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RESISTANCE BUTT WELDING OF TITANIUM ALUMINIDE γ-TiAl WITH VT5 ALLOY*

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In the work, the peculiarities of formation of dissimilar joints of Ti–46A1–2Cr–2Nb alloy on the base of titanium aluminide γ-TiAI with titanium alloy VT5 in resistance butt welding, in particular, using interlayers in the form of nanolayer foils were studied. In resistance butt welding without the use of nanolayer foils it was failed to provide the defect-free joints: in the butts the presence of areas of cast metal and cracks was detected. It was found that the use of Ti/Cu and Cu–Ti/Ni–C systems as an interlayer of nanolayer foils of an eutectic type significantly influences the activation processes of the surfaces to be welded and the formation of joints in resistance butt welding. The presence of nanolayer foils in the contact zone facilitates the formation of a thin layer of the liquid phase at the initial stage of the heating process, localization of heat evolution process, activation of surfaces of both alloys with the duration of heating stage of 50–60 % of such at the direct resistance butt welding of alloys γ-TiAI and VT5. The two-stage pressure cyclogram provides formation of defect-free joints at the values of heating temperature, which are lower than those of the liquidus temperature in the system Ti–AI. According to the data of scanning electron microscopy and the EDS-analysis, the absence of the areas of cast metal and the remnants of nanolayer foils in the zone of joints was established, which testifies the solid-phase nature of the formation of joints and the complete displacement of nanolayer foils beyond the cross-section of the billets. 12 Ref., 8 Figures.

Keywords: *titanium aluminide, VT5 alloy, resistance butt welding, nanolayer foil, solid-phase joint*

The promising materials for production of components of aircraft and automobile engines are the intermetallic-based alloys, in particular, titanium aluminides [1–5]. Due to low specific weight and high heat resistance, titanium aluminides and the alloys based on them have advantages over the existing titanium and nickel alloys in a wide range of temperatures. The titanium aluminides are envisaged for using in manufacture of valves in automobile engines [2] and parts of aircraft engines operating at high temperatures [4].

One of the reasons that inhibits the use of intermetallic alloys is the complexity of their technological treatment, in particular, welding, predetermined by extremely low ductility at room temperature, high sensitivity to thermal and deformation cycles of treatment [6]. Perspective for the permanent joint of intermetallic alloys in similar and dissimilar combinations is the use of pressure welding methods [7–11], in particular, resistance butt welding (RBW) [10, 11]. The development of an effective technology for RBW of intermetallic alloys is associated with a number of problems, in particular, with a nonuniformity of heating and deformation processes of near-contact material volumes, considerable resistance to plastic deformation, high electrical resistance and a large temperature range of brittleness of these alloys.

An effective technological procedure, which facilitates the activation of welded surfaces and intensification of diffusion processes in the joint zone, is the use of intermediate layers. As such layers, nanolayer foils (NF) on the base of reaction elements which are the part of materials welded [9–11] can be used. To weld dissimilar materials, it is important to use intermediate layers that will, on the one hand, facilitate the establishment of physical contact and on the other hand, prevent the mixing of elements being a part of materials welded. To such requirements intermediate layers in the form of NF correspond, having a nonuniform distribution of structure parameters across the thickness.

The previous experience shows the effectiveness of applying NF as interlayers and activators in RBW of alloys based on titanium aluminides in a homogeneous combination. The positive effect of using NF is manifested in the localization of the processes of heat evolution and deformation in the contact zone, which facilitates the activation of surfaces welded and

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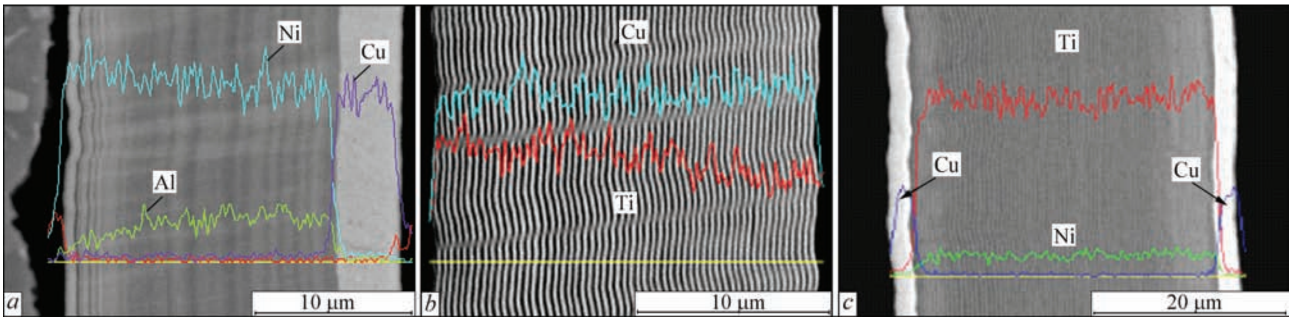


