FRICTION WELDING OF PIM HEAT-RESISTANT STEEL TO STEEL 40Kh

I.V. ZYAKHOR and **S.I. KUCHUK-YATSENKO**
E.O. Paton Electric Welding Institute, NASU, Kiev Ukraine

Experimental data are given on evaluation of structure of heat-resistant steel AISI310 produced by the powder injection moulding technology. The investigation results are presented on peculiarities of formation of dissimilar joints between steel AISI310 and structural steel 40Kh under different thermal-deformation cycles of friction welding in manufacture of bimetal shafts for automotive engine turbocharger rotors.

Keywords: *friction welding, bimetal joints, powder injection moulding, welded joints, turbocharger rotor shafts*

One of the new powder metallurgy methods is powder injection moulding [1–5], which in the English technical literature is collectively known as the PIM-technology. Powder injection moulding has been gaining an increasingly wider acceptance in the last years owing to a number of advantages over traditional methods of metal processing, first of all in manufacture of complex-geometry and mass-production parts. According to the data given in [3], density of the finished parts produced by the PIM-technology is 96 to 100 % of its theoretical value, while the detected pores and non-metallic inclusions have small sizes and a spherical shape, and are uniformly distributed in the bulk.

The promising market for the parts produced by the PIM-technology is the automotive engine construction industry. The issue of current importance in terms of technology and economy is application of the PIM-technology to manufacture complex-configuration parts. For example, these are wheels of bimetal shafts for automotive engine turbocharger rotors (TCR). Compared to the currently applied investment casting method, the PIM-technology provides an increased productivity, minimal possible deviations of sizes and a high quality of the surface of the wheels for the TCR shafts.

The technological cycle of manufacture of the bimetal TCR shafts provides for the use of friction welding (FW) of a heat-resistant alloy wheel to a structural steel shank. Friction welding is applied to advantage to join materials produced by the casting, thermo-mechanical deformation and powder metallurgy methods [6–8]. However, no information on application of FW for the parts produced by the PIM-technology has been found in technical literature so far. Therefore, it is of scientific and practical interest to study the effect of structure of the PIM-materials on the possibility of joining them to structural steel to manufacture bimetal TCR shafts.

The purpose of this study was to investigate formation of dissimilar joints between heat-resistant steel AISI310 produced by the PIM-technology and structural steel 40Kh under different thermal-deformation cycles of FW for manufacture of bimetal TCR shafts.

General view of the TCR shaft wheels made by the PIM-technology from steel AISI310 (feed stock — BASF «Catamold» [3]) is shown in Figure 1. Chemical composition of the materials welded, as well as their mechanical properties are given in the Table.

Austenitic stainless steel AISI310 (domestically produced analogue — steel 20Kh25N20S2 (EI283)) combines satisfactory heat resistance and high oxidation resistance at high temperatures. Bimetal TCR shafts were produced by join-

Chemical composition and mechanical properties of materials welded

Steel grade	Content of elements, wt.%							Mechanical properties			
	C	Cr	Nb	Si	Mn	Fe	Ni	σ_y, MPa	σ_t, MPa	δ, %	ψ, %
AISI310	<0.2	24–26	<0.2	1.5–2.0	1.0–1.4	Base	18–21	>205	>515	>40	>50
40Kh	0.36–0.40	0.8–1.1	–	<0.35	0.5–0.8	Same	<0.3	>720	>860	<14	<60

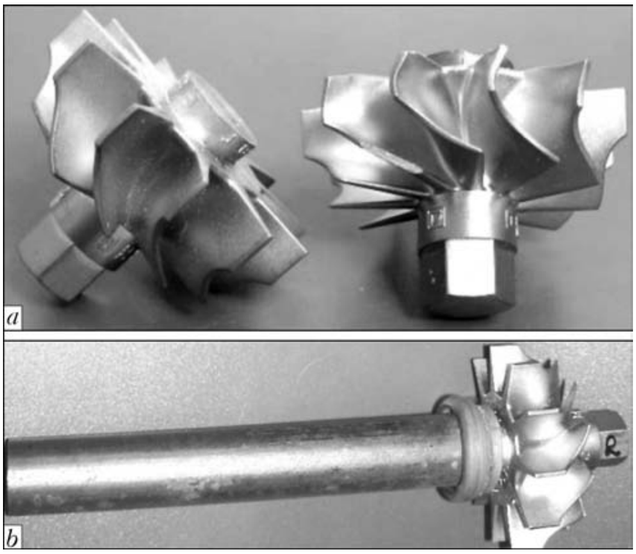
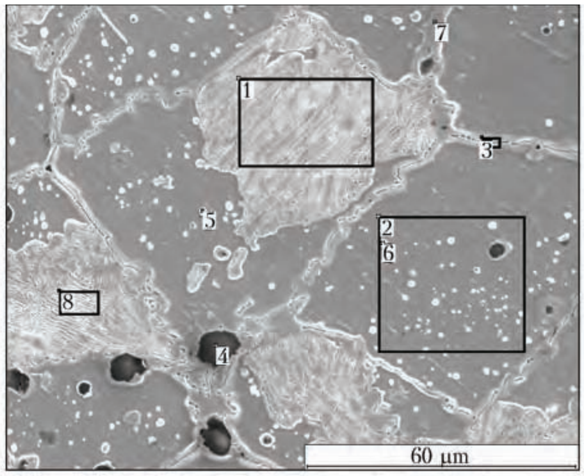


Figure 1. Wheels for TCR shafts of steel AISI310 produced by the PIM technology (*a*), and welded TCR shaft (*b*)

ing wheels of steel AISI310 to shanks of structural steel 40Kh under different conditions of conventional and combined FW [7, 8].

Experiments on FW were carried out by using machine ST120, which was upgraded to implement different thermal-deformation cycles corresponding to conventional, inertia and combined FW [9]. Structure of the materials welded and of the bimetal joints was examined by optical microscopy («Neophot-32», Germany) and by scanning electron microscopy (SEM) (JSM-35CA, JEOL, Japan). X-ray spectrum microanalysis (EDS-analyser INCA-459, «Oxford Instruments», Great Britain; probe diameter — approximately 1 μm) was conducted, and microhardness of the joining zone metal was measured under a load of 1–5 N (microhardness meter M400, LECO, USA).

