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DETERMINATION OF THE OPTIMAL THICKNESS OF THE INTERLAYER IN ADVANCED STEELS FOR THE PROTECTION OF SPECIAL EQUIPMENT

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The influence of the thickness of the copper layer in the composite on its strength in static and dynamic tests is shown. The increase in armor-piercing resistance of multilayer composites of the St-Cu-St and Cu-St-Cu-St-Cu types was analyzed. The tested samples were obtained by the method of hot rolling in vacuum (HRV) and batch method.

INTRODUCTION

The use of multilayer metal materials can significantly increase the service life of parts and structures operating under high temperature and force loads while saving costly alloying elements. A significant advantage of such composites is the realization of extremely high service characteristics, which are almost impossible to obtain when using monometallic billets.

The problems of using multilayer composites that complicate their widespread use are the risk of their destruction in the welding zone during subsequent deformation. The weld zone consists of the weld boundary and the adjacent areas of the source materials. During the development of products (samples), it is necessary to rely on parameters that characterize the strength and deformation properties of the material. The traditional yield strength and tensile strength, which can be obtained by standard mechanical tests, are usually used as these parameters. Determination of the actual mechanical properties of the welding zones will allow for a more reliable prediction of the performance of structures made of multilayer composites. In this work, standard experimental tensile test methods are used.

TECHNOLOGIES AND MATERIALS

Various technologies for the production of multilayer composites (MLC) were used:

– hot rolling in vacuum (HRV) using induction heating of billets in the SWAPR unit;

– a batch method of producing MLCs using sealed bags with different thicknesses of copper layers.

Low-carbon steel X18H10T and copper were used in the manufacture of specimens for uniaxial tensile testing. Dynamic tests were carried out with billets made of different types of high-carbon steels and steels such as St3, St20, and copper.

Experimental comparative tests were conducted after dynamic impact.

EXPERIMENTAL PART

The purpose of this work is to study the effect of the thickness of the copper layer during static fracture on the mechanical properties of the St-Cu-Cu (steel-copper-steel) bimetal and the fracture energy of the Cu-St-Cu-St-Cu (copper-steel-copper-steel-copper) MLC during dynamic tests. Bimetals obtained by hot rolling in a vacuum were used in the study. The mechanism of formation of a compound of dissimilar metals during vacuum rolling is described in the literature [1]. The HFR method makes it possible to produce bimetals, where the sample fractures during tensile tests along the weakest metal that is part of the heterogeneous system (multilayer system), rather than along the interface.

Samples with copper layers of the following thicknesses were tested: h_{1Cu}=0.05 mm (χ=0.01), h_{2Cu}=0.7 mm (χ=0.14), h_{3Cu}=0.4 mm (χ=0.08), where χ is the relative thickness. Calculated by the formula:

$$\chi = \frac{h}{d}, \quad (1)$$

where h – is the thickness of the copper layer; d – is the diameter of the sample.

The shape and dimensions of the specimens for mechanical testing are shown in Fig. 1. Multilayer composites of the X18H10T-Cu-X18H10T type were used during the tests. Prior to the tests, the samples were vacuum quenched at a temperature of 800 ^{0}C for 1 h. The carbon content of X18H10T steel was 0.12% (low value). The evolution of the structural-phase state of the transition zones was not considered in this work [2, 5].

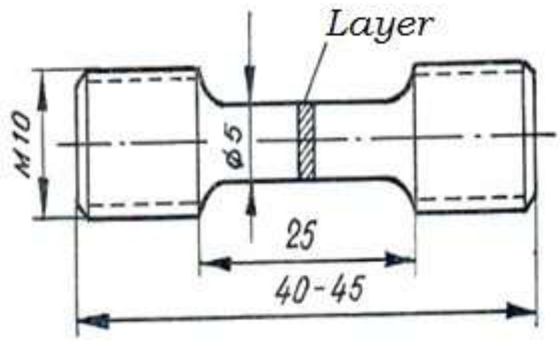

Fig. 1. Shape and dimensions of specimens for mechanical properties testing

The uniaxial tensile tests were performed using a BISS NANO servo-hydraulic testing rig. It provides a tensile force of up to 25 kN. The deformation rate of the samples was 2 mm/min.

The internal architecture of the multilayer composite consisted of three (St-Cu-St) and five (Cu-St-Cu-St-Cu) layers. To separate them, a force equal to the tensile strength of the less solid body, which is copper, must be applied. As shown in Fig. 2, the tensile strength is different for different thicknesses of the copper layer. This fact was the object of the test.