Figure 1. Electron microscopic image and distribution of components in NF of Al/Ni–Cu (*a*), Cu/Ti (*b*), Cu–Ti/Ni–Cu (c) systems

provides the formation of joints at essentially lower values of energy input [11].

The aim of investigations was to establish the peculiarities of formation of dissimilar joints of alloy on the base of γ-titanium aluminide with high-strength titanium alloy in RBW, i.e. directly and with the use of NF at a nonuniform distribution of structure parameters.

The influence of RBW modes on the formation of Ti–46Al–2Cr–2Nb (γ-TiAl) titanium aluminide joints with the alloy VT5 (hereinafter — joint γ-TiAl + VT5) was investigated. A comprehensive research methodology was developed, which included producing welded joints by different technological schemes: directly by RBW and RBW using NF of different chemical composition. To carry out investigations, the machine K766 was modernized to provide a high quick-response of compression mechanism and precision control of compression forces during the welding current passing. The range of technological parameters change was optimized based on previous experiments in such a way that to provide a predetermined value of upsetting during welding. The parameters of RBW mode were changed within the following limits: pressure at heating P = 2–10 MPa, pressure during upsetting of 10–50 MPa, welding time 1.5–3.5 s.

The structure of joints and presence of defects were determined by metallographic examinations of sections prepared using the chemical method of detecting the structure. An optical microscopy (Neophot-32), scanning microscopy (Auger-microprobe JAMP-9500F and scanning electron microscope JSM-35SA, JEOL), micro X-ray spectral analysis of elements distribution (EDS-analyzer INCA-450, Oxford Instruments), measurements of microhardness (M400, LECO, at loading of 1–5 N). The mechanical properties of joints were evaluated by the distribution of microhardness of metal in the zone of joint and in the zone of thermomechanical effect on the butts.

For conducting experiments on RBW with the use of intermediate layers, NF of system Ti/AI and foils with a nonuniform distribution of parameters of the structure of two types were selected: discrete (TiNb/Al, Ni/Ti–Al, Ti/Ni–Cu, Ni–Ti/Cu–Ni, Ti–Al/Ni–Ti, Al/Ni–Cu) and gradient (Cu/Ti). The thickness of NF was 30–60 μm, the thickness of each layer was 10–50 nm. The microstructure and the results of micro X-ray spectral analysis of NF Al/Ni–Cu, Cu/Ti and Cu–Ti/Ni–Cu across their thickness are presented in Figure 1.

An essential characteristic of the discrete type of foils, used as an intermediate layer in RBW is the material of outer layers. According to the research methodology, it was envisaged that the use of NF of a discrete type with an outer layer having thermophysical characteristics different from those of alloys welded should have a significant influence on heating, deformation processes, character and intensity of diffusion processes in the contact zone during welding.

Thus, for the NF of Ti–Al/Ni–Ti the outer layer (titanium) corresponded to the base of both alloys welded; for the NF of Cu–Ti/Ni–Cu and Ni–Al/Ni–Ni, the outer layers (copper and nickel) form the low-melting eutectic with the base of both alloys. It was envisaged that during metallographic examinations of the joints, the difference in detection of the NF structure and the base metal of alloys would allow establishing the regularities of behavior of the near-contact volumes of metal and material of the interlayer in the process of welding.

The influence of RBW modes in a wide range of changes in technological parameters on the formation of γ-TiA1 + VT5 joints was investigated. The structure of the joint zone produced by RBW at the optimal mode without the use of intermediate layers is shown in Figure 2, *a*, *b*, respectively, in the central and peripheral parts of the section of billets. The presence of areas of cast metal and microcracks in the joint zone is noted.