Parameters of the FW process were varied within the following ranges: heating pressure P_h = 50–150 MPa, forge pressure P_f = 150–300 MPa, peripheral velocity v = 0.5–2.5 m/s,



Spectrum	C	Si	Cr	Mn	Fe	Ni	Nb
1	0.14	0.63	19.13	0.69	52.76	24.19	2.44
2	0.11	1.19	24.30	0.10	50.18	21.69	2.43
3	0.18	0.88	21.40	1.12	53.87	22.57	0
4	0.42	83.91	8.49	1.61	2.97	1.46	1.14
5	0.40	1.02	24.65	0.94	51.73	21.18	0.08
6	0.12	0.72	24.37	1.12	52.62	20.15	0.90
7	0.16	0.28	24.49	0.29	53.16	21.61	0
8	0.20	0.90	18.35	1.30	56.84	21.45	0.96

Figure 3. Microstructure of the base metal of steel AISI310 (SEM), and results of X-ray spectrum microanalysis of metal of the investigated regions (wt.%)

heating time t_h = 5–30 s, deceleration time t_d = = 0.2–2.5 s, and burn-off rate v_b = 0.1–1.0 m/s. Diameter of the billets welded was 15 mm.

Microstructures of the base metal of steel AISI310 and compositions of structural components are shown in Figures 2 and 3. Steel AISI310 has equiaxed crystalline structure with grain size of about 60 μm. Optical microscopy allows revealing dark and light grains (Figure 2, *a*), individual pores with a size of up to 15 μm located along the grain boundaries, and randomly arranged particles of non-metallic SiO_2 inclusions with a size of 2–10 μm (Figure 3, spectrum 4).

Structure of the dark grains (see Figure 3, spectra 1 and 8) is lamellar, consisting of alternate light- and dark-etchable laminae less than 1 μm thick. The content of chromium in the grains

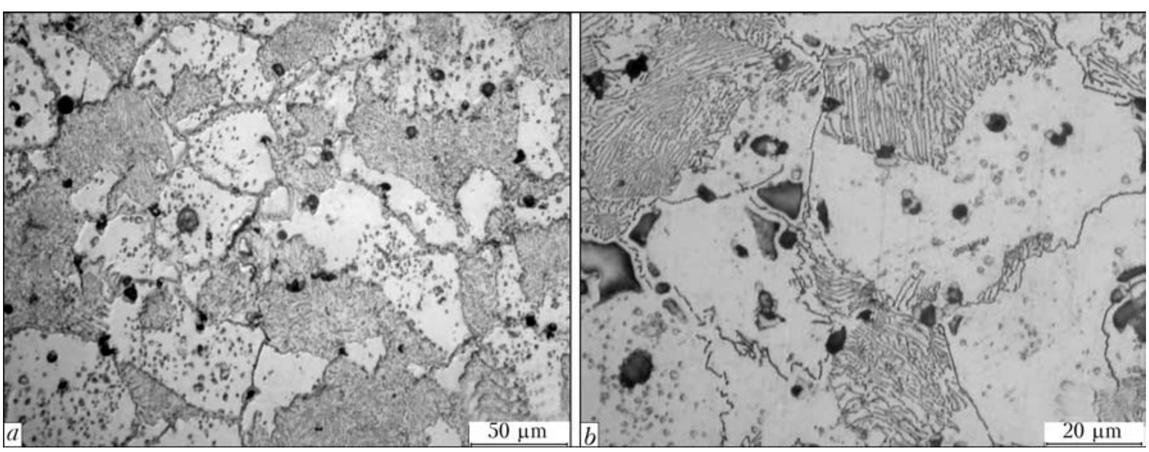


Figure 2. Microstructures of steel AISI310 (optical microscopy)

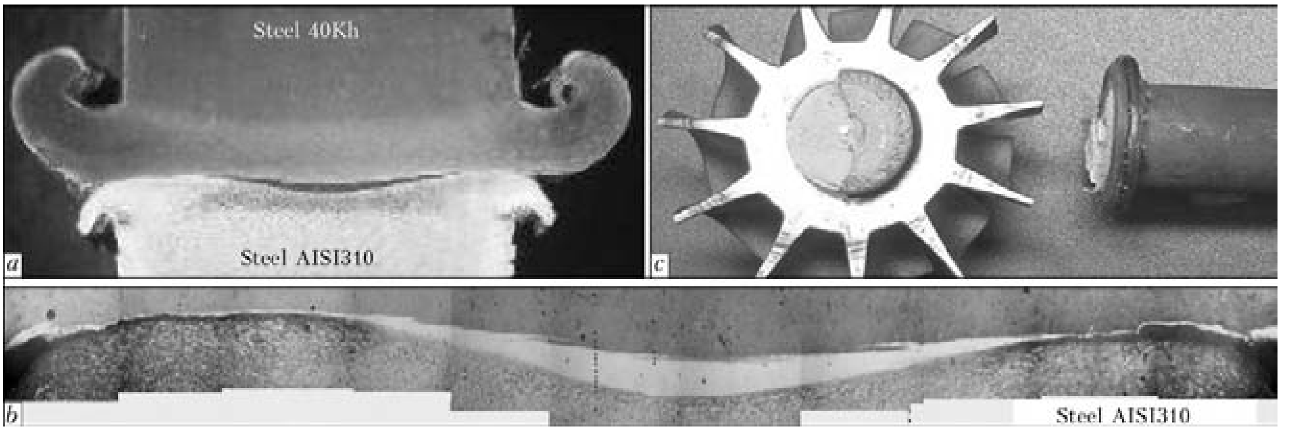


Figure 4. Macrosection of the AISI310–40Kh steel joint made in mode 1 (*a*), panoramic view of section of the welded joint (*b*), and welded TCR shaft after tensile tests (*c*)

with a lamellar structure is somewhat lower, compared to its content in the light grains. Chemical composition of the light grains (spectrum 2) corresponds to the requirements of standard AISI, except for the increased niobium content. Dispersed (1–2 μm) particles of a round shape (spectra 5 and 6) can be distinguished in the bulk of the light grains. These particles do not differ in chemical composition from those in the bulk of the dark grains. However, they have lower niobium content. No substantial liquation of alloying elements and impurities along the grain boundaries is fixed (spectra 3 and 7). Presence of the grains with a lamellar structure evidences that the sintering process was performed at a temperature close to T_S [10–12].

