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FRICTION WELDING OF POWDER INJECTION MOULDED PARTS

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Abstract. *Microstructure of heat-resistant alloy IN713C produced by the powder injection moulding (PIM) technology was investigated. The bimetal turbochargers were produced by friction welding (FW) of PIM-alloy IN713C wheels to steel 40X rods under different conditions of direct drive and hybrid FW. Experimental data are given on evaluation of microstructure of dissimilar PIM-alloy IN713C – steel. The results of the scanning electron microscopy of welded joints using JAMP-9500F Field Emission Auger Microprobe "JEOL" are presented. The joints made by hybrid FW with controlled deformation have fine-grained, dynamically recrystallised structure with the up to 5 µm wide transition zone. The metal of joining zone contains no pores and no segregations of alloying elements and non-metallic inclusions. The transition zone metal is characterised by a dramatic change in the concentration of alloying elements and the absence of variable-composition interlayers. The parts of the PIM-materials can be applied to provide sound bimetal joints by using FW.*

Keywords*: friction welding, microstructure, alloy IN713C*

1. INTRODUCTION

One of the efficient powder metallurgy method is powder injection moulding (PIM) (Hamill, 1993, Simonov *et al.* 2005, Graboy and Thom, 2005, Sam, 2007, Dovydenkov *et al*. 2008, Salk, 2011). In the last years, PIM technology has been gaining an increasingly wider acceptance owing to a number of advantages over traditional methods of metal processing, first of all in manufacture of complex-geometry and mass-produced parts.

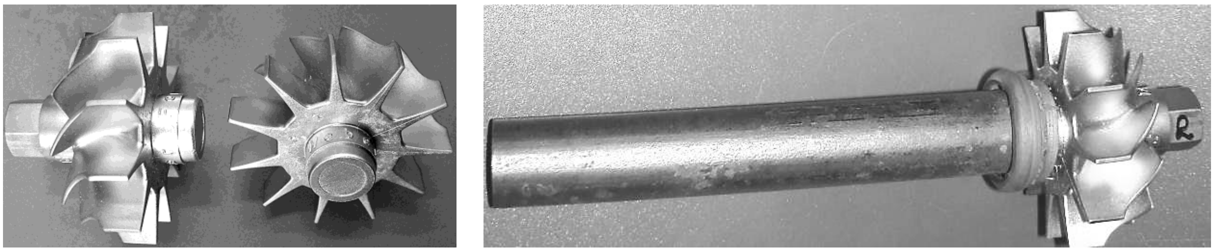
Feed stock for the PIM-technology is produced, as a rule, from fine powders mixed with a thermoplastic binder. Moulding is performed by using standard automatic thermoplastication devices into the moulds, which are manufactured with allowance for subsequent shrinkage of a part in sintering. A binder is removed from castings after the injection moulding stage, and then the resulting powder billets are subjected to annealing to provide dense parts. According to the data given in (Simonov *et al.* 2005), density of the finished parts produced by the PIM-technology is 96 to 100 % of its theoretical value. Pores and non-metallic inclusions detected in the parts 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, which are wheels of bimetal turbocharger for automotive engine. 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 wheels for the turbochargers.

The technological cycle of manufacture of the bimetal turbochargers provides for the use of friction welding (FW) (Lebedev and Chernenko, 1987, Hamill, 1993, Friction Welding, 2006) of a nickel superalloy wheel to a structural steel shank. It is of scientific and practical interest to study the effect of structure of the PIM- alloy IN713C on the weldability to steel to manufacture the bimetal turbocharger. The purpose of this study was to investigate formation of dissimilar joints between the PIM- alloy IN713C to steel 40X in different thermal-deformation cycles of FW for manufacture of the bimetal turbochargers.

2. EXPERIMENTAL PROCEDURE

General view of the wheels for the bimetal turbochargers made by the PIM-technology (BASF "Catamold" feedstock (Graboy and Thom, 2005)) is shown in Fig. (1), a. Chemical composition of the materials welded is given in Tab. (1). Mechanical properties of the materials are given in Tab. (2). Alloy IN713C is a nickel-base material with a content of Al, Ti and Nb (strengthening γ'-phase forming elements) equal to more than 8 %, this leading to its high deformation resistance and sensitivity to cracking in welding and heat treatment. The bimetal turbochargers (Fig. (1b)) were produced by joining wheels of alloy IN713C to shanks of l steel 40X under different conditions of conventional or direct drive FW (Fig. (2a)) and hybrid FW (Fig. (2b)).