The analysis of the results of oscillography of the value of welding current and the measurement of temperature by thermocouples indicate that, in this case, during RBW process, the formation of the joint occurred through a melt layer which solidified after the stage of deformation of billets in the cooling process. During RBW without melting directly, it was not possible to form joining of the alloys γ-TiAl + VT5, as the defects of the type of oxide films and lacks of penetration were detected.

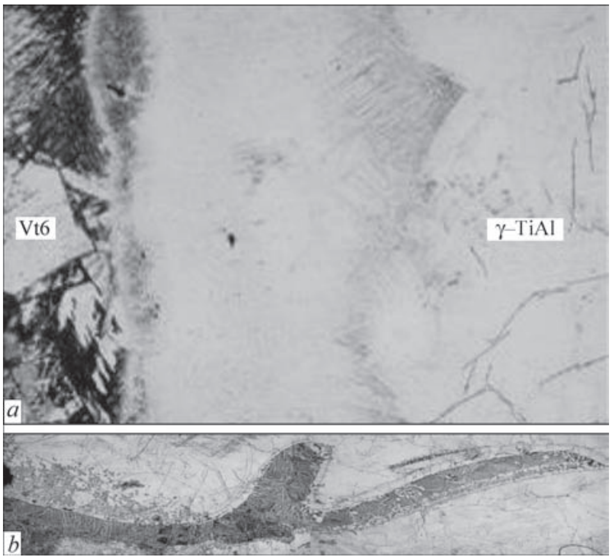


Figure 2. Microstructure (x100) of joint of the alloys γ-TiAl + VT5 at direct RBW: central part of the cross-section (*a*), peripheral part of the cross-section (*b*)

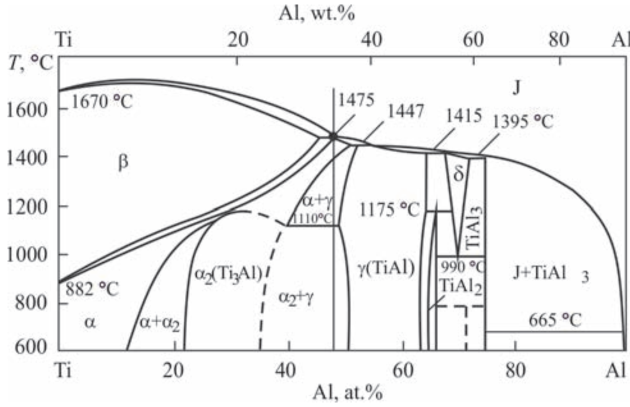


Figure 3. Diagram of state of the Ti–Al system [12]

The influence of RBW modes on the structure of joints of γ-TiAl + VT5 alloys produced through NF of Ti/Al system was investigated. The temperature-time parameters of the welding process provided exceeding the melting temperature of the alloys γ-TiAl ($T_{liquidus}$ = 1475 °C) and VT5 ($T_{liquidus}$ = = 1670 °C) in the contact zone according to the state diagram of the Ti–Al system (Figure 3) [12]. In this case, the axial force at the stage of upsetting was not increased (single-stage pressure cyclogram). It was established that during air cooling of γ-TIA1 + VT5 joints produced by RBW with a single-stage pressure cyclogram, the cracks are formed in welded butts directly throughout the diffusion zone or in the areas of the γ-TiAI alloy adjacent to it (Figure 4, *a*), obviously, due to structural transformations «melt → α-phase → (α + γ) → (α_2 + γ), which are accompanied by the appearance of significant welding stresses.

The structure of joints of alloys γ-TiAI + VT5, produced by RBW through the NF of Ti/Al system with a two-stage pressure cyclogram, was investigated when the melting temperature of the alloy γ-TiAl was reached in the contact zone. During the analysis of the joint microstructure, the formation of common grains at the contact boundary of the alloys γ-TiAl + VT5 (Figure 4, *b*) is observed.

Obviously, in the process of heating during RBW, a short-term local achievement of the liquidus temperature of alloys was provided, at the same time the melt areas were solidified at the stage of deformation of billets during upsetting. In this case, the solid-phase nature of the formation of the joint γ-TiA1 + VT5 in the α-region of the state diagram of the Ti-Al system was provided. The registration of thermal cycles with the help of thermocouples established that the use of NF provides localization of heat evolution in the contact area (along the axis of billets) and a more uniform heat evolution across the section of billets as compared to RBW without the use of NF.