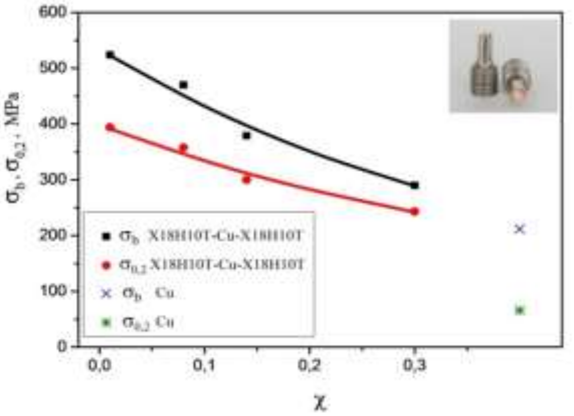

Fig. 2. Graph of the dependence of the tensile strength and yield strength on the layer thickness (T_0=800 ^{0}C – 1 h)

Fig. 2 shows the dependence of the tensile strength and yield strength of composite samples on the relative thickness χ of the copper layer. Different values of χ were obtained by changing the thickness of the layer (according to formula (1)). In all cases, the destruction of the samples occurred along the copper layer. Thus, the strength of the composition was determined by the strength of copper under specific experimental conditions (both static and dynamic tests). Fig. 2 shows that the strength of copper in the composition depends on the relative thickness of the layer. With a decrease in the value of χ, the average destructive stress increases with a hyperbolic dependence.

It was previously shown [3, 4] that the most likely reason for the increase in the strength of the plastic layer in static tests in the composition is the blocking of the sliding planes along the “plastic metal-strong metal” interface.

The principle of operation of two-layer steel armor is as follows: the outer (front) high-strength layer takes the main impact and thermal load when a bullet hits, deforms or crushes it and dissipates kinetic energy. The least strong and therefore most viscous, inner (back) layer prevents the outer layer from chipping or brittle fracture. Thus, it ensures further dissipation and absorption of kinetic energy through layer separation, bending and stretching [6].

During the transition from hot rolling in vacuum to rolling sealed packages, a technological layer of copper or steel is added to the composition of the St-St bimetal. In the batch process, multilayer composites are produced in the following copper-steel-copper-steel-copper architecture. In vacuum rolling, it is steel-copper-steel. During the analysis of the stress in the middle of the obstacle, after the impactor stops, it was found that the maximum stress is concentrated at the interface between the two layers, in some cases leading to mechanical rupture of the layer connection.

To study the effect of the thickness of the copper layer on increasing the armor-piercing (penetration) resistance of two-layer armored steels, the resistance of the back layer to tearing during dynamic impact is largely determined. The main technological challenge is to ensure a reliable connection between the layers.

Based on this, the thickness of the copper layer between the layers should, on the one hand, be such that after the first layer is pierced, no delamination occurs over the entire plane of the second layer, and on the other hand, minimize the impact of the obstacle on the second layer (soft). By increasing the area (diameter) of energy dissipation of the striking element due to delamination on the copper (Fig. 3a). Thus, by changing the thickness of the copper between the hard and soft layers, we can increase (a thicker layer – 300…400 μm) the diameter of the ring at the interface of the layers or decrease (100…300 μm).

When comparing the results of the experimental samples after dynamic testing with and without a copper layer (see Figs. 3a and 3b) in terms of the rear strain parameter, it is clear that the sample with a copper layer has a strain diameter of approximately 7 cm. At the same time, in the sample without a copper layer, the diameter of the deformation is up to 2 cm. The experimental conditions were the same in both cases - the fracture rate and energy were the same. Fig. 3b shows a sample of the same design (same materials), but without a copper layer. It had a through penetration.

The batch-welded samples had high (0.9%) and medium (0.3%) carbon content. After welding and hot-rolling in the atmosphere, the billets were quenched at 800 ^{0}C for 1 h. The final heat treatment was carried out at a temperature of 830 ^{0}C. With this technology, the thickness of copper layers ranged from 90…400 μm. The front (outer) and inner layers had the same thicknesses.

The first experiments of dynamic testing of the Cu-St-Cu-Cu-St-Cu bimetal produced by the batch method revealed delamination of the layers along the copper (its thickness was 400 μm). The thickness of copper in the initial state h=1 mm after welding and rolling to a thickness of h=8…10.5 mm ranged from 90 to 400 μm.

The ballistics tests of the samples obtained by the HRV method and the batch method were carried out in the thickness of the batches of 8…10.5 mm at bullet velocities from 700 to 850 m/s. The bullet velocity and energy were calculated using the IBX-731/4 measuring optoelectronic complex.

Fig. 3a. Photo of the sample after ballistic testing

At bullet velocities up to 750 m/s (E≅2.2 kJ), samples with a copper layer thickness of 200 to 300 μm had no breakdown or chipping of the hard layer. At speeds of 850 m/s (E≅4 kJ) and more, the delamination diameter was largest in samples with a copper layer thickness of 250 to 400 μm. At copper thicknesses of 80…200 μm, the delamination diameter (in copper) was smaller.

