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PROSPECTS OF INCREASING THE STRENGTH OF ALUMINUM BY REINFORCING IT WITH STAINLESS STEEL WIRE. (A REVIEW)

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The theoretical and experimental strength of aluminum reinforced with stainless steel wire is analysed. Various methods of producing the composite material and it's static and cyclical strengths are considered. The reinforcement of aluminum with stainless steel wire was accomplished from the perspective of increasing the specific strength of aluminum and it's alloys, increasing the strength of the material with respect to high and low temperatures, as well as increasing the cyclical strength. The production of the composite aluminum-stainless steel wire material with approximated or calculated strenghtening is possible by any of the considered methods. The selection of the proper production technology depends on precise details and conditions of application of the material.

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PROSPECTS OF INCREASING THE STRENGTH OF ALUMINUM BY REINFORCING IT WITH STAINLESS STEEL WIRE (A REVIEW)

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The theoretical and experimental strength of aluminum reinforced with stainless steel wire is analyzed. Considered are various methods of producing the composite material (hot rolling, hot pressing, casting, blast loading) and its static and cyclical strengths. /57*

The reinforcement of aluminum with stainless steel wire was accomplished from the perspective of increasing the specific strength of aluminum and its alloys, increasing the strength of the material with respect to high and low temperatures, as well as increasing the cyclical strength. The production of the composite aluminum-stainless steel wire material with approximated or calculated strengthening is possible by any of the considered methods. The selection of the proper production technology depends on precise details and conditions of application of the material.

Of the composite metal-metal materials currently under development, aluminum reinforced with stainless steel wire receives particular attention. This is due to a number of reasons.

Aluminum is, after iron, the second most frequently utilized metal as a construction material. In the last 10-15 years, it was possible to significantly increase its strength by alloying. It's sufficient to point out that the strength of multicomponent aluminum alloys has today reached 60 - 70 kg/mm^2. However, the cyclical strength, an extremely important characteristic of a material only increased about 2 kg/mm^2 while the limits of strengthening for alloys increased from 30 to 70 kg/mm^2, which is apparent from the data presented in Fig. 1 [1]. This leads to the conclusion that increasing the structural

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* Numbers in margin indicate pagination in foreign text.

strength of aluminum via alloying does not provide a pronounced effect, and that it pays to seek new methods of increasing the static and cyclical strengths of aluminum alloys. Some favorable results were attained by strengthening aluminum by dispersing Al_2O_3 particles (SAP -sintered aluminum powder), especially with respect to the /58. increasing of corrosion resistance and temperature ceilings of aluminum based materials. However, under normal temperatures, with respect to strength and plasticity, SAP is inferior to high-strength aluminum alloys [2]. One of the prospective means of further increasing of strength and heat resistance of aluminum is the reinforcement of aluminum with high-strength fibers, filamentary ceramic crystals, or metallic wires.

This article examines the theoretical and experimental strength of aluminum reinforced with stainless-steel wire. Selection of stainless steel as the reinforcing material was occasioned by the fact that it has high strength and sufficiently high plasticity. Use of low-plasticity wire results in fragmentation of the filaments as early as under conditions of low deformation of the matrix, thus sharply reducing the strength of the composite material, especially if a low fiber volume exists. Additionally, low plasticity gives rise to a number of technological difficulties during the production of the composite material.

Today, stainless steel wire with strength limits between 200-350 kg/mm^2 is available. Thiallows the creation of materials whose specific strength is higher than that of the best aluminum and titanium alloys. Figure 2 depicts the calculated strength diagrams for aluminum-stainless steel wire composite material at various limit values for wire strength (from 50 to 350 kg/mm^2). The strength limit of the composite material σ_c is placed on the ordinate axis, whereas the volume proportion of filament V_f is on the abcissa. The magnitude of σ_c is calculated by the formula:

$$\sigma_c = \sigma_f V_f + \sigma_m^*(1 - V_f) \quad (1)$$

where σ_f is the wire strength limit and σ_{m*} is the tension in the matrix at the moment that the filament bursts.

