduction 60%, in two passes with intermediate preheating		-	●
Testing	Measurement of wires strain		●	●
	Quasi-static longitudinal tensile test		●	●

Legend to the Table 1:
● – experiments were performed
- – experiments were not performed

The only exception in the experimental series was roll-bonding of non-reinforced sandwiches with AW-6063 matrix in one pass. In this case, the delamination of sandwiches occurred immediately after rolling, possibly due to an insufficiently high rolling temperature of 200 °C. Further analysis of this composite was impossible.

After the roll bonding, the cross-sections of the manufactured composites in the longitudinal and transversal (to the rolling direction) planes were made to analyze the position and form of the wires in the matrix material. The cross-sections were prepared using abrasive cutoff machine and a subsequent grinding with sandpaper up to 4000 grit. The form and position of the wires in the cross-sections were analysed and measured using a digital microscope Keyence VHX5000.

To analyze the net distortion of the sample's length and width, one of the matrix layers was removed to reveal the net fabric. For this purpose, one of the aluminium layers was ground and subsequently chemically removed using 5%-solution of NaOH until the net became visible. Photographs of the net inside the composite were taken using digital microscope Keyence VHX5000.

To calculate strain values, the initial sandwich thickness h_0 was interpreted as the sum of thicknesses ($2 \times h_{al}$) of the aluminium matrix without factoring in the thickness of the net fabric. The elongation factor μ_Σ for sandwich and finished composites were defined as the ratio of their cross-sectional areas before ($h_0 \times b_0$) and after the rolling ($h_1 \times b_1$). The longitudinal $\mu_{wL}{}^{90}$ and transversal $\mu_{wT}{}^{90}$ wire elongation factors of the Type 90 composites were calculated as a ratio between the initial and final areas of the wire projection on the transversal (across the rolling axis) and longitudinal cross-sectional planes correspondingly. The ovalization of the wires in this type of composite ($O_w{}^{90}$) was determined as a ratio of width b_w to height h_w (Fig. 2). The elongation factor $\mu_w{}^{45}$ and wire ovalization $O_w{}^{45}$ for the Type 45 sandwich were defined as analogous to the ones for Type 90. In this case however, the average area of wire projections and the average width and height of the ovalized wire on the longitudinal and transversal cross-section planes were used for the calculations. The number of measured wires was 5-12 for the longitudinal and 3-7 for the composite's transversal plane.

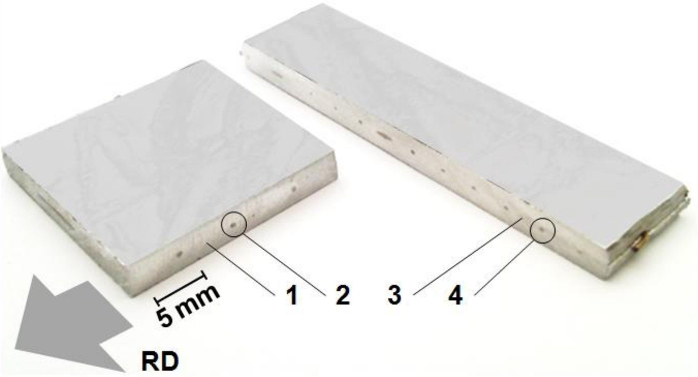

Figure 2 – Scheme for the evaluation of elongation factor and ovalization of the wire inside the Type 90 composite: RD - rolling direction; 1 – the longitudinal cross-sectional plane of the composite; 2 - projection of the transversal wire (T) on the longitudinal plane; 3 – the transversal cross-sectional plane of the composite; 4 - projection of the longitudinal wire (L) on the transversal plane.

In the Type 45 composite, the net elongation factor is not proportional to the wire elongation factor. They are related via changing of cell angle. The net cell elongation factor $\mu_c$can be defined with a help of the scheme, presented in Fig. 3.

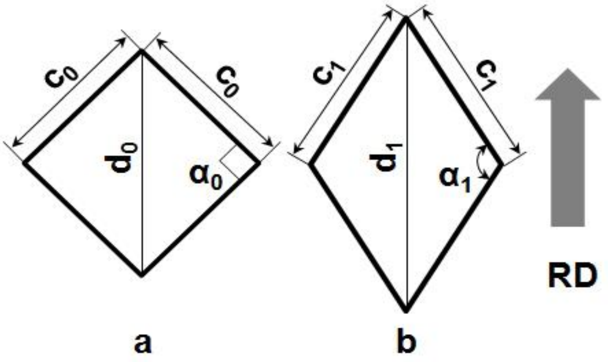

Figure 3 – Scheme for calculation of the net cell elongation factor for the net oriented diagonally to the rolling axis: a – net cell before rolling; b – net cell after rolling; c_0, d_0 and α_0 – respectively, initial edge length, diagonal length and cell angle; c_1, d_1 and α_1 – respectively, edge length, diagonal length and cell angle after rolling.

According to Fig. 3: $c_1 = c_0 \times \mu_w^{45}$; where: μ_w^{45} – the elongation factor of the wires in Type 45 sandwiches. $\mu_w^{45}$was calculated from the measured wire contraction in cross sectional planes. The length of diagonal d_1 can be calculated using the edge length c_1 and an angle α_1 measured after the etching. The net cell elongation factor μ_c is equal to the ratio d_1/d_0. Because the above mentioned local deformation in the wire intersections is omitted during calculations, the net cell elongation factor is overestimated by to 5-%-8%.

For the analysis of the mechanical properties, the standard (EN 6892-1:2009) samples for uniaxial tensile tests were cut from the composite in as-rolled condition, i.e. without heat treatment, along the rolling direction using spark erosion cutting. Three samples with the width of the machined part of 12.5 mm and the width of the gripped ends for the machine clamps equal to 18 mm were sampled from the composite strips for each condition. The tensile tests were carried out on the universal hydraulic testing machine MTS Landmark 250 using a tension speed of 4 mm/min. As a result, the yield strength $R_{0,2}$, the tensile strength R_m as well as two types of elongation at fracture, $A_{5(Rm)}$ and A_5, were measured for each specimen. $A_{5(Rm)}$ – is a calculated value reflecting the sample non-proportional elongation at maximal stress; A_5 – is a measured total sample elongation after the test. For every condition, the mean values of the properties measured from three specimens were taken for further analysis. Images of the samples' length during tension were also taken in equal time intervals using a digital high-speed camera.