Formation of the dissimilar joints between steels AISI310 and 40Kh was investigated under different thermal-deformation cycles corresponding to conventional and combined FW.

Mode 1 («soft» mode) was conventional friction welding (CFW) [7, 8] with the minimal values of P_h, P_f and t_d, and the maximal values of v and t_h in the ranges under investigation. Mode 2 («rigid» mode) was CFW with the maximal values of P_h and P_f, and the minimal values of v, t_h and t_d in the ranges under investigation. Mode 3 was the technology developed by the E.O. Paton Electric Welding Institute for combined FW with controlled deformation. For this technology the values of v and P_h were set proceeding from the requirement to provide the certain deformation rate (burn-off rate) in heating, which was varied during the heating process within the v_b = 0.1–1.0 m/s range, forge pressure being applied at a stage of rotation deceleration regulated following the preset program [9]. In combined FW the values of t_h and t_d were set on the basis of the results of preliminary experiments, so that the total length loss for all the modes investigated was Δ_w = 6 mm.

As seen from Figure 4, *a*, deformation of the billets during welding in mode 1 occurs mainly due to steel 40Kh. The transition zone with a width varying from 25 μm in the peripheral part of a section to about 500 μm at the centre, which

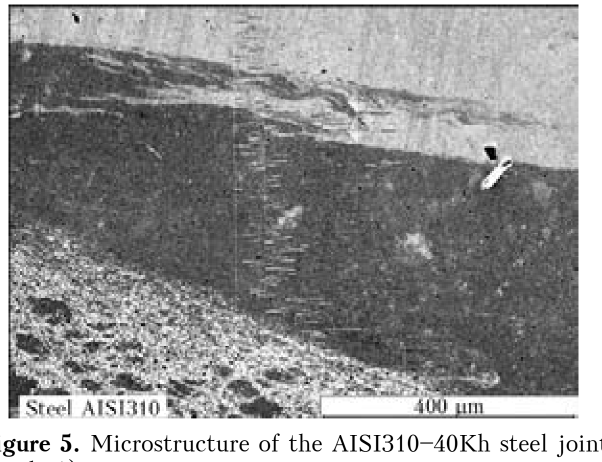


Figure 5. Microstructure of the AISI310–40Kh steel joint (mode 1)

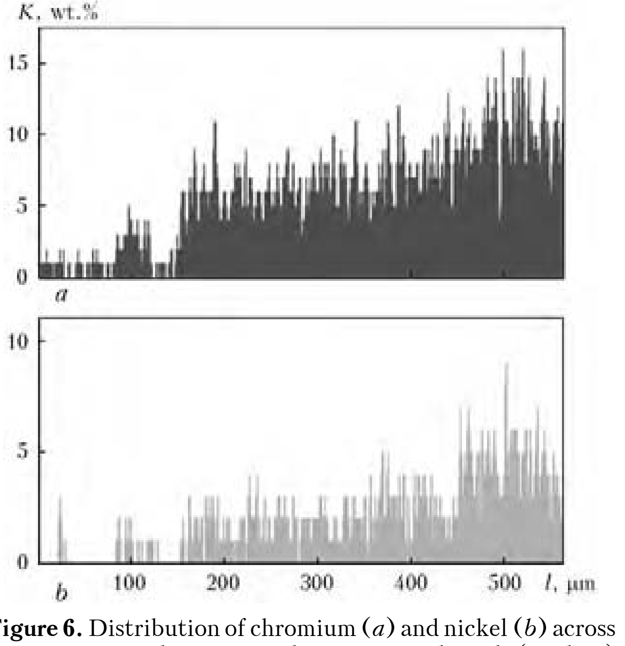


Figure 6. Distribution of chromium (*a*) and nickel (*b*) across the joining zone between steels AISI310 and 40Kh (mode 1)

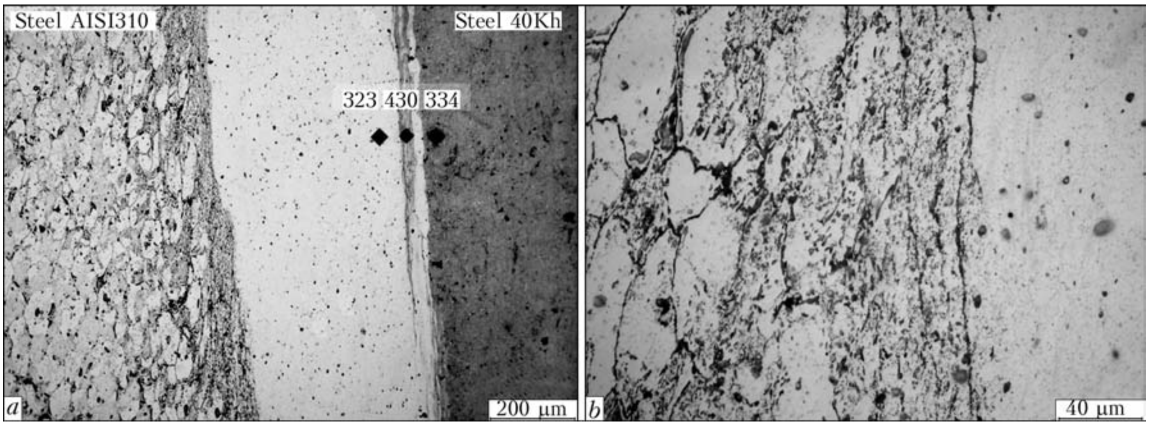


Figure 7. Microstructures of the transition zone (*a*) (indentations *HV*3, MPa·10^{-1}) and metal of the joint on the side of steel AISI310