(a) (b)

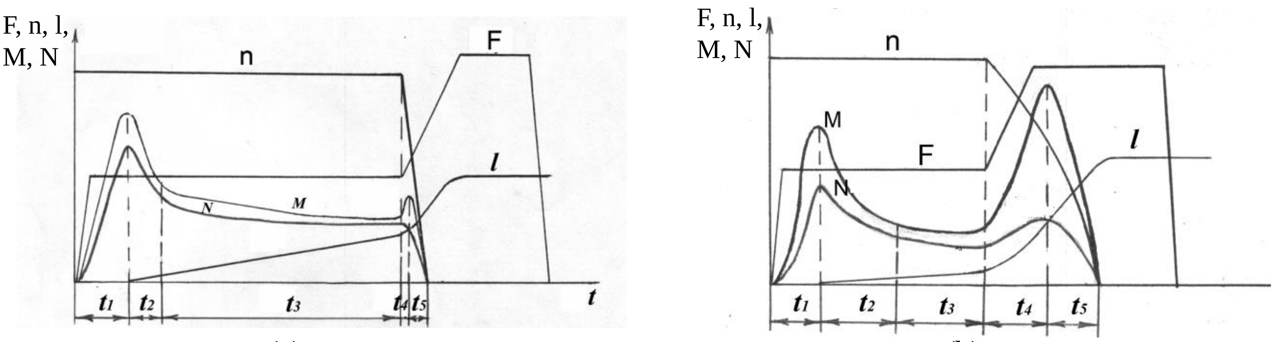
Figure 1. Wheels of PIM-alloy IN713C (a), welded turbocharger (b)

Table 1. Chemical composition of materials welded

Alloy grade	Content of elements, wt. %									
	C	Cr	Ti	Al	Mo	Nb	Si	Mn	Fe	Ni
IN713C	<0.2	13-15	0.75-1.25	5.5-6.5	3.5-5.5	1-3	<0.35	<0.35	<1	Base
Steel 40X	0.36-0.40	0.8-1.1	-	-	-	-	<0.35	0.5-0.8	Base	<0.3

Table 2. Mechanical properties of materials welded

Alloy grade	σ_y, MPa	σ_t, MPa	δ, %	ψ, %
IN713C	>690	>760	>3	-
Steel 40X	720	860	14	69



(a) (b)

Figure 2. Cycle patterns of the process of conventional (a) and hybrid (b) friction welding: F – force, M – moment of friction forces, N – heat release power, n – rotation velocity, *l* – length loss, *t* - time

Experiments were carried out by using machine ST120, which was upgraded to implement different thermal-deformation cycles corresponding to conventional and hybrid FW. The technology was developed for hybrid friction welding with controlled deformation (Patent No. 46460, 2004). 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.

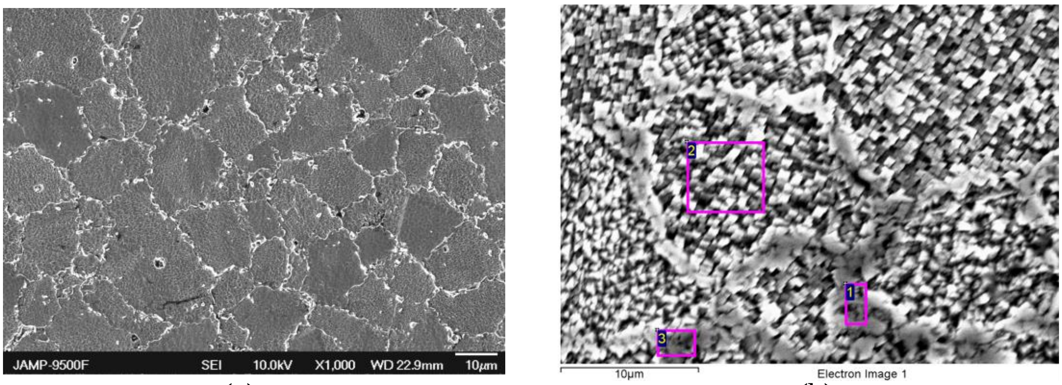
Structure of the materials welded and of the bimetal joints was examined by optical microscopy (“Neophot-32”) and by scanning electron microscopy (JSM-35CA, “JEOL”). Investigation of distribution of chemical elements were carried out by using JAMP-9500F Field Emission Auger Microprobe “JEOL” equipped with the “Oxford Instruments”EDS-analyser INCA-450. Microhardness of the joining zone metal was measured under a load of 5 N (microhardness meter M400, “LECO”).

Parameters of the friction welding process were varied within the following ranges: heating pressure Ph = 100-250 MPa, forge pressure Pf = 250-400 MPa, peripheral velocity V = 1.0-2.5 m/s, heating time th = 5-30 s, deceleration time td = 0.2-2.5 s, and burn-off rate Vb = 0.1-1.0 mm/s. Diameter of the billets welded was 15 mm.