3. Results

3.1. General results. The explicit delamination of the sandwiches during the roll bonding process, as well as at the outlet of the rolling stand were not observed for the whole range of experiments. During the rolling, the wires rather uniformly filled the length and width of the composite strips. No visible breaks or gaps were detected. The chemical removal of one of the matrix layers revealed that the net cells inside the composite were unevenly deformed (See Fig. 4). Thus for the Type 90 reinforcement, the visible substantial bending of transversal wires in the central part of the composite, as well as uneven increase in the distance between them was noticed. (Fig. 4a). The analysis of the transversal wire distortion showed that the thicker “A”-netting is more inclined to bending than the thinner-wire “B”-netting.

At the same time, rolling sandwiches with AW-5056 matrix at a temperature of 500°C results in less wire bending than the rolling of sandwich with AW-6063 matrix at 200°C. The increase of the strain in the investigated range predictably leads to the increased bend in transversal wires. The angle between the wires (See Fig. 4b) in the Type 45 composite changed during rolling, but the wire contraction was still less than the Type 90 composite.

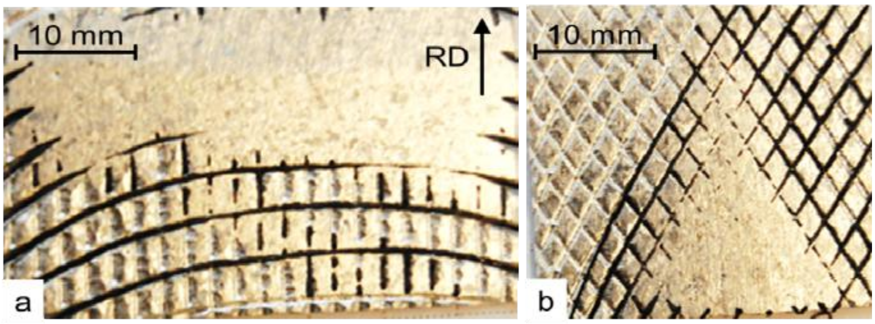

Figure 4 – Examples of the net distortion in Type 90 (a) and Type 45 (b) composites after rolling: RD – rolling direction.

Analysis of the net wires intersection area in Type 45 composite (See Fig. 5b) shows that zones of a localized intensive deformation can be detected near these intersections. Their appearance is caused by wire-to-wire compression and by the simultaneous movement of these intersections towards the rolling direction due to the axial tension and elongation of the whole composite.

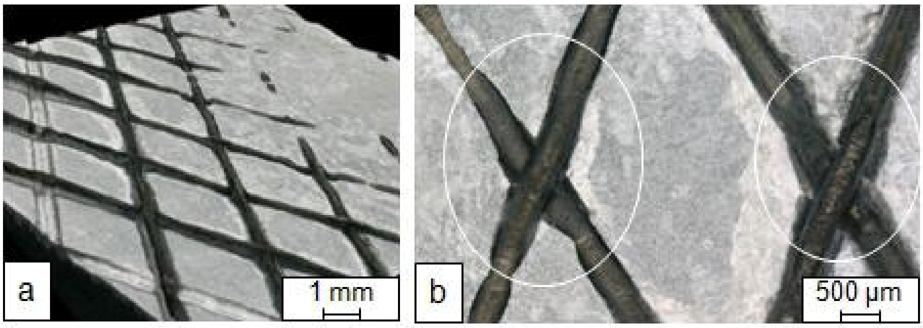

Figure 5 – 3D reconstruction of the net (a) and the intersections of the net wire (b) inside the rolled Type 45 composite. Marked areas – zones of the localized intensive deformation.

The digital microscope image presented in Fig. 5a is a 3D reconstruction of the net inside the rolled Type 45 composite. Thus, rolling with a 30% nominal reduction, the maximal deviation of the intersection angle α_1 from α_0 in ”A”-net was 12° and 13° for composites with AW-5056 and AW-6063 matrices respectively. For the “B”-net, these values were equal to 16° for the both matrix materials. For the composite with AW-6063 matrix, rolled in two passes, the intersection angle α changed on 32° for the both net types.

3.2. *Roll bonding of sandwiches with AW-5056 matrix*. The main measured and calculated strain parameters of this roll bonding series are presented in Table 2.

Table 2 – The strain parameters of rolling sandwiches with AW-5056 matrix.

Experiment code*	e_h	e_b	e_l	μ_Σ	μ_c	μ_w^{45}	μ_{wL}^{90}	μ_{wQ}^{90}	O_w^{45}	O_{wL}^{90}	O_{wT}^{90}	F_w, %
5056-A-90-30	-0.32	0.03	0.28	1.28	-	-	1.44	1.08	-	1.13	1.07	2.90
5056-A-45-30	-0.38	0.07	0.34	1.37	1.49	1.36	-	-	1.15	-	-	3.29
5056-B-90-30	-0.37	0.07	0.31	1.35	-	-	1.13	1.02	-	1.1	1.04	1.14
5056-B-45-30	-0.38	0.09	0.33	1.37	1.38	1.21	-	-	1.08	-	-	2.73
5056-0-0-30	-0.37	0.06	0.35	1.35	-	-	-	-	-	-	-	-

Legend to Table 2:
* - The experiment code is: the type of the matrix alloy - net type - sandwich type - nominal reduction at rolling;
e_h, e_b, e_l – true logarithmic strain over the height, width and length of the sample, respectively;
μ_Σ – elongation factor of the whole composite;
μ_c – elongation factor of the net cell;
μ_w^{45} – wires elongation factor in Type 45 composite;
μ_{wL}^{90} – longitudinal wires elongation factor in Type 90 composite;
μ_{wT}^{90} – transversal wires elongation factor in Type 90 composite;
O_w^{45} – wires ovalization after rolling in Type 45 composite;
O_{wL}^{90} – longitudinal wires ovalization after rolling in Type 90 composite;
O_{wT}^{90} – transversal wires ovalization after rolling in Type 90 composite;
F_w,% – part of the composite cross-section filled by the wires. It is calculated as a ratio of wires projections areas (Fig. 2, Pos. 4) to the area of the composite cross section (Fig. 2, Pos. 3).
The true values of the elongation factor for the transversal wires μ_{wT}^{90} are 2...4% lower, while the values of ovalization O_{wT}^{90} are overestimated due to the fact that these wires bent during the rolling and intersect the longitudinal plane at the angles that slightly differ from 90° (See. Fig. 4a).