Fig. 3b. Photo of the sample after ballistic testing without copper layer

Transition zones in bimetallic samples (steel-copper-steel, Cu-St-Cu-St-Cu) and thickness measurements were examined by light microscopy (Figs. 4a, 4b). In the samples after rolling, the interfaces of dissimilar metals are clear and thin, with no pores, discontinuities, or nonmetallic inclusions. This indicates the high quality of the bimetal components obtained by both vacuum rolling (a) and batch rolling (b). It should be noted that the production of MLCs using vacuum rolling technology is more expensive compared to the sealed package method. As the experiment illustrates the batch method more than meets, and sometimes exceeds, the results obtained by vacuum rolling.

Fig. 4a. HRV method of obtaining bimetal, copper layer thickness 80 μm

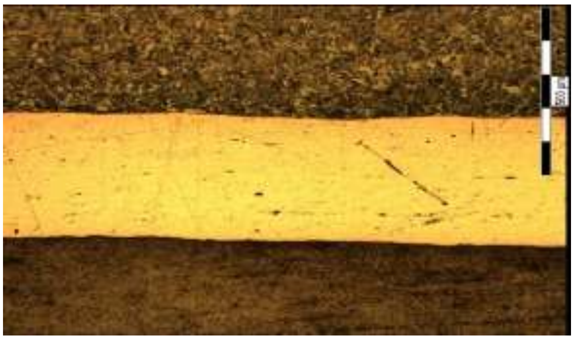

Fig. 4b. Batch method of producing bimetal, copper layer thickness 400 μm

The best results in dynamic tests were shown by samples with a copper layer thickness of h=100…200 μm. Samples produced by the batch method showed good results in some components of chip and fragment formation, and resistance to penetration in the outer (front) layer. This is due to a decrease in the cooling rate during quenching, which affected the stability of the MLC (Cu-St-Cu-St-Cu) [7]. In this component, they even surpassed the samples obtained by the HRV method.

The obtained strength test data for bimetals with a layer will be used to model the stress-strain state in the converter and the interference using the Johnson-Cook model [6]. This model allows analyzing and describing the dynamic tensile strength of metals subjected to large deformations, high strain rates, and high temperatures.

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}), \qquad (2)$$

where ε is the intensity of plastic deformation, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless plastic deformation rate, $\dot{\varepsilon}$ defined as the ratio of the instantaneous plastic deformation rate $\dot{\varepsilon}$ to its limit value $\dot{\varepsilon}_0$=1 c^{-1}; T* is the homologous temperature; A, B, C, n, m are the model parameters.

Thus, the initial data from the mathematical modeling of the stress-strain state of multilayer composites in the case of a striking element impact will provide a lot of useful information that will allow us to further analyze the process of collision between the striking element and a multilayer obstacle and formulate reasonable conclusions and practical recommendations for adjusting the thickness of the copper layer. In the future, our data will be used in the Johnson-Cook model (calculations according to formula (2)).

CONCLUSIONS

1. The obtained results of mechanical tests of standard stainless steel-copper-stainless steel samples with a copper layer thickness of 0.05…0.4 mm are in good agreement with the literature.
2. It has been shown experimentally that the maximum stress in dynamic tests is concentrated at the boundary of brittle and soft layers, so special attention was paid to the middle copper layer.
3. Based on the test results, copper layer thicknesses of 200 μm and thinner were selected for samples requiring dynamic strength tests without taking into account the influence of carbon.
4. Our experiments have shown the effectiveness and substantiated the feasibility of using copper layers in the architecture of the Cu-St-Cu-St-Cu composite during dynamic tests.
5. The rolling of sealed packages is the most productive (high efficiency, energy intensity, does not require highly qualified specialists) in the manufacture of multilayer composites for advanced steels for the protection of special equipment and personnel. At the same time, it solves the tasks in the best possible way.

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ВИЗНАЧЕННЯ ОПТИМАЛЬНОЇ ТОВЩИНИ ПРОШАРКУ У ПЕРСПЕКТИВНИХ СТАЛЯХ ДЛЯ ЗАХИСТУ СПЕЦІАЛЬНОЇ ТЕХНІКИ

М.І. Ільченко, В.І. Ситін, М.П. Одейчук, Ю.М. Ільченко

Показаний вплив товщини мідного прошарку у складі композиту на його міцність при статичних та динамічних випробуваннях. Проаналізовано зростання бронебійної стійкості багатошарових композитів типу Ст-Cu-Ст та Cu-Ст-Cu-Ст-Cu. Досліджувані зразки було отримано методом гарячої прокатки у вакуумі (ГПВ) та пакетним способом.