Mechanical properties of multilayer materials

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Abstract. This article presents a study of mechanical properties of multilayer steel materials after the static, impact and cyclic tests, and evaluation of stress and strain behavior of such materials. The studies have shown an increase in the strength, impact strength and the fatigue life with the increase of the number of layers. Also, it has been shown, that high impact strength is maintained down to cryogenic temperatures. That indicates an absence of a definite point for the ductile-brittle transition within such materials. The studies of the stress and strain behavior of multilayer steel materials have shown that the rolling forces increase effect is specific for the production of such materials.

1. Introduction
The multilayer steel materials represent a new class of promising structural materials, in which the modern approach to creation of a structure that provides an improved set of mechanical properties is utilized. Mechanical properties of the produced multilayer steel materials outperform the set of properties of the structural polycrystal materials used in the machinery engineering for now. The mentioned approach provides for making an oriented multilayer structure in the submicron range by preserving a high-angle misorientation on the interlayer boundaries. The use of hot pack rolling method seems to be the most efficient and highly productive as compared with ARB-rolling, for instance [1].

2. Materials and Methods
This work uses the multilayer steel materials manufactured under the experimental process flow. A pre-cleaned multilayer pack was formed, comprising of 100 interleaving steel sheets ordered alternatively, represented by two steel grades (50 sheets per each grade) with the thickness of 0.5 mm each [2, 3]. Then, the multilayer pack was vacuumed and hot rolled at the temperature of 1000 °C. The first process cycle output is a multilayer steel material with a thickness of 2 mm comprising of 100 layers with the thickness of a single layer of 20 µm. The multilayer steel material sheets produced as a result of the first cycle were used in the second process cycle. The completed second process cycle resulted in the increase of the number of 2mm thick layers within the multilayer steel material up to 1400 layers, and single layer thickness is decreased to 3 µm.

The following multilayer steel material compositions were studied – AISI430+AISI304, W108+AISI304, which were used to make samples for static, dynamic and fatigue tests.

The mechanical tensile tests were carried out by 100 kN Zwick/Roell Z100 universal testing machine. Flat samples with the dimensions of 2x10x180 mm were cut out from the central part of multilayer steel bands along the rolling direction. The impact strength tests were carried out at the temperature of 20 °C, −70 °C and −196 °C on the samples cut out from the hot rolled band with the thickness of 10 mm in the
transversal direction relative to rolling. The impact strength was evaluated in normal (\(\perp\)) and parallel (//) directions relative to the rolling plane.

The fatigue life was determined using the AISI430+AISI304 composition. The tests were carried out at the pure plane bending under symmetrical reverse loading by means of Schenk-Erlinger machine. The test load was 560 MPa (above the yield point of that composition after the first cycle, which equals 520 MPa, and lower than the second cycle yield point which equals 660 MPa).

A model experiment was carried out to evaluate the stress and strain behavior of the W108+AISI 304 multilayer steel material, during which the samples cut out from the hot rolled sheet in the normal direction relative to rolling were impacted by the Brinell machine ball with the diameter of 10 mm under 30 kN. After which microhardness of the first and the second process cycle samples was measured layer-by-layer by using longitudinal polished sections using the EmcoTest DuraScan 20 microhardness tester. The fractographic analysis of samples was carried out by Vega Tescan 5130 scanning microscope at the acceleration voltage of 20 kV.

3. Results and discussion

3.1. Study of the static properties

The mechanical properties of the studied composition samples are given in table 1. A low value of the elasticity modulus in comparison with the original steel grades, increase of the hardness and strength characteristics as layers thickness decreases, as well as a considerable decrease of the plasticity characteristics is specific for all compositions.

| Composition          | Number of layers | E, GPa | HB  | 0,2 σ | 0,2 σ | 0,2 σ | 0,2 σ | 0,2 σ |
|----------------------|------------------|--------|-----|-------|-------|-------|-------|-------|
| AISI 430+AISI 304    | 100              | 160    | 180 | 520   | 780   | 7,0   | 43    |
|                      | 1400             | 170    | 370 | 660   | 800   | 4,5   | 48    |
| W108+AISI 304        | 100              | 150    | 110 | 560   | 960   | 7,0   | 44    |
|                      | 1400             | 180    | 450 | 880   | 1470  | 4,0   | 18    |

3.2. Study of the impact strength

The studies have shown that the samples of AISI430+AISI304 and W108+AISI304 compositions tested in the direction normal to the rolling plane are not destructed by a drop hammer with the operational margin of 300 J, and demonstrate small breaks in the stress concentration area, after which they are affected by bending strain. With the decrease in the test temperatures, the sample values after the first process cycle, both in longitudinal and transversal directions, consistently decrease down to the minimum at the test temperature of \(-196 ^\circ \text{C}\) (table 2).

| Composition          | Concentrator position | 20°C | -70°C | -196°C |
|----------------------|-----------------------|------|-------|--------|
| AISI 430+AISI 304    | \(\perp\)             | 360a | 350a   | 160    |
|                      | //                     | 360a | 360a   | 360a   |
| W108+AISI 304        | \(\perp\)             | 350a | 350a   | 370a   |
|                      | //                     | 57   | 43     | 25     |

\(\text{KCU, J/cm}^2\)
The samples after two process cycles with 1500 layers of the cross-section (the nominator values) behave differently. In the direction normal to the rolling plane the AISI430+AISI304 and W108+AISI304 composition samples are not destructed down to the temperature of –196 ºC, which indicates an absence of the ductile-brittle transition point within the studied temperature range.