The analysis of the rolling results shows that while straining of transversal wires in the Type 90 composite almost did not occur, the longitudinal wires were intensely strained. The elongation factor of the longitudinal wire μ_{wL}^{90} which exceeds the elongation factor of the whole composite μ_Σ indicates additional localized deformation in net knots. In the case where the elongation factor of the longitudinal wires μ_{wL}^{90} is considerably smaller than the composite elongation μ_Σ, such as in specimen 5056-B-90-30, wires breakage inside the sandwich could be indicated. These assumptions were confirmed by the subsequent sample etching revealing the net structure. This may be caused by the embrittlement of the stainless steel wire during the heating at a temperature of 500 °C.

The smaller values of the wire elongation factor for the Type 45 sandwich μ_w^{45} are compensated for by altering the wire's intersection angle. The angle changed to 12° in the experiment 5056-A-45-30 which, together with the wire elongation factor μ_w^{45}

= 1.36, enabled net cell elongation factor results of μ_c = 1.49. The latter is greater than the elongation factor of the whole sandwich μ_Σ = 1.37.

The net cell elongation factor for the experiment 5056-B-45-30 μ_c was equal to 1.38, which is larger than the elongation factor for the entire sandwich μ_Σ. This finding indicates that there is a is relatively low probability of wire breakage in this sandwich. Furthermore, this probability is lower in specimens with a “A”-net, than in those with a “B”-net. Despite the elongation factor of the net cells μ_c = 1.38 being greater than the total elongation factor of the sandwich μ_Σ = 1.37, the wires’ fracture during rolling even occurred in the Type 45 sandwich. However, the development of methods for a quantitative evaluation of wire fracture probability may be the purpose of further research.

Using the same initial roll gap, the lowest reduction was achieved while rolling Type 90 and Type 0 sandwiches. The highest reduction resulted from rolling Type 45 sandwiches. This indicates that the diagonally oriented net promotes the metal flow in the core layer of the sandwich by reducing internal friction. This effect is greater for the thinner wires (“B”-net). The sandwich with smaller cells, thinner wires and a diagonal net orientation also show a greater widening when compared to specimens with a longitudinally oriented “A”-net. However, it should be noted that the widening in this experiment was insignificant.

3.3. Single-pass roll bonding of sandwiches with AW-6063 matrix. The main strain parameters of this rolling series are presented in Table 3.

Table 3 – Strain parameters of rolling sandwiches with AW-6063 matrix with a nominal reduction of 30%*.

Experiment code	e_h	e_b	e_l	μ_Σ	μ_c	μ_w^{45}	μ_{wL}^{90}	μ_{wQ}^{90}	O_w^{45}	O_{wL}^{90}	O_{wT}^{90}	F_w, %
6063-A-90-30	-0.36	0.04	0.32	1.37	-	-	1.68	1.3	-	1.25	1.04	2.51
6063-A-45-30	-0.35	0.05	0.33	1.35	1.49	1.35	-	-	1.11	-	-	4.35
6063-B-90-30	-0.36	0.03	0.34	1.39	-	-	1.24	1.05	-	1.08	1.09	0.91
6063-B-45-30	-0.36	0.04	0.34	1.38	1.45	1.27	-	-	1.1	-	-	3.51

* - for legend see Table 2.

A more intensive deformation of wires can be seen in this experimental series than with the composites based on AW-5056. Thus, the calculated stretching and ovalization of wires have higher values. In all cases, the elongation factor of wire μ_w, including extension of cells in Type 45 sandwiches, was greater than the total elongation factor of the entire sandwich μ_Σ. This finding indicates that the wires in the sandwich were not broken. The larger strain, compared to sandwiches with an AW-5056 matrix, can be explained by the favourable temperature range for the wires deformation. For the wire material, an austenitic stainless steel, the deformation occurs in a range of temperatures around 200 °C, referred to as warm rolling [12]. In Type 45 sandwiches, the cells’ diagonal length increased due to the cell transformation from a square form to rhombus. The amounts increased by 1.49 and

1.45 times for the “A”-net and “B”-net respectively. The probability of wire fracture in this case was minimal. Nevertheless, it is important to pay attention to minor differences between part of the “A”-net and “B”-net wires in the cross-sectional area of Type 45 composites.

3.4. ***Two-pass roll bonding of sandwiches with AW-6063 matrix***. The rolling was carried out in two passes with 30% of nominal reduction in the first pass and the total nominal reduction of 60% after two passes. Strain parameters for this experimental series are presented in Table 4.

Table 4 – Strain parameters of rolling sandwiches with AW-6063 matrix in two passes with a total nominal reduction of 60%*

Experiment code	e_h	e_b	e_l	μ_Σ	μ_c	μ_w^{45}	μ_{wL}^{90}	μ_{wQ}^{90}	O_w^{45}	O_{wL}^{90}	O_{wT}^{90}	F_w, %
6063-A-90-60	-0.74	0.10	0.69	1.90	-	-	2.38	1.06	-	1.58	1.28	4.91
6063-A-45-60	-0.73	0.09	0.68	1.89	2.56	2.07	-	-	1.47	-	-	4.00
6063-B-90-60	-0.81	0.09	0.74	2.06	-		1.65	1.03	-	1.29	1.04	1.80
6063-B-45-60	-0.81	0.10	0.75	2.04	1.4	1.13	-	-	1.26	-	-	5.79
6063-0-60	-0.88	0.10	0.81	2.19	-	-	-	-	-	-	-	

* - for legend see Table 2.

During the rolling process, the “B”-net was unable to withstand the high strain at rolling and fractured as a result. This can be seen in the ratio between the elongation factors of the net and composite, as well as from part of net in a cross-section of the sandwich. Two-pass rolling showed a significant difference in the final size of the samples rolled with the same roll gap. The sandwiches without a net were most significantly deformed. Thus, the final thickness of Type 0 composite without the net-reinforcement was 13% less than sandwiches reinforced with “A”-net. Sandwiches with a “B”-net behaved like a non-reinforced composite in that the broken net didn’t hinder the metal flow during rolling.