During the calculation of the magnitude σ_{m*}, the equal flow limit of aluminum (3kg/mm^2) was obtained. The initial sectors of the strength diagram are shown on a larger scale in the upper corner of the figure. From the diagram one can see that when V_f = 60%, the strength of pure aluminum reinforced with wire of strength limit of 350 kg/mm^2 is greater than 200 kg/mm^2. Moreover, the specific strength of such a material is equal to 40 · 10^{6}mm (compared to 26 · 10^{6}mm for the best aluminum alloys. /59.

Introduction of the stainless steel wires into the aluminum may be accomplished by the following means: 1) powder mettallurgy, 2) hot rolling, 3) hot pressing, 4) casting, and 5) burst force. D. Cratchley [3] produced reinforced aluminum with sufficiently strong bonds on the filament - matrix boundary by the powder metallurgy method. The entire method of material production may be shown by the following diagram:

Filament Cleaning with 1% HCl solution	—	Degreasing in Acetone	→	Acceptance of filament for application
Filaments and Aluminum Flakes Introduced into Mold	→	Orientation of Filaments	→	Pressing in Steel Mold T = 450°C Pressure = 8.4 kg/mm^2

To reinforce the material, wires of varying diameter from 50 to 127 microns were employed.

During the testing of the produced material's strength, with V_f = 5 ÷ 15%, experimental data correlated well with calculated ones. This indirectly indicates that the technology applied provides good bonding on the filament - matrix boundary. However, this production method also entails major difficulties during the formation of a structure with the required orientation. From this point of view, hot rolling is more effective. To bond the filaments to the matrix, it is necessary to conduct the rolling of the composite in a vacuum or in an inert atmosphere.

As the testing indicated, it is possible to receive a composite with satisfactory bonding on the boundary separating the filaments and the matrix via hot rolling in vacuum and favorable rolling stage selection. The technology of preparing the composite material is described in the following: "Sandwiches", consisting of altrnating layers of aluminum foil and aluminum sheet stock with circ coiled around it (Fig. 3.) are placed in an aluminum foil jacket, whose seams have been welded shut in a vacuum. Then, hot rolling in stages selected to insure maximal bonding strength is carried out.

P. Forsyth and others [4] utilized a hot rolling method to re- /60. inforce aluminum alloys with composite webbing, plaited from various types of wires: from stainless steel (longitudinal wires) and from aluminum alloy (transverse wires). Material produced in this manner was then subjected to additional thermal and mechanical processing.

Table 1 shows data on the mechanical properties of reinforced and non-reinforced aluminum alloy L73 at various temperatures.

As we can see from Table 1, at 300°, the introduction of 8% filament increases the strength of the composite material almost thrice. Testing for material creep at 150° showed that the tension causing residual deformation 0.05% increases five-fold in comparison with non-reinforced matrices (from 6 to 30 kg/mm^2).

This project also investigated the static and cyclical strength of composite materials with respect to positioning of the reinforcing wire in the webbing both parallel to and at 45° angle to the axis of tension. From the data presented in Table 2 and Figure 4, we can /61. see that the time to rupture of material with wires at 45° is significantly higher that that where the wire is parallel to the axis of tension (Figure 4).

The testing of the effect of orientation both from static tension and from cyclical load and increased temperatures is highly interesting in determination of the optimal reinforcement conditions. In a study of an analogous composite material [5]; it was established that the strength of the composite increases with the angle of orientation $\pm$ 10°, and then falls concurrent with the increase θ, in composites with alternating wire layers at an angle $\pm\ \theta$ to the axis of tension (Fig. 5). It's notable that the variety of destruction changes with an increase in the angle of orientation. At $\theta = \pm\ 20°$, transverse fissures appear, and occasionally, the surface of the tear is scooped or conical in shape. At $\theta = \pm\ 30°$ the surface of thefilament - matrix boundary is destroyed; at $\theta = \pm\ 60°$, the shape showed significant stretching during destruction with the development of slippage in the matrix of the flat surfaces parallel to the filaments.