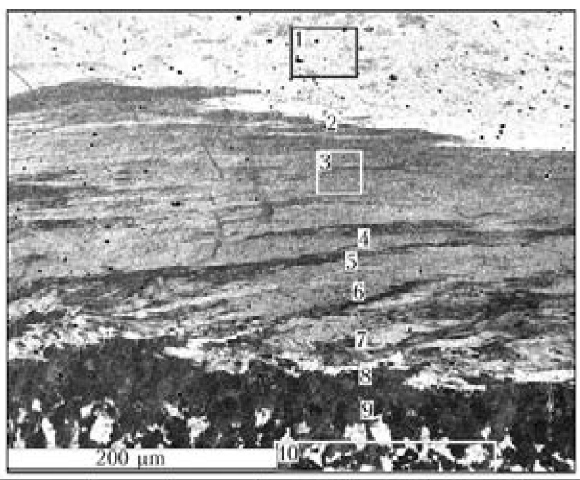
is non-uniform across the sections of the billets, can be seen within the joining zone (see Figure 4, *b*).

X-ray spectrum microanalysis fixed a variable composition of the transition zone across the width (see Figures 5 and 6). The presence of uniformly distributed non-metallic SiO_2 inclusions in the transition zone proves that the latter forms on the side of steel AISI310. Size of the SiO_2 particles in the transition zone is 3–4 μm, this being indicative of their partial dissolution. Monotonous growth of the concentration of chromium and nickel in transition from steel 40Kh to steel AISI310 (Figure 6) may be related to diffusion migration of these elements during a comparatively long stage of friction heating (t_h = = 30 s). Interlayers of an intermediate composition (Figures 5 and 6), having an increased hardness (Figure 7), can be seen in the transition zone on the side of steel 40Kh. Formation of this composition of interlayers may result from dilution of contact volumes of metal of the steels welded in the liquid or solid-liquid state at the initial stages of FW. These interlayers lead to deterioration of ductility and decrease in corrosion resistance of the joints [13, 14].

Deformed, radially elongated grains can be seen in the zone of the thermal-deformation effect on the side of steel AISI310 (see Figure 7), residual porosity of the base metal being conserved in this zone. Steel AISI310 has a fibrous structure with structural components up to 10 μm in size in the immediate proximity to the transition zone. No segregations of non-metallic SiO_2 inclusions and porosity were detected in this zone.

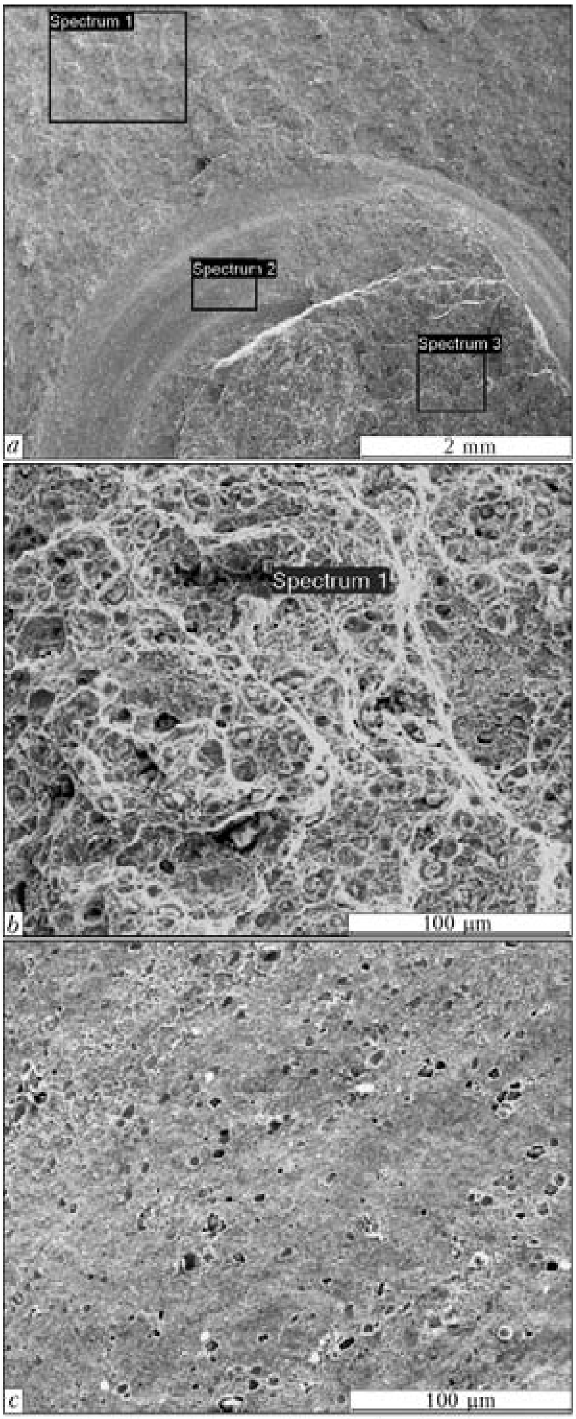
Annealing and repeated etching of the welded joints were carried out to reveal structure of the transition zone. As a result, the transition zone was found to have a lamellar structure and a composition intermediate between the steels welded (Figure 8, spectra 3–8).

In tensile tests, fracture of the welded joints occurred in the joining zone (see Figure 6, *b*). Chemical composition of metal on both sides of the fracture was close to that of steel AISI310. Fractography of the fractures revealed the presence of the two types of fracture within the limits of a section, i.e. tough and quasi-brittle (Figure 9). The increased niobium content was detected over the entire fracture surface and, particularly, in the circumferential region of the quasi-brittle fracture (see Figure 9, spectrum 2).