3.5. Results of tensile tests. Sandwiches with AW-5056 matrix.

Stress-strain curves obtained as a result of tensile tests of this composite type are plotted in Fig. 6. The best mechanical properties among the net-reinforced sandwiches were achieved by testing the 5056-A-45 composite. In this composite however, elongation at fracture was lower than the non-reinforced strip 5056-0-30. The reinforced composite 5056-B-45 showed slightly lower yield and tensile strength than 5056-A-45, and at the same time possessed a better ductility, which is comparable to one of the non-reinforced strips. It is worthy to note that the advanced properties of the sandwiches with a “B”-net-reinforcement were obtained despite the partial fracture of the reinforcing wires during rolling, as indicated by the elongation factor μ_{wL}^{90} which was smaller than μ_Σ (See Table 2). Testing of Type 90 composites revealed their relatively low properties: the ultimate tensile strength and elongation at fracture cannot reach the same characteristics measured in the non-reinforced 0-Type strip.

Figure 7 shows images of the samples taken during tensile testing directly prior to and after fracture. Based on an observation of composite samples during tensile testing, the mechanism of their fracture was established. It develops in the following sequence:

1. Fracture of a single layer of the composite
2. Delamination of the composite layers
3. Fracture of the second layer of the composite

In this case, the delamination may be limited inside the area of one or several net cells and does not occur throughout the sample length (See Fig. 7d).

3.6. Single-pass rolled sandwiches with AW-6063 matrix. The testing of the composite with AW-6063 matrix, rolled in one pass, showed that its strength and ductility are not strongly dependent on the type and orientation of the reinforcing wire (See Fig. 8). The composite reinforced with a thicker "A"-net is generally stronger. Additional strength can be achieved by means of longitudinal (Type 90) net-reinforcement.

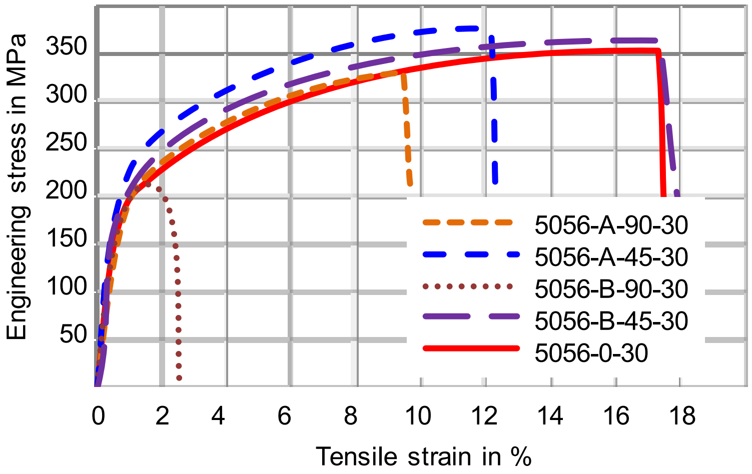

Figure 6 – Stress-strain curves of composites with AW-5056 matrix

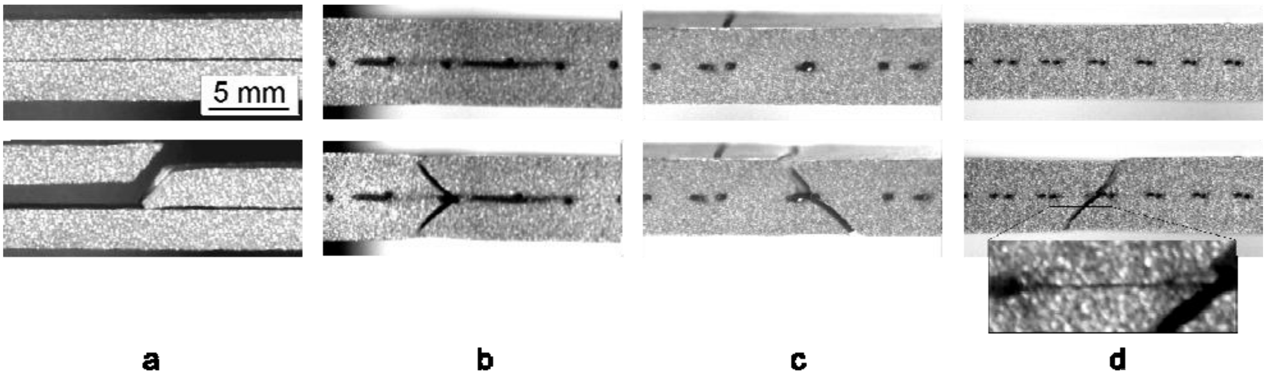

Figure 7 – The images of the composite with AW-5056 matrix taken during tensile tests directly before (upper picture) and after (lower picture) the fracture: a – Type 0; b – Type 90, "A"-net; c - Type 45, "A"-net; d - Type 45, "B"-net.

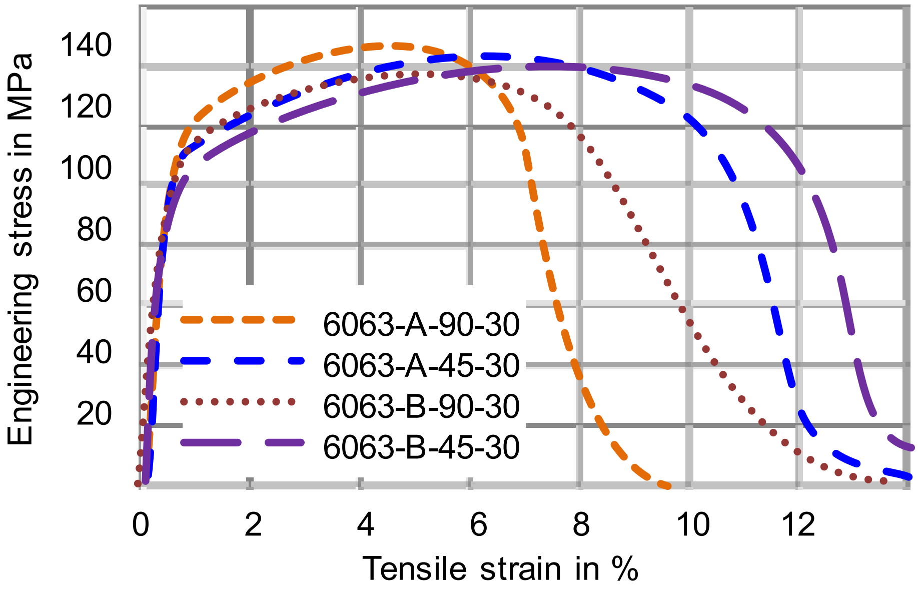

Figure 8 – Stress-strain curves of composites with AW-6063 matrix

Contrary to the sandwiches with an AW-5056 matrix, an analysis of the fracture mechanism in the AW-6063 matrix composite shows that under the initial tensile loading, the delamination of matrix layers occurs prior to fracture (See Fig. 9).