Hot pressing is a method with great possibilities and prospects. The static strength of reinforced aluminum obtained by hot pressing was explored in a study [6]. Wires of stainless steel (C = 0.08%, Si = 0.60%, Mn = 0.8%, Cr = 18%, Ni = 9.5%, Nb = 0.9%) 50 to 125 microns in diameter and modular elasticity $E = 18.2 \cdot 10^3$ kg/mm^2 and strength limits of $\sigma_f = 206$ kg/mm^2, were used as filaments. The matrix material was aluminum (99.99% pure) with $E = 7031$ kg/mm^2 and strength limits $\sigma_m = 4.2$ kg/mm^2. Before the actual production of the composite material, the wire was sheathed with aluminum; then, the hot pressing of the bunched sheathed wires in air, or in an inert atmosphere was accomplished. In another study [7], with these technological stages, a composite aluminum, reinforced with discrete filaments 6.35, 12.8 and 25.4 mm in length (stainless steel) and volume proportion of 20 - 30%, was produced. The method utilized to align the filaments in one direction is discussed in study [3]. /62.

Figures 6 and 7 depict the dependency between cyclical material strength and filament diameter and length. Here, coefficient B lies on the ordinate, and represents the relative increase in durability resultant to reinforcement:

$$B = \frac{N_{fc}}{N_{fm}} = \frac{1}{e_f^2} 4 N_{fc} \Delta e_p^2 \qquad (2)$$

where N_{fc} is the durability of the composite; N_{fm} the durability of the matrix; Δe_p the theoretical plastic deformation per cycle of the

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composite material; e_f is the material deformation up to rupture resultant to static stress. /63.

In Figures 6 and 7, the theoretical plastic flow per cycle is shown on the abcissa.for materials with continuous fibers according to formula:

$$\Delta e_p \sim \frac{2\sigma_c - (2\sigma_m/E_m)[E_f V_f + E_m(1-V_f)]}{E_f V_f + (\partial\sigma/\partial\varepsilon)(1-V_f)} \qquad (3)$$

and for materials with discrete fibers:

$$\Delta' e_p \sim \frac{2\sigma_c - (2\sigma_m/E_m)E_f V_f[1-(l_c/2l)] + E_m(1-V_f)}{E_f V_f[1-(l_c/2l)] + (\partial\sigma/\partial\varepsilon)(1-V_f)} \qquad (4)$$

where σ_c is the composite's strength limit; σ_m is the matrix flow limit; $\frac{\delta\sigma}{\delta\varepsilon}$ is the rate of matrix strengthening; l_c is the critical fiber length; E is the fiber elasticity modulus; V_f is the fiber volume proportion; l is the fiber length.