Spectrum	Si	Cr	Mn	Fe	Ni	Nb
1	1.77	21.93	0	51.76	22.20	2.33
2	0.85	16.51	0	57.09	25.55	0
3	0.82	12.77	1.52	72.14	11.05	1.70
4	0	10.65	0	80.97	8.38	0
5	0.62	11.38	1.33	73.68	13	0
6	0	10.05	1.55	74.22	12.86	1.32
7	0.49	10.83	1.45	71.76	15.47	0
8	0.67	8.62	0.97	81.25	8.49	0
9	0	0.78	1.18	98.04	0	0
10	0	1	0.99	98.01	0	0

Figure 8. Microstructure of the AISI310–40Kh steel joint made in mode 1 after annealing, and results of X-ray spectrum microanalysis of metal of the investigated regions (wt.%)



Spectrum	Si	Cr	Mn	Fe	Ni	Nb
1	2.91	22.20	0.42	51.57	16.74	6.16
2	1.64	25.11	0	40.17	16.88	16.20
3	3.16	25.03	2.66	44.15	20.24	4.75

Figure 9. Fracture surface of the AISI310–40Kh steel joint (mode 1) on the side of steel 40Kh (*a*), regions of tough (*b*) and quasi-brittle (*c*) fractures, and results of X-ray spectrum microanalysis of metal of the investigated regions (wt.%)

Results of the fractographic examinations show that fracture of the joints occurs between the transition zone and steel AISI310, and is localised in segregation clusters of the redundant phases with the increased niobium content.

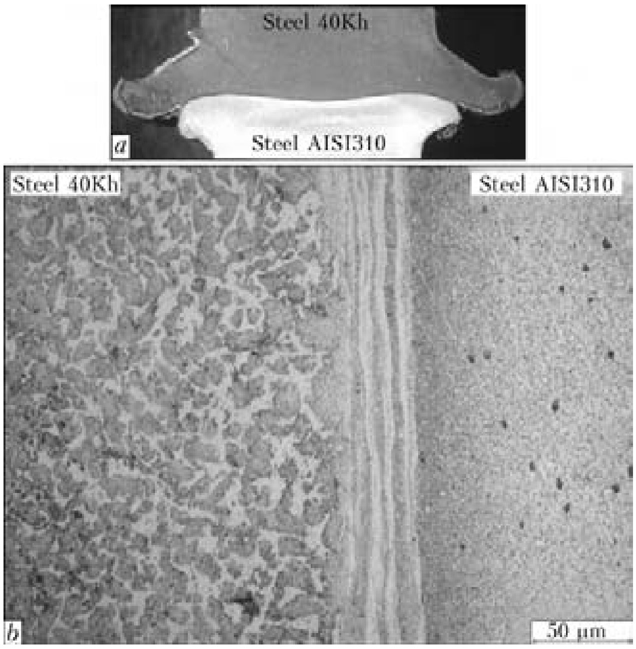
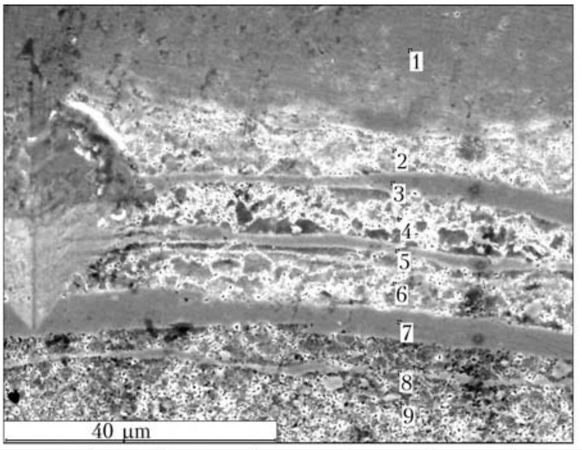


Figure 10. Macrosection (*a*) and microstructure (*b*) of the AISI310–40Kh steel joint (mode 2)

Therefore, the presence of an insignificant porosity and dispersed inclusions of SiO_2, having a high melting point (T_{melt} = 1713 °C), in the base metal of steel AISI310 does not exert any substantial effect on formation of the welded joints. At the same time, the presence of the segregations of niobium, which forms eutectic (T_{melt} = 1355 °C) with iron and leads to the «contact melting» phenomenon [15], in the base metal exerts a negative effect on the composition and mechanical properties of the joints in the «soft» mode of CFW.

Structure of the joint made in the «rigid» mode of CFW (mode 2, after annealing) is shown in Figure 10. The 40–60 μm wide transition zone, which is almost uniform across the section of the billets and consists of alternate layers with different etchability, was fixed in the joining zone. The character of variations in the concentrations of chromium and nickel (Figure 11) when passing from steel 40Kh to steel AISI310 cannot be caused by diffusion migration of these elements, but is a result of dilution of the steels welded.

Analysis of microstructure of the welded joints made at t_h = 0.5–1.5 s (initial stage of the FW process) showed that the lamellar structure of the joining zone was formed at the early stages of the FW process, and was determined by the character of contact interaction of the faying surfaces at the set level of the process parameters. At a low peripheral velocity and a high heating pressure the predominant mechanism of contact interaction at the initial stages of FW is the process of deep tearing out and dilution of contact



Spectrum	Si	Cr	Mn	Fe	Ni	Nb
1	0.47	0.62	0	98.60	0	0.31
2	0.83	5.49	1.35	73.78	18.54	0
3	0.84	4.28	1.01	90.03	3.84	0
4	1.78	5.01	0.39	63.81	27.04	1.97
5	0.23	8.10	1.86	71.49	18.32	0
6	0.59	8.45	1.03	67.30	22.14	1.49
7	0.61	6.40	0	87.76	5.23	0
8	1.56	13.55	1.46	63.58	19.53	0.32
9	1.33	11.46	0	54.60	25.37	7.24

Figure 11. Microstructure of the AISI310–40Kh steel joint (mode 2), results of SEM and X-ray spectrum microanalysis of metal of the investigated regions (wt.%)

volumes of the materials welded in the plasticised or solid-liquid state, going to a depth of several hundreds of microns [16, 17].