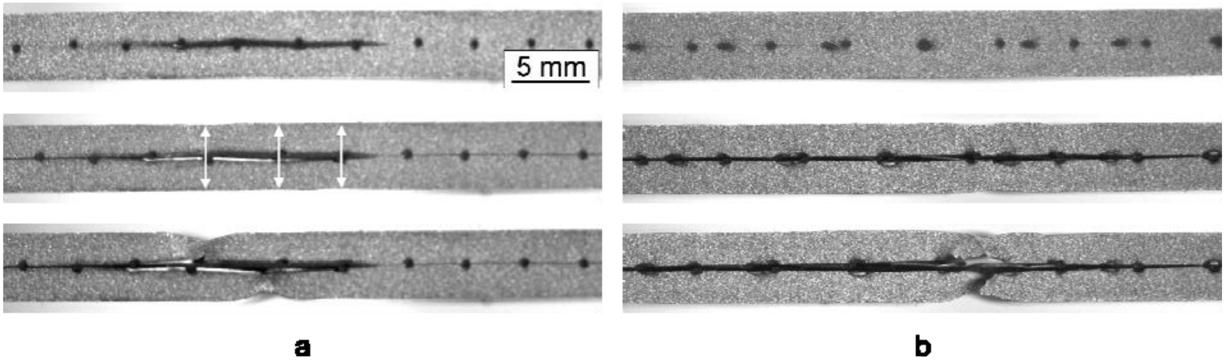

Figure 9 – The images of the single-pass rolled composite with AW-6063 matrix, made during tensile tests prior to their fracture: a – Type 90, "A"-net (the arrows indicate the necking places of the aluminium matrix); b – Type 45, "A"-net.

Thus, the thinning of the aluminium matrix in Type 90 composite occurs at the location of the transversal wires which serve as stress concentrators, especially after the complete delamination of the composite. In Type 45 composites the role of stress concentrators playsnet knots.

Two-pass rolled sandwiches with AW-6063 matrix. An analysis of tensile tests results show that all reinforced Type 45 composites, when compared to non-reinforced composites, have slightly higher tensile strength values (See Fig. 10). In terms of reinforcing nets, the comparison of Type 45 composites shows that the sandwiches with "A"-net-reinforcement have higher yield strength, and the ones reinforced with "B"-net have higher ductility values. The strength and ductility of Type 90 composites are 10%-15% and 35%-50% below this level, respectively.

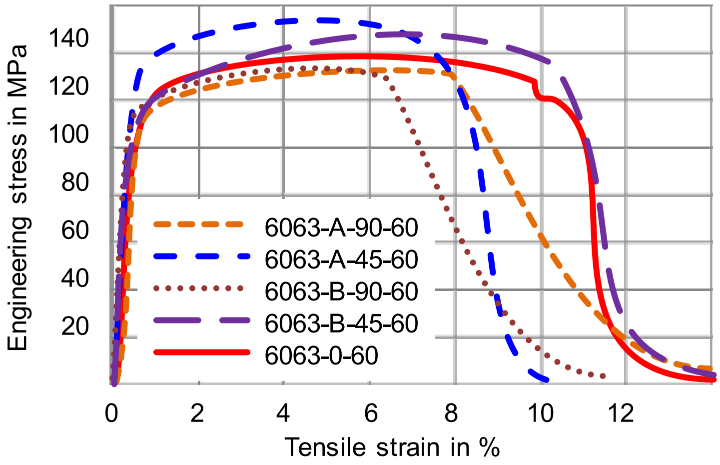

Figure 10 – Stress-strain curves of composites with AW-6063 matrix rolled in two passes

The images captured prior to the fracture of tensile samples (See Fig. 11) show that rolling in two passes provided the solid compound of aluminium matrix layers with a proper bonding between them. There was no significant delamination observed in any test performed.

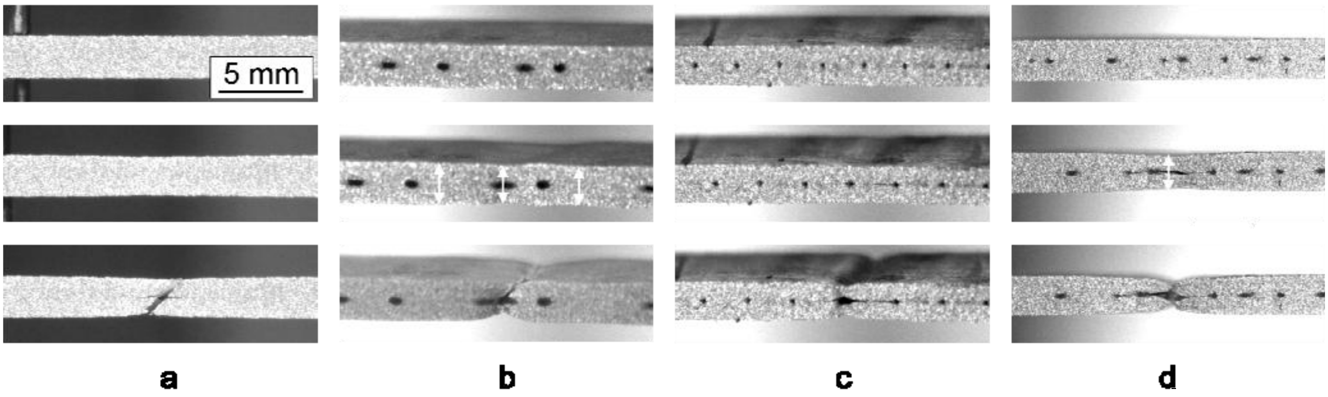

Figure 11 – Images of two-pass rolled composites with an AW-6063 matrix taken during tensile tests prior to the fracture (the arrows indicate the necking places of aluminium matrix): a - Type 0; b –Type 45, “A”-net; c – Type 90, “B”-net, d – Type 45, “B”-net.

The main feature of the Type 45 composite, observed at its fracture, is a multiple necking of the sample in the zones between net knots. Due to a strong bonding between the matrix and reinforcing wires, these wires impede strain development. It is also important to note that only a limited delamination in the Type 0 composite was observed, while no delamination was observed in the reinforced Type 45 composite.

