Study of thermal expansion anomalies of multilayer steel materials at high temperatures

V E Kabantseva¹, M D Safonov¹ and A I Plokhikh¹

¹Bauman Moscow State Technical University (National Research University); (Bauman MSTU), 5, 2nd Baumanskaya Str., bldg. 1, 105005, Moscow, Russian Federation

Abstract. The paper presents the results of a study of the anisotropy of the thermal coefficient of linear expansion (CTE), which was found in a multilayer metallic material based on steels, made by hot batch rolling. It is established that the material consisting of alternating layers of steel, has abnormally low CTE values in the direction perpendicular to the rental plane. To explain this phenomenon, a hypothesis was proposed about the relationship between normal and tangential stresses arising at the interlayer boundaries of such material. The confirmation of the hypothesis of the leading role of reactive stresses in the manifestation of the specified invar effect are the results of metallographic analysis. It is also shown that the conduct of cyclic high-temperature heating provokes recrystallization at the interlayer boundaries caused by the difference in the thermal expansion coefficient values of the adjacent layers and the effect of high temperature.

1. Introduction
Currently, intensive research of materials scientists is aimed at creating methods to improve the performance characteristics of traditional materials by implementing a special type of structures in them. Such structures, possessing non-linear characteristics, are capable of adaptive response to external influences. Such effects are usually observed in composite materials and are the result of the interaction of local microscopic fields of elastic stresses, which is not found in materials with a homogeneous structure.

The study of the theoretical aspects of the creation of composite materials with anomalous characteristics was conducted by many researchers [1-9]. The detected effects in composites led to the intensification of work on the creation of materials with a negative Poisson ratio, as well as the search for materials with similar characteristics of the thermal coefficient of linear expansion (CTE). [10-13].

So, in particular, a mathematical model is known, according to which, CTE may have negative values in materials with a layered structure based on binary (iridium + invar) or triple (iridium + tungsten + invar) metal compositions. The main criterion when choosing materials for compositions is a significant difference in the value of CTE, which may differ by 4-5 times for selected materials [12,13].

However the technological aspects related to the compatibility of such materials, the interlayer diffusion of alloying elements, ways of creating an inextricable connection between the layers, due to which the manifestation of this effect would be possible, were not considered. Therefore, the idea of implementing the developed approaches in structural metallic materials having a layered structure, but obtained on the basis of available and technological materials, for example, on the basis of steel, is relevant.

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2. Materials and methods
On the basis of the presented considerations, two model compositions composed of steels X5CrNi18+08kp and X5CrNi18 + U8 were investigated. It is known that the difference in the values of the thermal expansion coefficient and the modulus of normal elasticity is not as significant as that of the materials of the above mathematical model [12], and in the temperature range studied will differ by no more than 1.5 times [14].

The primary composite blanks consisted of 100 alternating sheets of specified steels with a thickness of 0.5 mm, i.e., 50 sheets of each grade, respectively. According to the previously developed experimental process map (Figure 1), blanks for a 100 mm wide strip and 10 mm thick were obtained [15]. Obtained after the first cycle strips 10 mm thick were rolled to a thickness of 2 mm, cleaned, assembled into a bag and, in accordance with the described process map, they went through the second treatment cycle by carrying out hot batch rolling to a thickness of 10 mm.

For dilatometric studies, samples were cut in three directions: along the rolling direction (RD), in the rolling plane (TD) and in the direction perpendicular to the rolling plane (ND).

The measurements were performed on a Dil-402C dilatometer manufactured by Netzsch (Germany) with a corundum holder and pusher in the temperature range 20 to 1200°C during heating and cooling of the furnace at a rate of 5 deg/min in an atmosphere of technically pure argon. The temperature was measured by a platinum – platinum – rhodium thermocouple (type S) located in the immediate vicinity of the sample, with an error not exceeding 5°C.

3. Results and discussion
The dilatometric study showed (Figure 2) that the test X5CrNi18 + U8 multilayer material, obtained after the first and second technological cycles, has an anomaly of thermal expansion (∆L/L) in the direction of ND. The transformation observed at a temperature of about 900°C in the direction of ND corresponds to the α → γ transition in carbon steel, which is part of the composition under study. In Fig. 2, one can see that the anomaly in the direction of ND begins to manifest itself at temperatures of warm deformation, which coincides with the onset of the release of dislocations from the atmospheres of impurity atoms in low carbon steels.