Therefore, the key feature of the joints made in the «rigid» mode of CFW is the presence of alternate constant-composition interlayers (Figure 11), including those corresponding to steels of the martensitic (see Figure 11, spectra 3 and 7) and austenitic grades (Figure 11, spectra 2, 4–6 and 8). It is commonly supposed [7, 8] that FW is a solid-state process of joining of materials. However, the presence of the lamellar structure consisting of alternate «alloys» of different compositions allows a conclusion that the local melting processes occurring in the contact interaction zone, at least at the initial stages of the FW process, play an important role in formation of the dissimilar joints.

No interlayers with the increased niobium content were fixed in the joint made in mode 2, despite the presence of local clusters of this element in the immediate proximity to the joining zone (see Figure 11, spectrum 9). The main difference between the «rigid» and «soft» modes of CFW consists in the burn-off rate during the friction heating process (v_b = 0.9 mm/s for mode 2, and 0.15 mm/s for mode 1). It is likely that a high burn-off rate and a short time of the heating stage (t_h = 6 s) in the «rigid» mode of CFW prevent formation of interlayers with the increased niobium content.

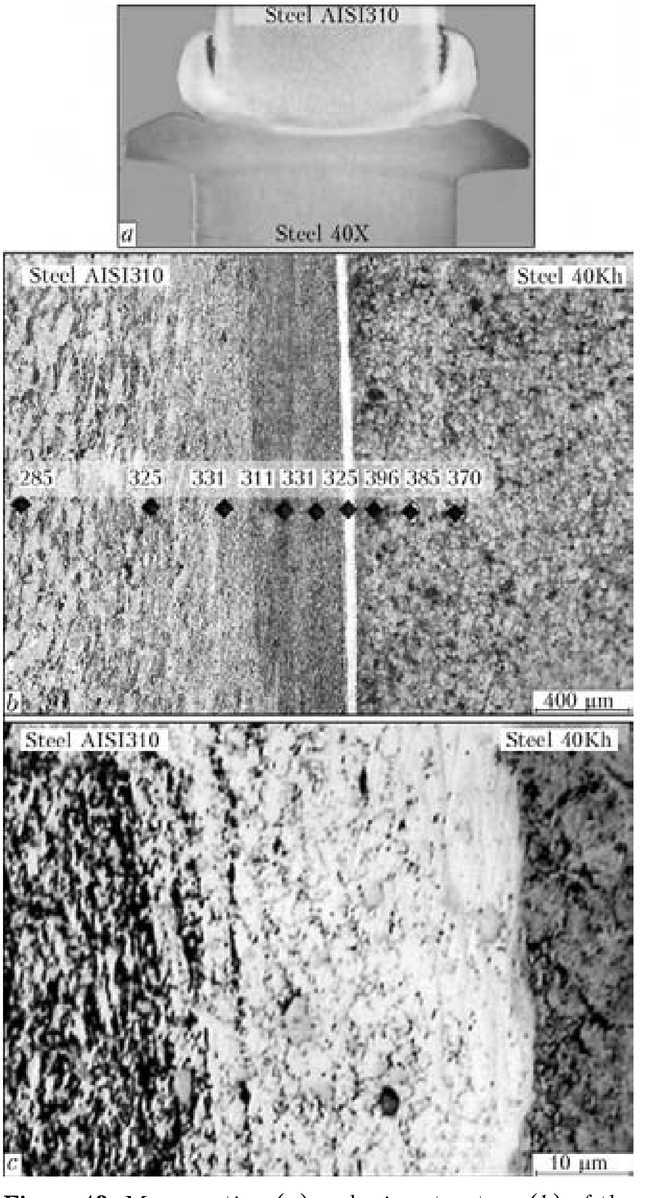
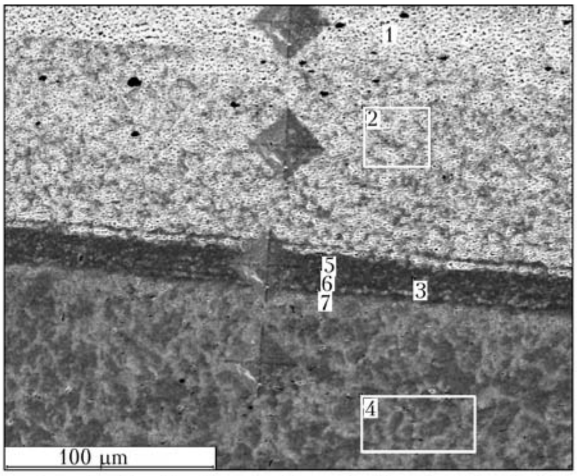


Figure 12. Macrosection (*a*) and microstructure (*b*) of the AISI310–40Kh steel joint, mode 3 (indentations *HV*3, MPa·10^{-1})

The joint made in mode 3 (combined FW with controlled deformation) was found to contain no increased-hardness interlayers. The up to 40 μm wide transition zone, being almost uniform across the section (Figure 12) and having a grain size of 5–6 μm, was fixed in this joint. The composition of metal of the transition zone across its width corresponded to that of steel of the austenitic grade (Figure 13, spectra 2, 3, 5–7), this preventing any decrease in corrosion resistance of the joints and eliminating the risk of cracking.

Of notice is the absence of local segregations of phases with the increased niobium content and the dramatic change in the concentrations of chromium and nickel in passing from steel 40Kh to steel AISI310, this being indicative of minimisation of dilution of the steels in the solid-liq-



Spectrum	Si	Cr	Mn	Fe	Ni	Nb
1	1.71	26.15	1.25	47.44	21.09	2.37
2	0.56	23.31	1.47	53.88	20.39	0.40
3	1.22	22.67	0	54.03	20.62	1.46
4	0.55	1.26	1.61	96.58	0	0
5	0.67	23.40	0.47	56.23	18.88	0.36
6	0.22	19.37	2.45	60.92	17.04	0
7	0.53	18.20	0	58.59	22.68	0

Figure 13. Microstructure of the AISI310–40Kh steel joint (mode 3), results of SEM and X-ray spectrum microanalysis of metal of the investigated regions (wt.%)

uid state and insignificant development of the diffusion processes in the joining zone. The thermomechanically affected zone with fine-grained, dynamically recrystallised structure is immediately adjacent to the transition zone. No pores and non-metallic inclusions of SiO_2 were fixed in this zone, which was clearly shown by analysis of microstructure of the joint both in the as-welded state (see Figure 13) and after annealing (Figure 14). Disappearance of the SiO_2 particles from the joining zone may be related to their partial dissolution and the earlier established phenomenon of destruction of oxides by a flow of moving dislocations [18–21], including under the thermal-deformation conditions of inertia and combined FW.