4. Discussion

The fact that visible delamination after deformation was not observed suggests the possibility of producing the net-reinforced composites with a matrix of the studied alloys by means of roll-bonding at temperatures of 200-500°C, with a total reduction of about 30%.

It was established that the reduction in these roll bonding experiment is limited by the strength of the reinforcing wire.

The error in the determination of the logarithmic strain was 0.04%-4.63%, caused by the unavoidable inaccuracy in the measuring of the composite length after rolling.

The error in the determination of the elongation factor, wire ovalization and change of cross-sectional area is estimated as ± 3%.

For the majority of experiments, stretching was the main type of wire deformation observed. However, a local reduction of the wires' cross sectional area is observed in the knots of their intersection, particularly for the "A"-net. The relation of ovalization (flattening) to the stretching of the wires depends on the parameters of the deformation zone at rolling. In particular, it depends on the reduction and rolls diameter. The application of netting without intersecting knots can be a purpose for further research.

The "A"-net was most intensely deformed in the Type 45 composite. To avoid wire fracture in this type of composite, the elongation factor of cell diagonal μ_c should be directly correlated with a total elongation factor of the composite μ_Σ. If the total elongation factor of the composite μ_Σ is higher than the elongation factor of cell diagonal μ_c, then there is a high probability of wire fracture. Furthermore, even if the elongation factor of cell diagonal μ_c is the same or slightly higher than composite μ_Σ, the probability of breakage remains. The balance of these factors requires further clarification. The probability of wire fracture can be estimated as the correlation of the elongation factors of composite and wires, considering a maximum possible elongation for the material of current wire.

Longitudinal wires assume the main deformation in the Type 90 composite. The elongation factor of wire μ_{wL}^{90} should be directly correlated with the elongation factor of the composite μ_Σ to predict the possible fracture of these wires.

In the "A"-net, the strain of longitudinal wires of the Type 90 composite is 29%-33% higher than the strain of transversal wires, and does not depend on the matrix material and reduction in the conducted experiments. This difference is about 10%-60% for the "B"-net.

Wire ovalization largely depends on reduction at roll bonding. The ovalization of transversal wires in the Type 90 composite is minimal; a moderate ovalization was observed in the wires of Type 45 composite; and the maximum of this criterion was reached by the longitudinal wires in Type 90 composite.

Deformation of transversal wires in the Type 90 composite occurs mainly due to bending in the rolling direction. The ovalization of transversal wires was negligible for the majority of experiments.

The Type 90 composite showed unsatisfactory results at the tensile tests. It could be related to the exhaustion of plastic properties of the longitudinal wires at rolling, and also to the fact that transversal wires serve as stress concentrators under the tension.

Type 45 composite showed the best results in the tensile tests due to the low stretching of wires at rolling.

Comparison of obtained results with calculated theoretical strength value for reinforced composites shows that the latter was reached only once. The single composite showing so high performance was 5056-A-45-30. The theoretical strength was calculated proportionally to the part of composite cross-section filled by the wires (F_w) taking into account estimated tensile strength of wire equal to 900 N/mm^2 using the formula described in [13]. In Fig. 12 the chart showing the ratio of obtained strength (R_m) to theoretical ($R_{m(T)}$) strength of rolled composites is presented. The reasons for not reaching of the theoretical values during the experimental investigations seem like a chain of following fails: stress concentration in the net knots as well as near transversal wires; delamination; premature breakage of wires and split of matrix with reinforcement due it`s geometrical distortion.

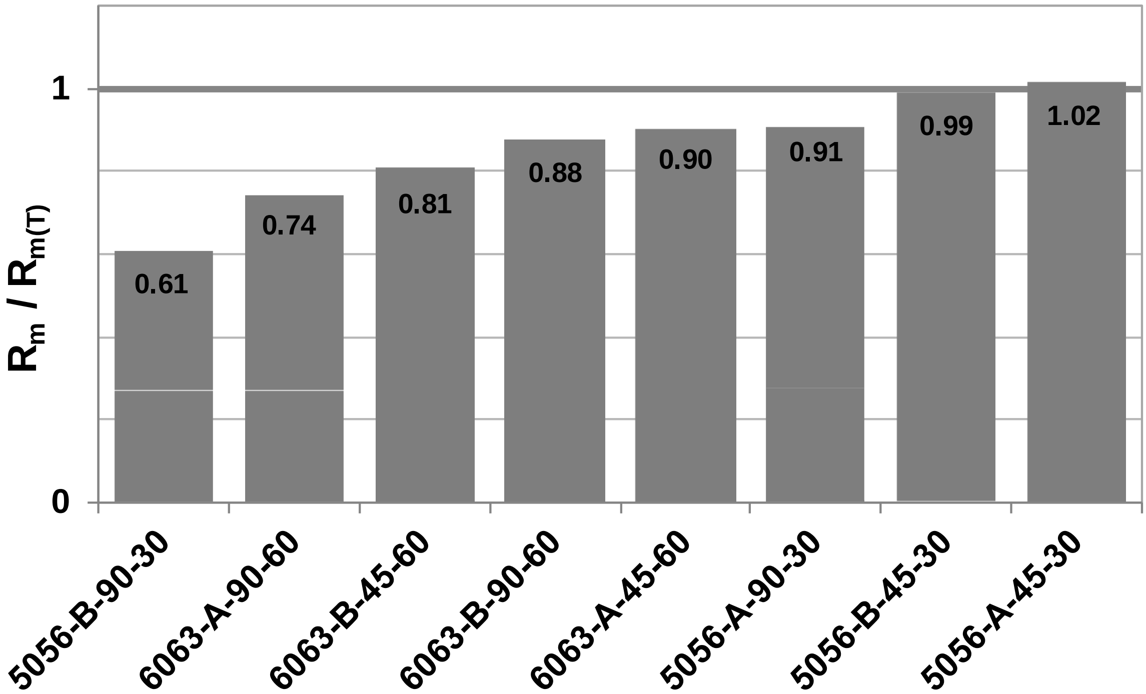

Figure 12 – Ratio of obtained strength (R_m) to theoretical ($R_{m(T)}$) strength of rolled composites

Wire fracture at rolling reduces the mechanical properties of the whole composite. However in some cases, it also improves mechanical properties when compared to non-reinforced composites. This suggests that composite's strengthening results from the net-reinforcement as well as from the local hardening of the aluminium matrix induced by wires.

