Impact toughness of multilayer steel materials at low temperatures

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Abstract. The results of a number of studies show that there are ways to drastically change the temperature dependence of the impact strength of structural steels, which at first glance have a paradoxical character. It was established that when the test temperature decreases down to cryogenic temperatures, the work of failure of impact samples cut in certain directions of rolled products does not change, which indicates the absence of a formal viscous-brittle transition threshold and an increase in material reliability at low temperatures. The reason for this phenomenon is the layered structure formed during the hot batch rolling process, due to which complete failure of impact samples with a U-shaped concentrator does not occur.

1. Introduction

For most engineering steels, the transition from a viscous to a brittle state occurs at insignificant negative temperatures, which represents a significant danger in the operation of machinery and structures in conditions of low climatic temperatures. Given that cold resistance primarily depends on the viscosity of the material, the main methods aimed at its increase are associated with a decrease in the number of harmful impurities, the number and size of non-metallic inclusions, as well as additional doping. However, the results of a number of studies show that there are ways to drastically change the temperature dependence of the toughness of machine-building steels. The authors [1,2] found that with decreasing temperature the test work of failure of the impact sample increases, which indicates the absence of a formal threshold for viscous-brittle transition (VBT) and an increase in the reliability of the material at low temperatures. This becomes possible after a special type of thermomechanical processing in low alloyed steels due to the formation of a layered structure, which leads to an increase in the values of impact strength, and the formation of the fracture having a terraced structure.

It is also important that high values of toughness and strength at the same time can be achieved in multilayer materials [3-5]. This combination of characteristics makes it possible to use these materials in electronic devices, armor materials and various branches of engineering [6-8].

2. Materials and research methods

To study the temperature dependence of impact strength in the low and cryogenic temperatures the samples of multilayer materials consisting of 100 alternating steels with a thickness of 0.5 mm each were selected (50 layers of each grade): AISI 430 + AISI 304, W 108 + AISI 304, AISI 420 + AISI 304 [9]. Using the experimental technological route, including dimensional cutting of blanks from sheets, processing their surfaces, assembling sliced sheets into a package, evacuating the package and subsequent plastic deformation by hot rolling, the billets 10 mm thick were prepared. These compositions underwent two complete technological cycles. After the implementation of the first technological cycle, the resulting material consists of 100 layers, each layer of about 100 microns
thick, and after the second - 1500 layers of approximately 5 microns thickness.

Studies were conducted on samples of toughness with U-shaped pin in the direction of hubs perpendicular and parallel to the rolling direction, in the temperature range from 20°C to -196°C.

3. Results and discussion

According to the test results, it was established that the investigated multilayer materials with 1500 layers have a significant margin of fracture toughness in the direction perpendicular to the rolling plane. Samples do not fail by a pile with a margin of work of 300 J and have a tear in the area of stress concentrator, and then subjected to bending deformation.

Such results can be explained by the fact that under dynamic loading of multilayer samples with a notch located in the direction of braking of the front of the crack, the interfaces between the layers serve as barriers to the propagation of the crack. Splitting cracks arising in the way stop it, and for the further development of the fracture, the formation of microcracks on a new surface is necessary, which requires extra energy. The resistance to failure in this case increases, and the greater it is, the more layers in the structure of the material and the more often the effect of its separation manifests itself are.

These data are supported by the work of the authors of [10], who study the behavior of toughness in thirteen-layer Ti-6Al-4V material. The authors of [1-2,11] also believe that in crack limiter configurations attenuation and deflection of cracks are the dominant mechanisms and can lead to a noticeable increase in toughness. It should be noted that this effect of hardening by “peeling”, leading to an increase in impact toughness is observed not only in steels [1-2,12], but also in ceramics [13] and pyrolytic carbon [14].

When the temperature of the test is lowered in order to determine the threshold of VBT, the values of the reduced work in the direction perpendicular to the direction of hire are not reduced (Table 1), while the samples that have passed the second process cycle of production fail. Samples of compositions AISI 430 + AISI 304, W108 + AISI 304 have a formal threshold VBT is absent to the test temperature of -196°C. For samples of the composition AISI 420 + AISI 304 at this temperature, normal failure of the samples is observed, which for the studied materials can be considered the reaching the VBT threshold.

| Table 1. Impact toughness values on compositions with 1500 layers. |
|---------------------------------------------------------------|
| Composition | Layer thickness μm | Concentrator, cut by relation to RD | KCU (Apr), J/cm² |
|-------------|-------------------|-----------------------------------|-----------------|
|             |                   | 20°C  | -70°C | -196°C |
| AISI 430+AISI 304 | 5.0              | 360 a  | 360 a  | 360 a  |
| W 108+AISI 304 | 5.0              | 340 a  | 325 a  | 360 a  |
| AISI 420+AISI 304 | 5.0              | 70    | 60    | 35     |
| AISI 420+AISI 304 | 5.0              | 70    | 60    | 50     |

The test results of the samples in the direction parallel to the direction of rolling are characterized by significantly lower values of impact strength, with the additional work of failure being expended on opening the interlayer boundaries with the formation of delamination cracks.

Similar results were obtained by the authors of [15], who established the advantage of the layered
structure on steels of different phase composition at temperatures from 20°C to -196°C. They carried out experiments on composite five-layer samples of two stainless steels: ferritic steel 08Kh18T1 and austenitic steel 10Kh18AG19. In the experiments, the author found that the effect of increasing the toughness of the composite samples depends on the orientation of the sample on the test pile and is maximum if the direction of impact of the guillotine pendulum is perpendicular to the plane of the pairing plates.

Confirmation of the results obtained are also found in the works of the authors [1,2], presenting results showing the positive effect of a particular type of structure on the value of the impact strength of ferritic steels in the region of low climatic temperatures. This paper shows the results of the study of steel with different heat treatments:

- **QT** - quenching and tempering at 500°C, **TF** - quenching at 500°C and deforming. In the experiments, a sample of TF steel showed an inverse temperature dependence of toughness at low temperatures (Fig. 1).

![Figure 1. The dependence of the energy of failure of Charpy impact samples for two types of QT and TF treatment](image)

There are other works in which data are given on the positive effects of a special kind of multilayer structures in steel brazed materials: an increase in the number of layers in the material leads to both increased toughness values and lower threshold of the viscous-brittle transition [16,17].

Thus, the results of a number of studies show that there are ways to drastically change the temperature dependence of the impact strength of structural steel, having at first glance a paradoxical character. It is shown that when lowering test temperature, the work of failure of the impact sample increases, which indicates the absence of a formal threshold for viscous-brittle transition and an increase in the reliability of the material at low temperatures. The formed layered structure is the main cause of such dramatic changes in the behavior of structural materials.

### 4. Conclusion

Complete failure of samples is absent in compositions AISI 430 + AISI 304, W108 + AISI 304 to temperatures equal to -196°C, and up to -70°C for samples of the composition AISI 420 + AISI 304, which indicates the absence of a formal threshold of VBT. However, the found effect is not a violation of the general theory, but serves as its confirmation.

Considering that with a decrease in temperature, a natural increase in the yield limit is observed, it becomes natural to increase work on the plastic strains of specimens that, due to the multi-layered structure, do not completely fail, but undergo bending deformation.
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