The high-temperature pseudo-invar effect in multilayer steel materials

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Abstract. The paper presents the results of research into Coefficients of Thermal Expansion (CTE) in multilayer steel material produced by hot pack rolling. It has been discovered that the material comprised of interleaving layers of steel features abnormally low CTE values in the direction normal to the rolling plane. A hypothesis has been proposed to explain the phenomenon by an interrelation between normal and tangent stresses generated in the interlayer boundaries within the material. A leading role of reactive stresses is confirmed by the results of the metallographic analysis. It has been shown that cyclic heating at a high temperature provokes recrystallization on the interlayer boundaries due to the difference between the CTE values of the adjacent layers and the high-temperature impact.

1. Introduction

Today, great efforts of the material scientists in research and development are focused on making the methods to improve operational characteristics of conventional materials by implementing the special types of structure in them. These structures can demonstrate adaptive behavior under an external impact due to non-linear strain or thermal characteristics. These effects are generally observed in composite materials and are caused by an interaction of local microscopic fields of elastic stresses, which is not the case for the uniform structured materials.

Many scientists worked on the theoretical aspects of production of such composite materials, which resulted in discovery of some interesting effects within the composite materials, and induced a search for the materials with a negative coefficient of thermal expansion (CTE) [1-5]. There is a mathematic model according to which CTE could have negative values within the materials with a layered structure based on binary (Iridium+Invar) or triplex (Iridium+Tungsten+Invar) metal compositions [6, 7]. The main criterion for selection of the composite components is the high difference in the normal elasticity modulus E and CTE values that may be 4-5 times different for the selected materials.

However, technological aspects concerning the compatibility of these materials, interlayer diffusion of alloy elements and the methods of making a continuous link between the layers that would make it possible to reveal this effect, have not been considered. This is why it is relevant to implement the approaches developed in the production of structural metal materials with layered structure, based, however, on the available and processable materials, such as steel.

2. Materials and Methods

Based on the considerations given above two model compositions made of AISI304+1008 and AISI304+AI5IW108 steel have been studied. The primary composite blanks were 100 interleaving
sheets of the mentioned steels with the thickness of 0.5 mm, i.e. by 50 sheets per each grade. The output of the experimental process flow (Figure 1) was the flat steel blanks with a width of 100 mm and thickness of 10 mm [8-10]. The first cycle output bands with the thickness of 10 mm were rolled to the thickness of 2 mm, cleaned out and assembled into a pack, then, according to the described process flow, the blanks underwent the second hot pack rolling cycle to the thickness of 10 mm.

The samples were cut out in three directions to perform dilatometric studies: along the rolling direction (RD), in the transversal direction (TD) and in the normal direction (ND).

3. Results and discussion
The dilatometric study has shown (Figure 2) that the studied multilayer material AISI304+AISIW108 produced after the first and the second process cycles features the anomaly of thermal expansion ($\Delta L/L$) along the ND. The transformation observed along the ND at $\sim$900°C corresponds to the $\alpha\rightarrow\gamma$ transformation within the carbon steel which is a component of the studied composition. The studies of AISI304+1008 composition have shown the presence of the thermal expansion anomaly as well, that means the multilayer structure influences revealing of the discovered effect.

As we can see, the discovered invar-type effect increases after completion of the second process cycle and shifts into the area with lower temperatures. A hypothesis on the interaction between the reactive tangent and normal stresses during heating has been proposed to explain this effect. According to the hypothesis, the CTE values decrease is observed in RD and TD within the multilayer material due to mutual compensation of the thermal expansion of heterogeneous layers (Figure 3, a). This effect is highly visible within the interval $\alpha\rightarrow\gamma$ of carbon steel transformation. Thus, a decrease in the matrix
parameters during the reverse transformation is compensated completely by the expansion of the AISI304 steel, which is demonstrated by the absence of the anomaly on the dilatograms in RD and TD. On the other hand, the compression effect is enhanced in ND, which is related to the expansion of the AISI304 steel overlapping the compressed layers undergoing $\alpha \rightarrow \gamma$ transformation (Figure 3, b). It is the compression which results in the CTE values in ND, corresponding to the values within conventional invar-type alloys.

![Diagram](image)

**Figure 3.** Tangent (a) and normal (b) stresses impact diagram exemplified by the 08X18H10+1008 composition.

Analysis of the hundred-layered samples microstructure, originally comprised of the AISI304 and AISIW108 steels, has shown that after completion of the first process cycle the transformed structure represents interleaving layers of low carbon steel and the layers of former AISI304 steel (Figure 4, a). Presence of high volume ratio of a finely-dispersed carbide constituent generated from the directed carbon diffusion is specific for the layers of AISI304 steel (Figure 4, b) [11].

![Microstructure](image)

**Figure 4.** The microstructure of the AISI304+ AISIW108 (a) composition and AISI304 (b) steel layer.

To check this proposition hundred-layered samples of the AISI304+AISIW108 composition were repeatedly heated to the temperature of 1200°C, which knowingly is higher than the solution temperature of contained chromium carbides. As we can see (Figure 5), there are transformations within the layers of the studied multilayer material. Thus, carbide phase dissolved completely in the layers that formerly constituted the AISI304 steel, which resulted in active recrystallization with generation of a coarse-grained structure. At the same time the thickness of layers that formerly constituted the AISIW108 steel decreased from the original value of 100 µm in hot rolled condition at average down to 85–90 µm. Therefore, the increase of the thickness of layers that formerly constituted the AISI304 steel occurred due to the migration of the interlayer boundaries in direction of the layers that formerly constituted the AISIW108 steel.

Based on the foregoing we may conclude that this process is driven by interlayer stresses occurring due to the difference of the CTE values in the adjacent layers, which is different for the alloys.
with the similar chemical composition at given temperatures by more than 1.5 times. The mechanism of relaxation of these stresses is a dynamic recrystallization occurring on the boundary between the layers and shown by the metallography as interlayers. At the same time, the front of the moving boundaries is directed to the most plastic layer, which is explained by the least energy required for the microplastic deformation preceding the beginning of the recrystallization.

![Figure 5. The microstructure of the AISI304+ AISIW108 composition after heating to the temperature of 1200°C.](image)

In order to exclude the impact of diffusion processes on the mechanisms of interlayer stresses relaxation, similar studies have been performed on the AISI304+1008 compositions. It has been established (Figure 6, b), that repeated one-time heating to the temperature of 1200°C, also results in generation of an additional interlayer at the boundary of the layer facing the steel grade 1008. Three-time heating to the temperature of 1200°C has shown, that the thickness of this interlayer increases, which indicates recrystallization processes and confirms the proposition on a leading role of interlayer stresses in the structure generation in multilayer metal materials (Figure 6, c).

![Figure 6. The microstructure of the AISI304+1008 composition in the original condition (a) and after repeated one-time (b) and three-time (c) heating to the temperature of 1200°C.](image)

4. Conclusion

Therefore, the results of performed studies have confirmed the existence of the steel structural material which is capable of demonstrating flexible behavior under an external impact, as shown by distinct anisotropy of thermal expansion.

It has been established, that increase in the number of layers within the multilayer material, causes enhancement of the anomaly of thermal expansion in the direction normal to the rolling plane with a shift to the area with lower temperatures. It is demonstrated that such anisotropy of the properties is caused by the stresses occurring due to the difference of CTE values of steel grades contained in the
original multilayer material composition. The relaxation mechanism for such stresses is associated with a dynamic recrystallization that occurs on the boundary between the layers. The interlayer boundary migration is directed to the most plastic layer, which is explained by the least energy required for microplastic deformation preceding the beginning of recrystallization.

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