The oxide films, pores, cracks and other defects in the joining zone were not revealed. The analysis of microstructure of joint shows the presence of a diffusion zone with a width of more than 100 μm, in which the content of titanium gradually decreases from about 93 g, at.% in the alloy VT5 to 50 at.% in the alloy of γ-TiAl, which, in accordance with the

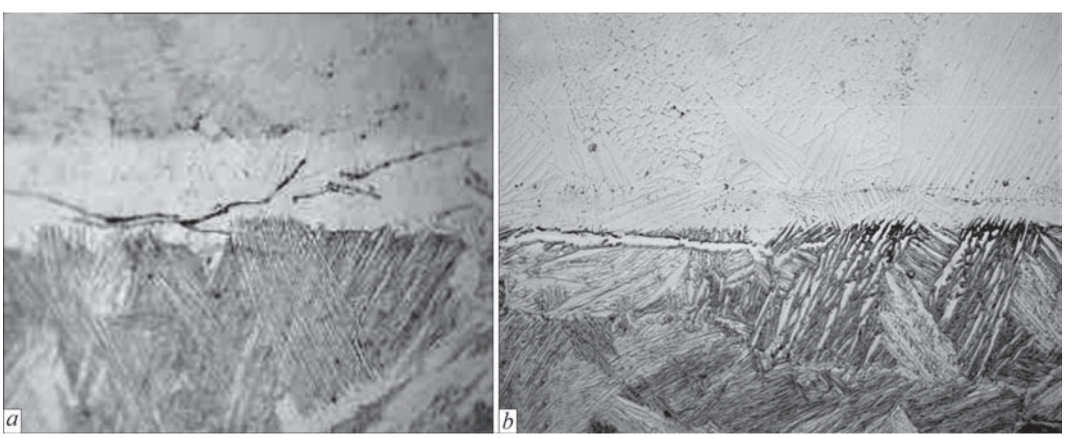


Figure 4. Microstructure (×200) of the joint γ-TiAl + VT5 in RBW through NF of Ti/Al system at one- (*a*) and two-stage (*b*) pressure cyclogram (alloy VT5 in the photo below)

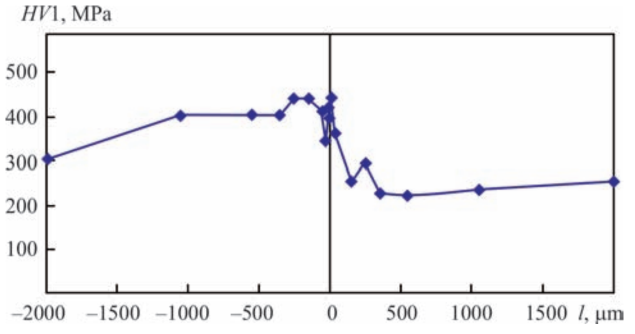


Figure 5. Change in microhardness in the joint γ-TiAl + VT5 in RBW through NF Ti/Al

state diagram of the system Ti–Al, predetermines the existence of several phases of different composition — α(Ti), α + α_2, α_2(Ti_3Al), α_2 + γ (TiAl). The nature of change of microhardness in the zone of joining of γ-TiAI + VT5 (Figure 5) indicates the absence of areas with decreased strength in the heat-affected zone of both alloys. The presence of a wide diffusion zone is a significant factor which can affect mechanical characteristics of welded butts, in particular, the formation of cracks during their heat treatment or operational loads.