Depending on the wire distribution in the composite cross-section and on the bonding strength in matrix-matrix and matrix-reinforcement interfaces, the fracture of composite occurs by the following mechanisms:

Delamination → Fracture of layers (D-F). This mechanism occurs when the composite has a low bonding strength in a matrix-matrix system, and also a relatively small part of wires in the cross section of the composite (Fig. 13).

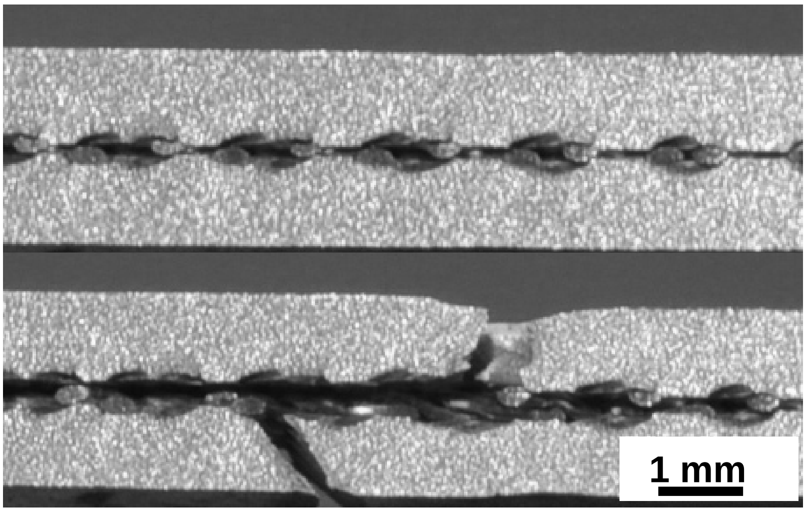

Figure 13 – Example of “D-F” mechanism at composite`s tension

Fracture of the first layer → Limited delamination → Fracture of the second layer (F1-D-F2). This mechanism is characteristic of the composite, in which the part of transversal wires (relative to the tension axis) is small and the bonding strength between matrix and reinforcement is higher than that between the matrix layers. In this case, at the elastic return of the destroyed first layer, the reinforcement “splits” the composite layers (Fig. 14).

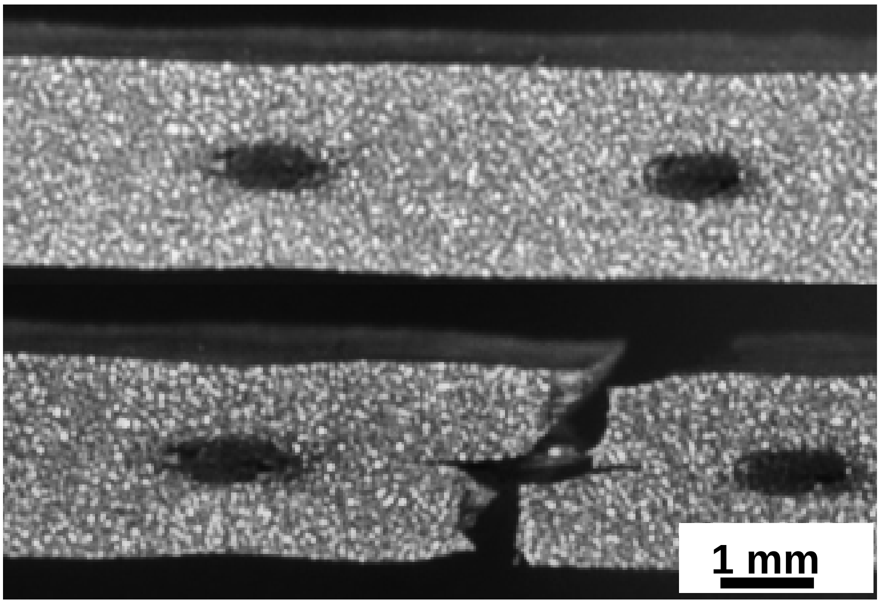

Figure 14 – Example of “F1-D-F2” mechanism at composite`s tension

Fracture without delamination (F). This mechanism is characteristic to the composite with a high bonding strength in a matrix-matrix and matrix-reinforcement interfaces as well as with a large part of wires in the cross section (Fig. 15).