It can be seen that after the completion of the second technological cycle, the detected invar anomaly is amplified and shifted to lower temperatures. To explain this effect, a hypothesis about the interaction of reactive tangential and normal stresses arising during heating has been put forward.
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Figure 2. The dependence of the relative elongation of the multilayer material in the directions RD, TD and ND in samples with a thickness of 10 mm with the number of layers 100 (a) and 1500 (b).

In accordance with the hypothesis, a decrease in the thermal expansion coefficient values of the multilayer material is observed in the RD and TD rolling directions due to the mutual compensation of the thermal expansion of dissimilar layers (Figure 3, a). This effect is particularly pronounced in the range of the $\alpha \rightarrow \gamma$ transition of carbon steels. Thus, the decrease in the lattice parameters during the reverse transformation is almost completely compensated by the expansion of steel X5CrNi18, which is manifested in the absence of an anomaly in the dilatograms of the RD and TD directions. On the other hand, in the direction of ND, a cumulative enhancement of the effect of compression is observed, which is associated with the expansion of steel X5CrNi18, which is superimposed on the compressing layers undergoing $\alpha \rightarrow \gamma$ transformation (Figure 3, b). It is this compression that leads to the appearance of thermal expansion coefficient values in the direction of ND, corresponding to the values for classical invar alloys.

Figure 3. Diagram of the effect of tangent (a) and normal (b) stresses on the example of the composition X5CrNi18 + 08kp.

The analysis of the microstructure of 100 layered samples consisting of X5CrNi18 and U8 steels showed that after the completion of the first technological cycle, the modified structure consists of alternating layers of low carbon steel and X5CrNi18 layers of former steel (Figure 4, a). Characteristic of the X5CrNi18 steel layers is the presence of a large volume fraction of the highly dispersed carbide phase, which was formed as a result of the directional diffusion of carbon (Figure 4, b) [16, 17].
Figure 4. The microstructure of the composition X5CrNi18 + U8 (a) and the layer of steel X5CrNi18 (b).

To check this assumption, hundred-layer samples of composition X5CrNi18 + U8 were reheated to a temperature of 1200°C, which certainly exceeds the dissolution temperature of present chromium carbides. Figure 5a shows that the carbide phase completely dissolved in the layers of the multilayer material under study, which led to the active recrystallization with the formation of a coarse-grained structure.

At the same time, the layers that were previously U8 steel decreased in thickness — from an average value of 100 μm in the original hot rolled state to values of 85–90 μm (Figure 5, b). Thus, the increase in the thickness of the layers that were previously X5CrNi18 steel occurred through the migration of interlayer boundaries in the direction of the layers that were previously U8 steel.

Figure 5. The microstructure of the composition X5CrNi18 + U8 after heating to a temperature of 1200°C.

Based on this, we can conclude that the driving force in this process is interlayer stresses arising from the difference in the CTE values of the mating layers, which for alloys with similar chemical composition at these temperatures differ by more than 1.5 times. The mechanism of relaxation of these stresses is dynamic recrystallization, which occurs at the boundary between the layers and is detected metallographically in the form of interlayers. In this case, the front of the moving boundary is directed towards the most plastic layer, which is caused by the lowest energy for the implementation of microplastic deformation, which precedes the onset of the recrystallization process.

To eliminate the influence of diffusion processes on the mechanisms of relaxation of interlayer stresses, similar studies were conducted on the composition X5CrNi18+08kp. It has been established
(Figure 6, b) that repeated single heating to a temperature of 1200°C also leads to the formation of an additional layer at the interface facing the 08kp steel. Threefold heating to 1200°C showed that the thickness of this layer increases, which indicates the development of recrystallization processes and confirms the suggestion of the leading role of interlayer stresses in the process of structure formation (Figure 6, c).

Figure 6. The microstructure of the composition X5CrNI18 + 08kp in the initial state (a) and after repeated once (b) and three times (c) heating to a temperature of 1200°C.

4. Conclusions

Thus as a result of the research carried out, the existence of a steel structural material, capable of demonstrating selective behavior in response to an external impact, which is manifested in a pronounced anisotropy of thermal expansion, was confirmed.

It has been established that with an increase in the number of layers in a multilayer material, the anomalous nature of thermal expansion in the direction perpendicular to the rolling plane increases and shifts to lower temperatures. It is shown that the reason for this anisotropy of properties is the stresses arising due to the difference in the values of the thermal expansion coefficient of the steels included in the composition of the original composition of the multilayer material. The mechanism of relaxation of these stresses is associated with dynamic recrystallization, which occurs at the boundary between the layers. The direction of migration of the interlayer boundary is directed towards the most plastic layer, which is caused by the lowest energy expenditures for the implementation of microplastic deformation, which precedes the onset of the recrystallization process.

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