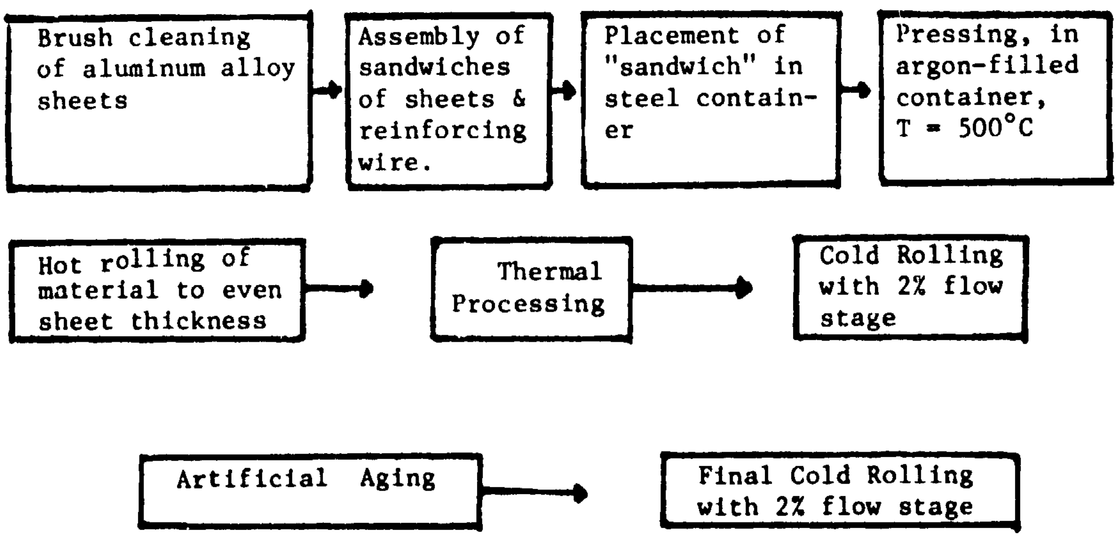
One can see that if the diameter of the reinforcing fibers is reduced, and their length increased, the coefficient of strengthening B, and consequently the durability of the composite as compared to the matrix, increases. Note that the relationship between the relative increase in durability and plastic flow, as depicted in Figures 6 and 7, is favorable. With low plastic flow per cycle, the curves sharply diverge, and with high plastic flow, they practically coincide.

Samples subjected to metallographic testing following fatigue testing indicated the existence of two basic mechanisms of composite material failure. With low magnitude plastic flow per cycle (Δe_p) durability of the sample is determined by the damagability of the matrix and surface separation between matrix and filament. When Δe_p increases, the fibers can not resist linear creep of the fatigue fissures; the durability of the composite approaches the durability of the matrix. Thus, under conditions of high plastic flow per cycle, the effect of reinforcing with continuous filaments approaches the effect of reinforcing with discrete filaments. We think that grinding the filaments, which leads to intense disruption of the matrix, would have a significant impact on the cyclical strength of the composite material with respect to low cycle fatigue.

Thus, the study of the mechanism of destruction of an aluminum-stainless steel wire composite under cyclical loading leads to the conclusion that increasing the fatigue strength can be attained by: 1.) increasing the strength of the filament-matrix bond; 2.) decreasing the distance that a fissure can move without encountering significant resistance (increasing fiber volume); 3.) increasing the total area of contact between fibers and matrix (decreasing fiber diameter while holding volume constant); 4.) increasing fiber plasticity with the aim of decreasing the effect of grinding them.

Never the less, further research to establish the optimal conditions of reinforcement, leading to an increase in durability also under conditions of low cyclical fatigue.

Another study [8] also investigated resistance to impact loading, damping, and other mechanical means of reinforcing material, produced in a contained inert atmosphere according to the following diagram. /64.



NS355 stainless steel wire, 228 microns in diameter and strength limits of 330 kg/mm^2 was used as reinforcing filament. Filament volume proportion varied between 15 and 50%. The maximal dimensions of the plates produced in this manner were 2.44 x 0.3 x 0.006 m, and the strength limits at room temperature after the final processing were 122 kg/mm^2. When the temperature was reduced, the material strength limits increased to 150 kg/mm^2 (Figure 8). A certain increase in resistance to impact loading effect was noted as well; as far as the utilization of damping means for reinforcement of aluminum went, they remained on the matrix material level. Today, the highest strength reinforced aluminum is the composite prepared by hot pressing.

Industrial application of aluminum strengthened with wire is significantly increased with the reinforcement of finished components, which may be easier to produce with casting. This method was employed by R. WIlliams and others [9].

The following diagram depicts the production of composite material by this method:

Fixing and tensing of steel wire in mold. → Heating of wires to 900 °C → Vacuum created at base of mold → Casting in vibrating metal mold.