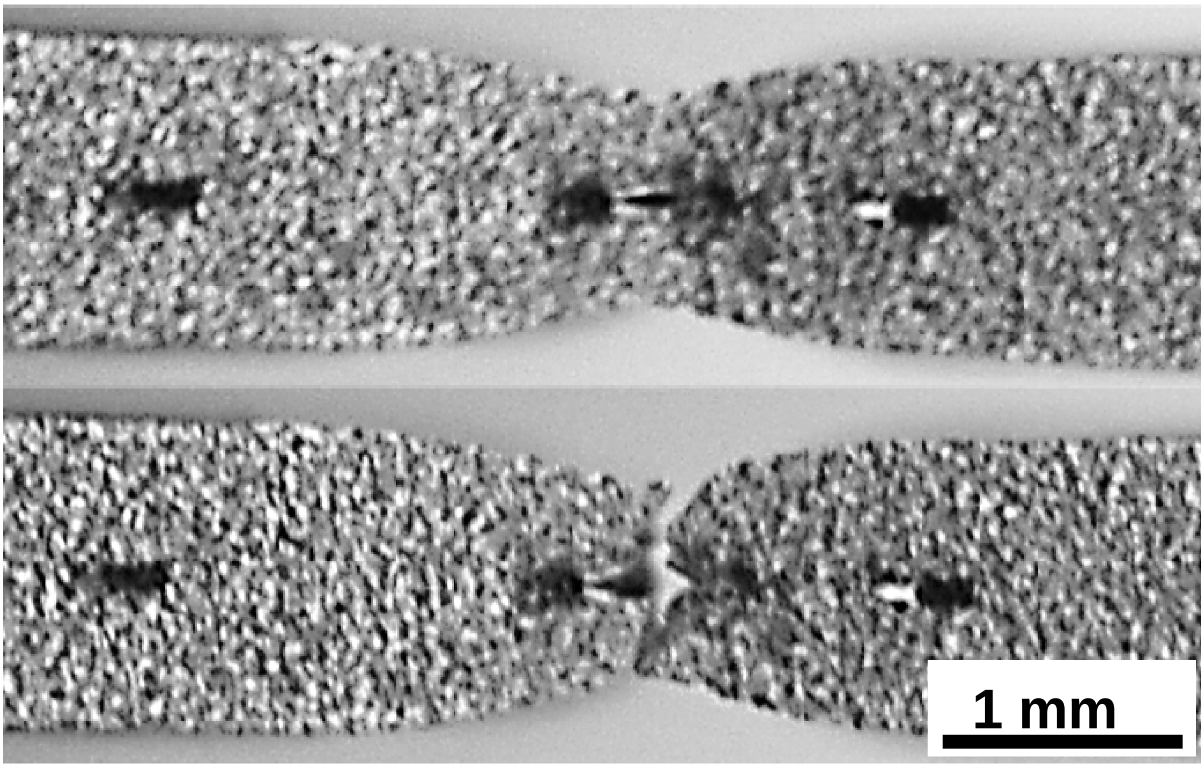

Figure 15 – Example of “F” mechanism at composite`s tension

These three main mechanisms change each other within development of rolling stresses.

6. Conclusions and outlook

Improving properties of net-reinforced composites is limited due to an accumulation of tensile strain on wires while rolling. Consequently, when combined with an additional localized intensive compression on the net knots, this effect leads to wire fracture and to an induced longitudinal tensile stress on the entire composite. Thus, there is a contradiction between the strain required for proper bonding of matrix layers (at a given temperature) and stress, induced by that strain, which causes excessive tension on reinforcement wires. The most favorable results in the longitudinal tensile tests were obtained using specimens with a reinforcing net placed diagonally to the rolling axis. On our opinion, a longitudinal orientation of wires is useless and a transversal orientation is dangerous due to the concentration of stress. Parameters of the deformation zone while rolling play a significant role in the distortion of wires inside the composite. The three types of composite fracture were detected. Each of them depends on own composition of followed factors: the part of wires in a cross section of the composite, properties of the wires, orientation of the wires to the rolling axis, 4) properties of the matrix, 5) bonding strength on the net-matrix and matrix-matrix interfaces.

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Анотація. Статтю присвячено дослідженню технологічного процесу армування алюмінієвих листів дротом для підвищення надійності обладнання для комплексної підготовки газу. Скорочення працюючих вугільних шахт, змушує більше уваги приділяти газовим і газоконденсатним родовищам. Перед подачею газу в трубопровід його обов'язково очищають від різних домішок на спеціальних установках комплексної підготовки газу. Застосовувана для цих цілей апаратура сепарації, абсорбції або адсорбційні колони та інше обладнання повинні бути зносостійкими, легкими і витримувати високі навантаження. Такими властивостями володіють армовані сіткою листи алюмінію. Актуальною є задача вдосконалення технології отримання таких листів з метою поліпшення якості та зменшення вартості виробів. У статті представлені результати експериментальних досліджень параметрів деформації прокатки алюмінієвої матриці, коли дротова сітка вставлена між шарами алюмінію. Під час експерименту два типи сітки з нержавіючої сталі, орієнтовані паралельно і по діагоналі вздовж осі прокатки, містилися між двома алюмінієвими смужками і прокатувалися. Проводилися процеси прокатки, в яких температура і тиск на матеріал змінювалися для зв'язування матричних шарів. Це дослідження присвячене виміру деформації на ділянках поздовжнього і поперечного перерізу; розтягування і овалізації сітки; виміру змін в сітчастих кутах осередку; і випробуванню механічних властивостей композитів вздовж напрямку прокатки. Основне протиріччя, що випливає з цього експерименту, полягала в наступному: контактний тиск, необхідний для з'єднання шарів алюмінію, створює екстремальну розтягувальну деформацію на вставлених сітчастих проводах, зменшуючи механічні властивості армуючої сітки і, таким чином, зменшуючи властивості всього композиту. Оптимальні результати в тестах поздовжнього натягу були досягнуті з використанням смуг з діагонально орієнтованої сіткою. Дослідження, результати яких наведені в даній статті, виконані в рамках спільного німецько-українського проекту «Praxispartnershaft Metalurgie», що фінансується німецьким товариством академічних обмінів DAAD.

Ключові слова: алюмінієва матриця, сталева сітка, армування, прокатка, відшарування, механічні властивості.

Аннотация. Статья посвящена исследованию технологического процесса армирования алюминиевых листов проволокой для повышения надежности оборудования для комплексной подготовки газа. Сокращение работающих угольных шахт, вынуждает больше внимания уделять газовым и газоконденсатным месторождениям. Перед подачей газа в трубопровод его обязательно очищают от различных примесей на специальных установках комплексной подготовки газа. Применяемая для этих целей аппаратура сепарации, абсорбционные или адсорбционные колонны и другое оборудование должны быть износостойкими, легкими и выдерживать высокие нагрузки. Такими свойствами обладают армированные сеткой листы алюминия. Актуальной является задача совершенствования технологий получения таких листов с целью улучшения качества и уменьшения стоимости изделий. В статье представлены результаты экспериментальных исследований параметров деформации прокатки алюминиевой матрицы, когда проволочная сетка вставлена между слоями алюминия. Во время эксперимента два типа сетки из нержавеющей стали, ориентированные параллельно и по диагонали вдоль оси прокатки, помещались между двумя алюминиевыми полосками и прокатывались. Проводились процессы прокатки, в которых температура и давление на материал изменялись для связывания матричных слоев. Это исследование посвящено измерению деформации на участках продольного и поперечного сечения; растяжению и овализации сетки; измерению изменений в сетчатых углах ячейки; и испытанию механических свойств композитов вдоль направления прокатки. Основное противоречие, вытекающее из этого эксперимента, заключалось в следующем: контактное давление, требуемое для соединения слоев алюминия, создает экстремальную растягивающую деформацию на вставленных сетчатых проводах, уменьшая механические свойства армирующей сетки и, таким образом, уменьшая свойства всего композита. Оптимальные результаты в тестах продольного натяжения были достигнуты с использованием полос с диагонально ориентированной сеткой. Исследования, результаты которых приведены в данной статье, выполнены в рамках совместного немецко-украинского проекта «Praxispartnershaft Metalurgie», финансируемого немецким обществом академических обменов DAAD.

Ключевые слова: алюминиевая матрица, стальная сетка, армирование, прокатка, отслоение, механические свойства

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