The increasing trend remains as to the destruction energy intensity for the multilayer steel materials and for the ones with the V-shaped concentrator. Thus, for the samples of AISI 430+AISI 304 composition tested at the temperature of 20 ºC there is an almost double increase of Astr, and almost four times increase at the temperature of 196 ºC below zero (table 3). This behavior within multilayer steel materials under impact loads nominally conflicts the common concepts of the ductile-brittle transition point within the polycrystal materials. The results of studies show that while decreasing the test temperature the work intensity of destruction of the impact low-alloy samples treated in the described way is increased, which indicates an absence of a definite ductile-brittle transition point (DBT) [4]. The absence of a definite ductile-brittle transition point in the multilayer steel materials can be achieved due to the oriented layered structure formation that increases the impact strength values in the direction normal to the rolling plane and improves the material strength at low temperatures.

Table 3. The impact strength values of the multilayer composition samples with V-shaped concentrator in the rolling direction (⊥).

| Composition          | Number of layers | Thickness of layer, µm | Astr (KCV), J/cm² | Sample condition (−196 ºC) |
|----------------------|------------------|------------------------|------------------|---------------------------|
|                      |                  |                        | 20 ºC       | −196 ºC          |                         |
| AISI 430+AISI 304    | 100              | 100                    | 140            | 80             | destructed              |
|                      | 1 400            | 7,0                    | 280            | 260            | not destructed         |
| W108+AISI 304        | 100              | 100                    | 80             | 15             | destructed              |
|                      | 1 400            | 7,0                    | 230            | 290            | not destructed         |

The analysis of breaks within multilayer steel materials shows that high values of the impact strength of the samples tested in the direction normal to the rolling depend on a partial breakdown of layers and further strain of a sample part which remains integral (Figure 1).

Figure 1. The samples of 08X18+08X18H10 composition with 1 400 layers after the impact bending test: a) ⊥ to rolling plane, b) // to rolling plane.
3.3. Study of fatigue properties (fatigue life)

The results of the fatigue life studies have shown that the fatigue life of the sample of multilayer steel material AISI 430+AISI 304 comprising of 100 layers is \(2.8 \times 10^4\) cycles before destruction. For the sample after the second process cycle with the number of layers about 1 500 it is \(4.6 \times 10^4\) cycles before destruction (Figure 2). Therefore, the fatigue life has increased 1.8 times with the increase of the number of layers within the sample from 100 to 1 500 (with a single layer thickness decrease from 20 µm down to 3 µm, accordingly). The obtained results have a good correlation with the tests carried out under cyclic tensile conditions [5]. The increase of the fatigue life can be explained by the following.

![Figure 2. The results of fatigue life tests of the multilayer steel material AISI 430+AISI 304 under cyclic loading at the pure plane bending by means of Schenk-Erlinger machine.](image)

It is known, that the fatigue life of a polycrystal material under cyclic loading will be high, provided that it has higher strength [6]. On the other hand, material fatigue greatly depends on its structural condition. Based on the Hall-Petch relationship, \(\sigma \sim h^{1/2}\) (where \(\sigma\) – plastic strain, \(h\) – grain size), we may assert, that the polycrystal material fatigue life will be high if it has a greater range of the structural grain fineness.

The multilayer metal materials demonstrate different specific stress and strain behavior as compared with the polycrystal materials. The strain mechanisms are impossible to describe using the Hall-Petch model and for those materials, it shall be considered in a view of single dislocation loops slippage parallel to the section surfaces [7].

3.4. Evaluation of the stress and strain behavior of the multilayer steel materials

The results of studies on evaluation of the stress and strain behavior of W108+AISI 304 composition show that the strain depth after the first process cycle, with 100 layers in total, is about 50 % of the sample thickness (Figure 3a). In the samples after the second process cycle, with 1 500 layers in total, the strain depth did not exceed 15 % of the sample thickness (about 1.5 mm) (Figure 3b).

Such behavior of the multilayer steel materials can be explained by the following. Earlier it has been discovered, that one of the features of the multilayer materials production is the effect of considerable rolling forces increase in comparison with the values obtained on the blanks with polyhedral structure [8]. It has been established, that at the same temperature, speed and strain parameters during the process, the rolling forces on the multilayer materials comprising of 100 interleaving layers of AISI 1008 and W108 steel grades, exceed the rolling forces obtained on the samples comprising of the interleaving
layers of W108 steel grade by 50% and exceed the rolling forces on the solid W108 steel sample by more than 100%. This effect is caused by the formation of special type structure, which is known as Bamboo-type, as well as by high interlayer stresses.

![Figure 3. Microhardness distribution within W108+AISI 304 composition after the first (a) and the second (b) process cycle.](image)

The study of the structure of layers within the area of strain, performed by an electronic scanning microscope on the samples of 100 layers has shown, that no visible strain is observed within the layers of AISI 304 steel grade, while the layers of W108 steel grade are impacted highly, which results in slippage strips formation in them (Figure 4).

![Figure 4. Electronic image of the structure of W108 steel grade layers affected by strain.](image)
4. Conclusions
The results of performed studies have shown that due to the creation of a laminar structure within the multilayer steel materials a unique set of mechanical properties is observed. These materials have high strength in combination with high impact strength which is preserved down to cryogenic temperatures, thus allowing improving the strength of structural material. These materials are promising for applications requiring cyclic loads due to their high fatigue life, which increases with the increase of the number of the laminar structured layers.

References
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