The influence of RBW modes on the structure of joints γ-TiA1 + VT5 produced with the use of NF of eutectic type with a nonuniform distribution of the structure parameters across the thickness: discrete (Ni/Ti–Al, Ti/Ni–Cu, Cu–Ti/Ni–Cu, Al/Ni–Cu) and gradient (Ti/Al, Cu/Ti). The technological parameters of the RBW mode were set so, that to provide a short-term eutectic temperature exceeding in the

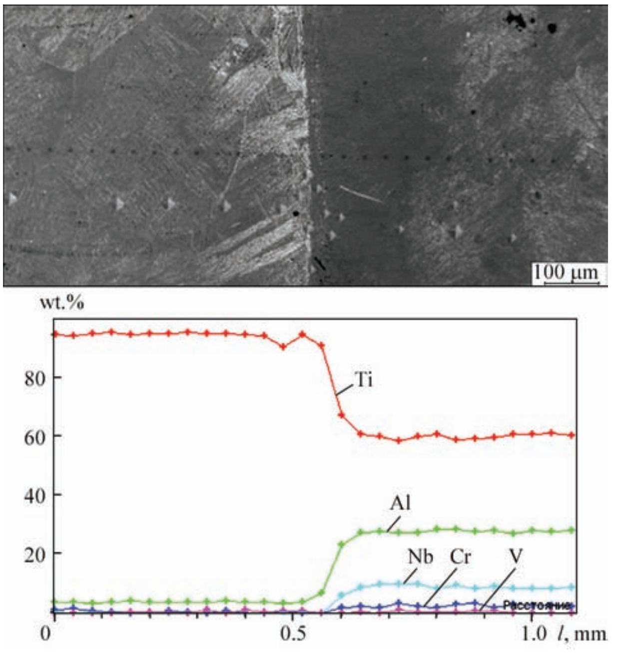


Figure 7. SEM of the image of microstructure and results of X-ray spectral analysis of the zone of the joint γ-TiAl + VT5 in RBW through NF Cu–Ti/Ni–Cu

titanium-material of external NF layer system in the contact zone.

In particular, for NF of the system Cu–Ti/Ni–Cu and Cu/Ti the heating temperature during RBW process should exceed the value of $T_{eutCu–Ti}$ = 885 °C for a short time in accordance with the state diagram of the system Cu–Ti [12]. At the same time, the temperature-time conditions of the RBW process (value

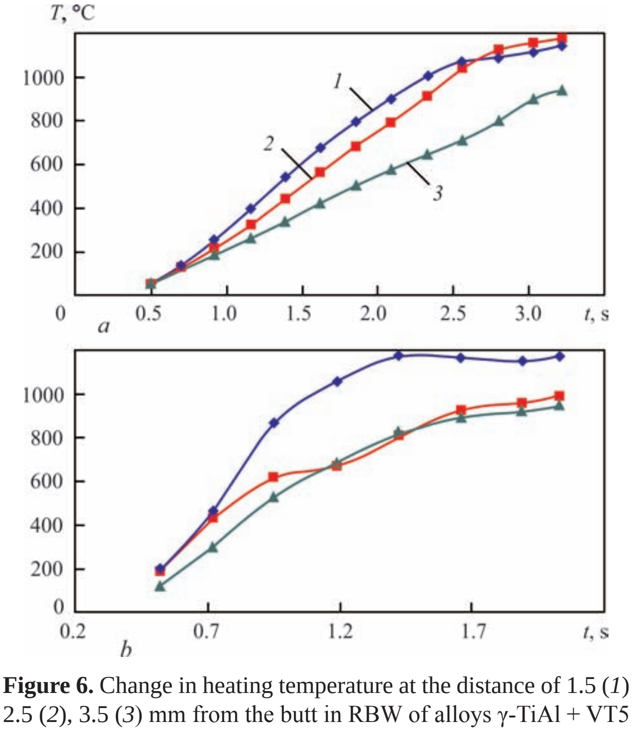
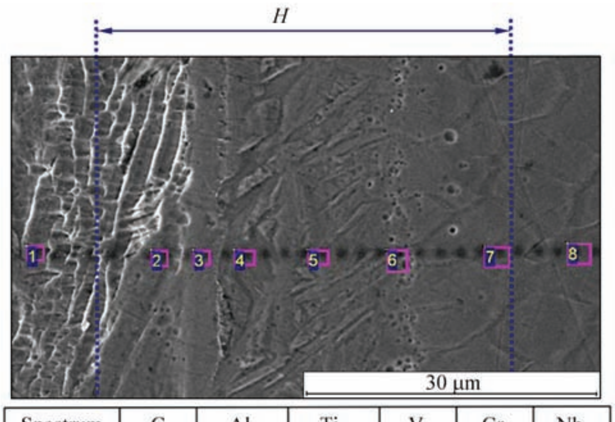