With this method, a stainless steel mold was employed for casting; the vacuum at the base and the vibration of the mold were done inorder to improve the quality of the casting. LM6 aluminum alloy (10% Si, 0.1% Cu, 0.1% Mg), with strength limit $\sigma_m = 17 \pm 8$ kg/mm^2 and $\delta = 4.8\%$, served as the matrix; this alloy is characterized by excellent castability and high resistance to the formation of intermetallic /65.
phases. Steel wire, 0.254 mm diameter, with strength limit σ_f = 265 kg/mm^2 and elongation at rupture of 6.8%, was used for reinforcing.

Our tests showed that selection of the proper melts and chemical composition of the smelted metal (matrix) could result in excellent bonds at the boundary -nd prevent fibring dispersal. Additionally, contact time between the fibres and the molten aluminum plays a significant role. Minimal contact time creates stable bonds on the boundary layer with minor intermetalloid layers (Fig. 9).

Finally, let us consider reinforcing via impact-loading. Today, the utilization of bursts to join different metals and to strengthen metals and alloys has a practical application; the possibility of applying such a method to reinforce metals with high-strength filaments (or wire) has not been researched yet. Certain dif... l-ties arise when joining metals of different types and chai tics, with respect to the necessary stages of shock loadin as: 1.) achieving the necessary bond between fiber and matr. 3.) elimination of damage of the created compos... aterial and the grinding of the fibers resulatnt to the shock wa... 3.) securing conditions of partial maintenance or reestablishment of the original plastic characteristics of the matrix (by thermal processing).

During the shock loading, in the process of extending the compressing shock wave, the material is subjected to three-axial tensile compression, during which the metal is sharply deformed, and stretched into the direction of the spreading wave. The production of this type of metal-metal composite requires loading with a flat single axis wave, thus preventing fully the rupture and deformation of the fibring and matrix materials. /66.

Results

1. The reinforcement of aluminum with stainless steel wire in order to increase the specific strength of aluminum and its alloys, and increasing the strength of the material under high and low temperatures, as well as increasing its cyclical strength.

2. Production of a composite aluminum-stainless steel wire material with a strength, close to the calculated strength, is possible through any of the considered methods (rolling, hot pressing, casting, and so forth).

Selection of the technological process to produce the material is determined by the true details and conditions of application.

Submitted February 13, 1968

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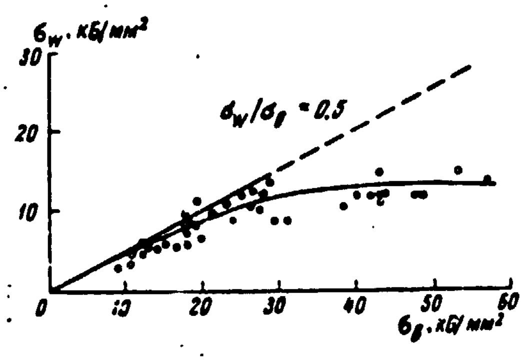

Figure 1. Relationship between the fatigue limit and strength limit of aluminum alloys (1).

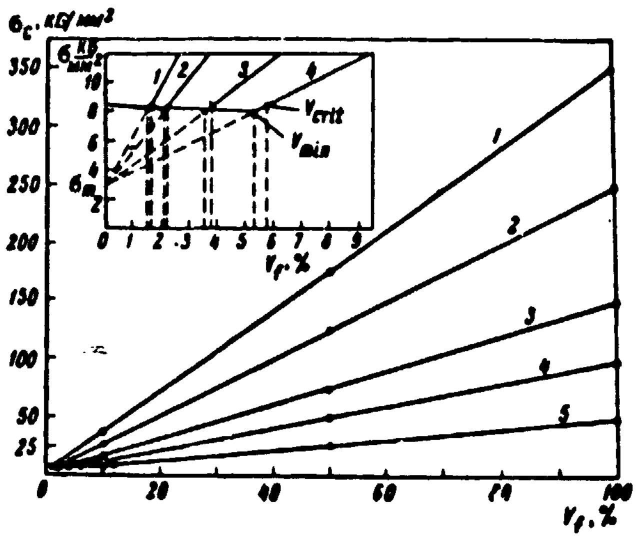

Figure 2. Calculated diagrams of aluminum-stainless steel wire composite material strength.:

1 - σ_f = 350 kg/mm^2

2 - σ_f = 250

3 - σ_f = 150

4 - σ_f = 100

5 - σ_f = 50 kg/mm^2

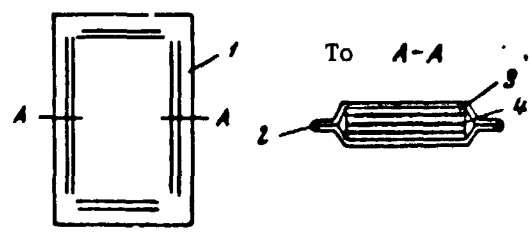

Figure 3. Production process for composite material via rolling in hermetically se:led container.

1. aluminum container jacket
2. welded seam
3. aluminum sleeve
4. alıminum sheet with wound wire

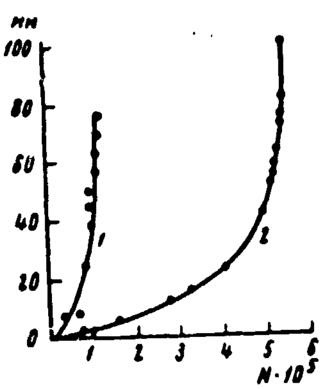

Figure 4

Relationship between fissure length and number of cycles during fatigue testing for aluminum alloy DTD687A (1) and aluminum alloy DTD687A(2), reinforced with one layer of stainless steel webbing FV520B, the cable of which is aligned 45 degrees to axis of tension.

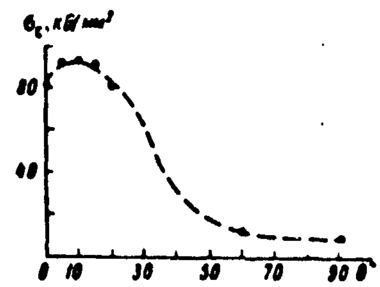

Figure 5

Relationship between aluminum-stainless steel wire composite material strength and fiber orientation with respect to direction of load applied

V_f = 35%

d_f = 50 microns (5)

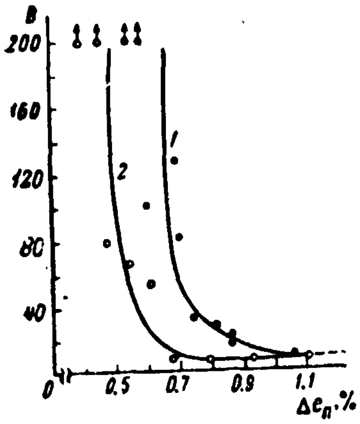

Figure 6. Relationship between relative increase in durability (B) and theoretical plastic flow per cycle (Δe_p) for samples reinforced with continuous fibers.

Diameters: 1 - 50 microns
2 - 127 microns

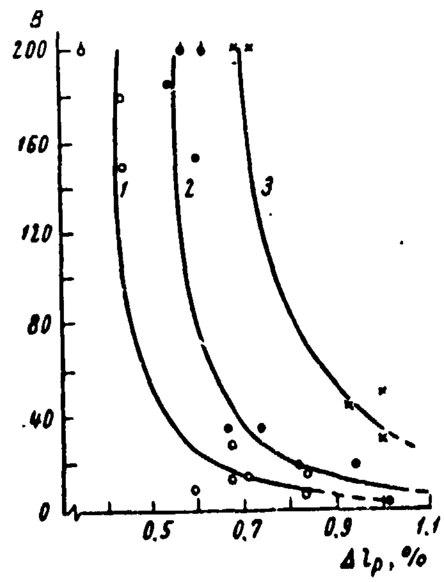

Figure 7. Relationship between relative increase in durability (B) and theoretical plastic flow per cycle (Δe_p) for samples, reinforced with discrete fibers.