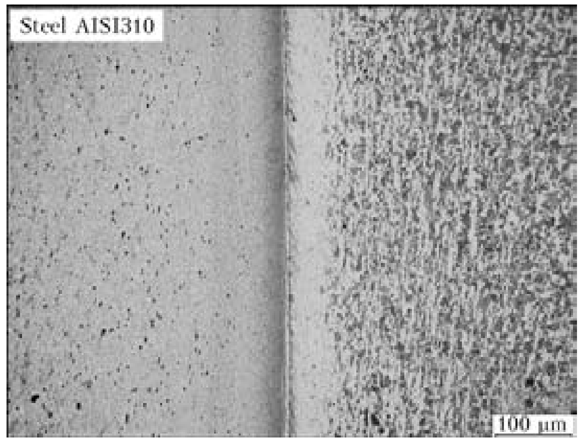


Figure 14. Microstructure of the AISI310–40Kh steel joint after annealing (mode 3)

Fracture of the joints in mechanical tests occurs in the base metal of steel AISI310 (Figure 15). The joints had tensile strength at a level of σ_t = 580–630 MPa. As shown by measurements of microhardness, metal of the joining zone with the fine-grained, dynamically recrystallised structure is characterised by the increased values of strength (see Figure 12), which is attributable to a substantial decrease (from 60 to 5–6 μm) in size of structural components.

Comparative analysis of structure and chemical composition of the zone of joints between PIM-steel AISI310 and steel 40Kh, made under different thermal-deformation cycles of FW suggests the following mechanism of formation of the transition zone in FW of the investigated materials combination.

At the initial stage of the FW process, because of a lower value of thermal conductivity of the austenitic steel, the surface of maximal shear deformations («friction plane») shifts towards austenitic steel AISI310. The «friction surface shift» phenomenon is known for other combinations of dissimilar materials as well [22–24]. The maximal values of the heating temperature are

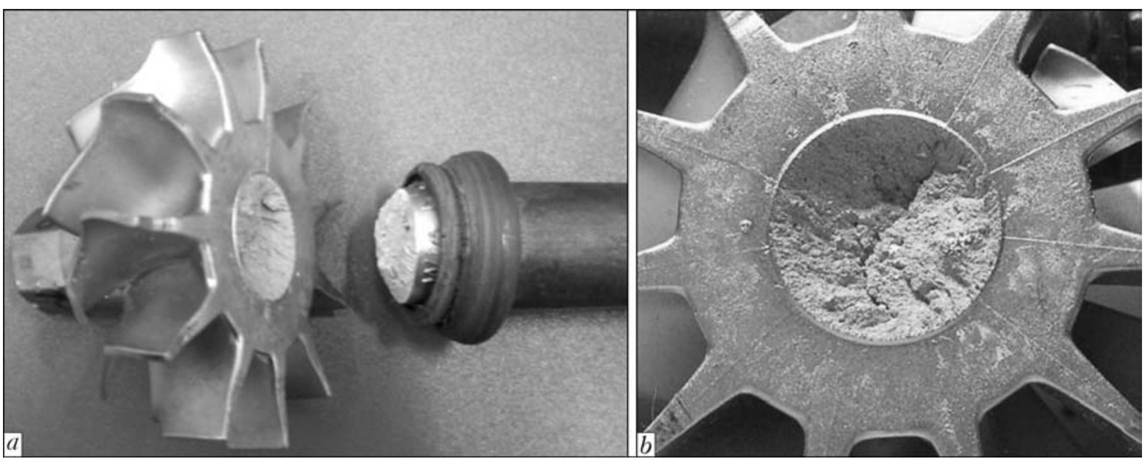


Figure 15. Welded TCR shaft after tensile tests (*a*), fracture surface in base metal of steel AISI310 made by the PIM-technology (*b*)

fixed in the friction plane. The transition zone, which in fact is an AISI310 steel based alloy «deposited» on steel 40Kh, forms between the friction plane and steel 40Kh. Burn-off of the billets and, therefore, displacement of the transition layer outside the section do not occur at the initial stage of the heating process.

As duration of the heating stage increases, width of the transition zone in peripheral parts of the section remains almost unchanged, whereas in the central part of the section it grows due to further displacement of the friction plane towards steel AISI310. This is proved by metallographic examinations of the joints made at different durations of the heating stage. As a result, the shape of the transition zone in the central part of the section becomes convex, directed to steel AISI310.

When CFW is performed in the «soft» mode, in the friction plane, where the heating temperature and tangential deformations are maximal, the rate of diffusion of alloying and impurity elements may be commensurable with that of the melts. As a result, clusters of low-melting point phases, in particular of the eutectic phases of iron with niobium, the redundant content of which was fixed in the base metal of steel AISI310, form in this zone.

The formed lamellar structure of the transition zone persists in passing to the quasi-stationary stage of heating, which is accompanied by burn-off of the billets. The process of burn-off of the billets occurs mainly due to steel 40Kh, the transition zone metal being partially displaced outside the section in the form of a thin layer deposited on the reinforcement surface of steel 40Kh. As the plane of maximal shear deformations is located in the austenitic steel, restoration of the «deposited» layer takes place simultaneously, i.e. there comes the state of equilibrium between the processes of formation and displacement of the transition zone metal.

The width and shape of the transition zone are determined by a difference in thermal-physical characteristics of the steels welded, and by the friction process parameters. «Soft» mode 1 is characterised by a low value of burn-off rate (about 0.15 mm/s). In this case the width of the transition zone is maximal, and the conditions for liquation of impurity elements and formation of low-melting point phases in the friction plane are most favourable. The applied force of forging performed on the non-rotating billets causes decrease in thickness of the transition zone, as well as partial displacement of the variable-composition interlayers and clusters of low-melting point phases from the joint, the remainder determining mechanical and service (corrosion, fatigue) properties of the welded joint.