Figure 6. Change in heating temperature at the distance of 1.5 (*1*) 2.5 (*2*), 3.5 (*3*) mm from the butt in RBW of alloys γ-TiAl + VT5 through NF Cu–Ti/Ni–Cu (*a*) and Cu/Ti (*b*)



Spectrum	C	Al	Ti	V	Cr	Nb
1	1.27	5.32	93.15	0.15	0.10	0
2	0.75	12.03	86.31	0.66	0.15	0.11
3	0.91	14.46	84.44	0	0.08	0.12
4	0.95	17.99	80.44	0.13	0.24	0.25
5	0.76	20.68	76.47	0	0.76	1.33
6	0.96	22.54	71.15	0	1.46	3.89
7	1.04	25.46	66.13	0	0.99	6.38
8	0.77	25.87	62.98	0.05	2.09	8.23

Figure 8. Microstructure and chemical composition of metal in different areas of the joint γ-TiAl + VT5 in RBW through NF Cu–Ti/Ni–Cu, wt.%, H — width of diffusion zone

of voltage, current, time, heating pressure, upsetting pressure) were controlled in such a way that to prevent exceeding the melting temperature of alloy γ-TiA1 in the contact zone (Figure 6). The process of forming the joint occurs in α-region or (α + γ) region according to the state diagram of Ti–Al system.

The experiments showed that the optimal conditions for formation of joints in RBW are provided with the use of NF of systems Cu–Ti/Ni–Cu and Cu/Ti. The microstructure of joint γ-TiA1 + VT5 at scanning electron microscopy (SEM) and the results of micro X-ray spectral analysis are presented in Figures 7, 8.

It was established that the use of NF significantly influences the processes of activation of surfaces welded and the formation of joints. The use of the systems Cu–Ti/Ni–Cu and Cu/Ti in RBW with a two-stage pressure cyclogram facilitates the formation of a thin layer of liquid phase at the initial stage of heating process, localization of heat evolution process, the activation of surfaces of both alloys and the formation of defect-free joints at the stage of upsetting with the duration of heating stage being 50–60 % of such at the direct RBW. With the help of SEM (Auger-microprobe JAMP-9500F, JEOL EDS-analyzer INCA-450), the absence of areas of cast metal, NF remnants was established in the joints zone, which proves the solid-phase nature of formation of joints and the complete displacement of NF beyond the boundaries of the cross-section of billets. The width of the diffusion zone in the joint γ-TiA1 + VT5 does not exceed 50 μm (Figure 8).

Conclusions

1. In resistance butt welding (RBW) of the alloy γ-TiA1 with titanium alloy VT5 without the use of intermediate layers it was not possible to provide defect-free joints: the presence of areas of cast metal and cracks was recorded in the butts. The formation of joints occurred through a melt layer, which solidified after the stage of deformation of billets during cooling of the butts.

2. In the butts produced by RBW through the NF of the Ti/Al system at a single-stage pressure cyclogram, the cracks are formed directly across the diffusion zone or in the areas of the alloy γ-TiA1 adjacent to it apparently, due to the structural transformations «melt → α-phase → (α + γ) → (α_2 + γ), which are accompanied by the appearance of significant welding stresses.

3. Two-stage pressure cyclogram in RBW through the NF of the Ti/Al system provides the formation of defect-free joints. The presence of a diffusion zone with a width of more than 100 μm is a significant factor that can affect the mechanical characteristics of welded butts, in particular, the formation of cracks during their heat treatment or operating loads.

4. The use of the eutectic type of the Ti/Cu and Cu–Ti/Ni–Cu systems as an intermediate layer of NF significantly affects the activation processes of welded surfaces and formation of joints in RBW. The presence of NF in the contact zone results in the formation of a thin layer of liquid phase at the initial stage of heating process, localization of heat evolution process, activation of surfaces of both alloys at the duration of heating stage of 50–60 % of such at direct RBW of alloys γ-TiAl and VT5.

5. In RBW with a two-stage pressure cyclogram, the formation of defect-free joints is provided at the values of heating temperature lower than the liquidus temperature in the Ti–Al system. According to the data of micro X-ray spectral analysis, the absence of the areas of cast metal and the NF remnants was established, which testifies the solid-phase nature of the formation of joints and the complete displacement of NF beyond the cross-section of the billets.

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