Lengths: 1 - 6.35mm
2 - 12.7mm
3 - 25.4mm

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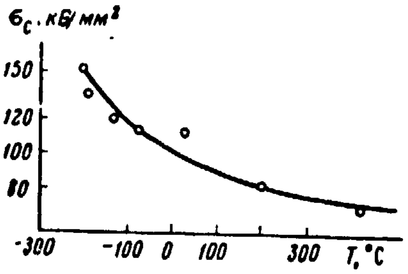

Figure 8. Relationship between aluminum stainless steel wire composite material strength and test temperature.

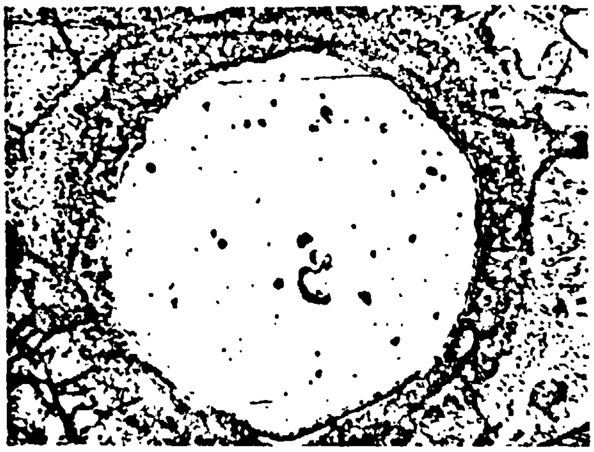

Figure 9. Microsectional structure of sample of aluminum-stainless steel wire composite material produced by casting.

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Table 1. Mechanical Features of L73 alloy and Composite Material L73 (Matrix) with FV 520B (Wire netting). (4.)

Material	T. °C	$\sigma_{0.2}$, kg/mm²	σ_b, kg/mm²	δ, %
L73	Room	40.0	43.5	10
	200	26.3	30.3	12
	250	10.0	12.0	20
	300	5.6	7.0	23
L73 +8% wire	Room	51.0	56.0	8
	200	34.6	40.7	8
	250	21.8	25	4.5
	300	11.6	20.4	4.5

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Table 2. Mechanical Features of Alloys DTD687 and BS L73, Reinforced with Steel Webbing STA1, FV 520B and "Elgiloy" Alloy.

№ п/п	Material	σ_{-1}, кГ/мм²	σ_b, кГ/мм²	δ, %	Number of cycles to rupture	E, кГ/мм²	Notes
1	DTD687	45.3	52.2	12.5	120 000	7360	Durability data - average of large number of experimental data.
2	DTD687 + 1 layer FV520B net	47.0	51.6	1.5	312 000	7410	
3	Like 2, but net aluminum sheathed.	39.6	46.7	2.6	289 000	7410	Wires ruptured during production
4	As 2, but wires in net inclined 45 degr. to axis of stress.	49.8	56.6	8.0	544 000	7360	-
5	DTD 687 + 2 layers "Elgiloy"	30.5	44.3	5.0	214 000	7500	As with No. 2
6	Like 5, but wires 45 degrees to stress axis.	31.5	43.5	7.3	296 000	7150	-
7	L73	40.3	46.0	10.0	455 000	7000	-
8	L73 + 1 layer FV520B sheathed with Al, 45 deg incl. to axis.	38.3	43.8	7.0	2 000 000	7560	Wires ruptured in production as in 2.
9	L73 + 1 layer STA1 wire.	36.3	45.5	7.7	1 120 000	7500	
10	Like 9, 5 layer STA1 with L73 sheathing	37.2	43.3	7.5	1 460 000	7500	σ_B of STA1 steel wire dropped from 250-255 to 125 mm/kg^2. (result of thermal processing)
11	As 9, but 4 layers STA1.	43.4	48.0	8.5	1 700 000	7700	No wire rupture.
12	As 11, 12 layers netting	37.2	47.3	7.0	2 600 000	7700	As 11.
13	L73 with 8 layers of netting and wire.	3.92	41.8	2.0	7 340 000	7770	Ibib.

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