As the peripheral rotation velocity is decreased and the heating pressure is increased («rigid» mode 2 of CFW), the deeper and deeper layers of metal of the billets welded are involved in the shear (tangential and radial) deformation process, burn-off rate substantially grows (up to 0.9 mm/s), and welding time is reduced. As a result of such a «rigid» thermal-deformation cycle of FW, the narrow (up to 60 μm) transition zone forms in the joint, consisting of alternate variable-composition interlayers, including those corresponding to steel of the martensitic grade. These interlayers forming at the initial stages of the FW process are not fully displaced from the contact zone at the subsequent stages of heating, and persist in the welded joint after forging.

As forging in CFW is performed after stopping of rotation of the billets, the effect on the transition zone metal is characterised by the presence of the radial deformation component. Burn-off occurs mainly due to deformation of metal in the heat-affected zone of steel 40Kh. Only decrease in thickness of the variable-composition interlayers takes place in this case.

The joints made by combined FW with controlled deformation (mode 3) are free from the above imperfections of structure. The fact that the transition zone contains no alternate interlayers corresponding in composition to martensitic and austenitic steels is caused by a peculiar quality of the initial stage of the FW process with controlled deformation. The process parameters (pressure, peripheral velocity) at this stage were set based on the requirement to minimise the processes of deep tearing out and dilution of contact volumes of the materials welded.

The absence of local segregations of low-melting point phases in the joint is caused by minimisation of duration of the quasi-stationary stage of heating, which is achieved by providing the preset rate of deformation (burn-off rate) of the billets at a certain combination of pressure and peripheral velocity values.

The forging stage plays the key role in formation of the joints. Programming of the duration of the rotation deceleration stage and application of increased forge pressure at this stage allow the burn-off rate and the intensity of deformation of contact volumes of the steels welded to be considerably increased. The fixed dramatic change in the concentrations of chromium and nickel within the joining zone in mode 3 is indicative of minimisation of the processes of dilution of the steels welded and local melting in the contact zone. Substantial increase in the intensity of the thermal-deformation effect on the joining zone metal in combined FW is proved also by the absence in this zone of the SiO_2 particles, which are present in the base metal of steel AISI310 and transition zone of the joints made in the «soft» mode of CFW.

Therefore, the peculiarities of structure and composition of metal of the AISI310 to 40Kh steel joints made by CFW and combined FW are determined by the character and intensity of deformation in the contact zone at the initial, quasi-stationary and final stages of the process when using the above types of friction welding. The peculiar feature of the deformation effect in the contact zone at the final stage of formation of the joints in CFW is the presence of the radial component caused by applying the increased forge pressure to the non-rotating billets. Forging in this case provides an insignificant decrease in width of the transition zone and thickness of the brittle interlayers formed at the initial stages of the FW process.

Combined FW with controlled deformation creates conditions for minimisation of the processes of local melting and dilution of metal volumes in the solid-liquid state. The effect on the joining zone metal at the final stage of the FW process is characterised by the presence of both radial and tangential components under conditions of the temperature gradient growing during the rotation deceleration process. Localisation of deformation and a substantial increase in its intensity at the final stage of welding provide dispersion and destruction of oxide phases, as well as displacement of interlayers outside the section welded. The transition zone with a fine-grained, dynamically recrystallised structure and a dramatic change in the concentration of alloying elements is formed in the joint.

The data obtained served as a basis for the development of the technology for FW of the wheels of nickel superalloy Inconel 713C made by the PIM-technology to shanks of steel 40Kh.

CONCLUSIONS

1. Characteristic features of heat-resistant steel AISI310 produced by the powder injection moulding technology (feed stock — «Catamold») are the equiaxed crystalline structure with a grain size of about 60 μm, presence of austenite grains with a homogeneous and lamellar structure, insignificant residual porosity, as well as presence of uniformly distributed non-metallic inclusions of silicon dioxide, 2–10 μm in size, and segregations of phases with the increased niobium content.

2. In the «soft» mode of CFW of steel AISI310 to steel 40Kh, the 25 to 500 μm wide transition zone forms within the joining zone. This transition zone is non-uniform across the section, has a lamellar structure and is an AISI310 steel based «alloy» deposited on steel 40Kh. Constant-composition interlayers, including those corresponding to steel of the martensitic grade, are revealed in the transition zone on the side of steel 40Kh. Fracture of the joints in tensile tests occurs between the transition zone and steel AISI310. It is localised in segregation clusters of the redundant phases with the increased niobium content.

3. No segregations of low-melting point phases were revealed in the joints made in the «rigid» mode of CFW. However, alternate constant-composition interlayers corresponding to steels of the martensitic and austenitic grades were fixed. These interlayers form at the initial stages of the FW process. They are not fully displaced from the contact zone at the subsequent heating stages and in forging performed after stopping of rotation of the billets.

4. The presence of the lamellar structure consisting of alternate «alloys» of different compositions in the joints made by CFW is indicative of the dilution of the steels welded both in the plasticised and solid-liquid states occurring in the contact interaction zone at the initial stages of the FW process.

5. The technology was developed for combined FW with controlled deformation. With this technology the values of the process parameters are set based on the requirement to provide the certain deformation rate (burn-off rate) at the heating stage, while the forge pressure is applied at a stage of rotation deceleration that is controlled following the preset program.

6. The joints made by combined FW with controlled deformation have fine-grained, dynamically recrystallised structure with the up to 40 μm wide transition zone that is uniform across the section. The composition of metal of the transition zone across its width corresponds to steel of the austenitic grade. This metal contains no pores and no segregations of alloying elements and non-metallic inclusions. The transition zone–steel 40Kh interface is characterised by a dramatic change in the concentration of alloying

elements and absence of increased-hardness interlayers.

7. Parts of the materials made by the powder injection moulding technology can be applied to provide sound bimetal joints by using friction welding, subject to setting the appropriate values of the process parameters.

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