3. MICROSTRUCTURE OF THE ALLOY IN713C BASE METAL

Microstructure of the base metal of PIM-alloy IN713C, and chemical composition of structural components are given in and Fig. (3). PIM-alloy IN713C has equiaxed grain structure (Fig. (3a)). Grain size of the γ-phase is D_{90} = 20 μm (90 %

of grains are less than 20 μm in size). Dispersed particles of the strengthening γ'-phase (solid solution based on intermetallic compound $Ni_3(AlTi)$) are cubic in shape and uniformly distributed within grains of the γ-phase (Fig. (3b)). Size of the γ'-phase particles is about 500 nm both in the central and peripheral regions of the grains, in contrary to the casting alloy characterised by the intradendrite heterogeneity of distribution of the γ'-phase precipitates. Intergranular regions of PIM-alloy IN713C are depleted in chromium and rich in titanium and niobium. Carbide (Nb, Ti)C precipitates are distributed along the grain boundaries (Fig. (6a)). Scanning electron microscopy allows revealing individual up to 2 μm pores located along the grain boundaries.



(a) (b)

	Al	Ti	Cr	Ni	Nb	Mo
1	4.37	3.46	4.45	66.28	20.03	1.42
2	6.04	0.96	12.81	73.67	2.58	3.94
3	5.32	4.22	6.13	68.48	14.60	1.25

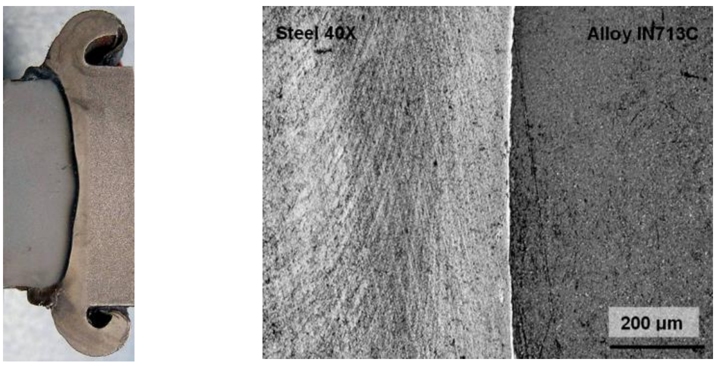
Figure 3. PIM-alloy IN713C microstructure (a), and fine structure (b), etching to reveal γ‘-phase

4. FORMATION OF ALLOY IN713C – STEEL 40X JOINTS

Formation of the dissimilar joints between PIM-alloy IN713C and steel 40X in different thermal-deformation cycles corresponding to conventional and hybrid FW was investigated.

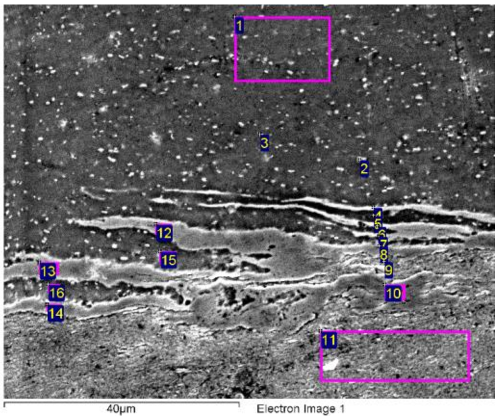
Mode 1 (“soft” mode) was conventional friction welding (CFW) (Lebedev and Chernenko, 1987, Friction Welding, 2006) with the minimal values of P_h, P_f and t_d, and the maximal values of V and t_h of the ranges under investigation. Mode 2 (“rigid” mode) was the technology developed by the E.O. Paton Electric Welding Institute for hybrid 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), which was varied during heating within the V_b = 0.1-1.0 m/s range, while forge pressure P_f was applied at a stage of rotation deceleration regulated following the preset program (Patent No. 46460, 2004). In hybrid FW the values of t_h and t_d were set on the basis of the results of preliminary experiments, so that total length loss Δl for all the modes investigated was Δl = 6 mm.

Macrosection of the alloy IN713C – steel 40X joint is shown in Fig. (4), a. Burn-off of the billets occurs practically due to steel 40X, this being characteristic of formation of welded joints between heat-resistant nickel alloys and steel. The up to 20 μm wide transition zone is detected in the joint (Figs. (4b) and (5)). Morphology of the carbide (Nb, Ti)C phase precipitates changes from almost continuous precipitates along the austenite grain boundaries in the base metal to uniformly distributed dispersed particles 1-2 μm in size in the joining zone and TMAZ (Fig. (5b)).

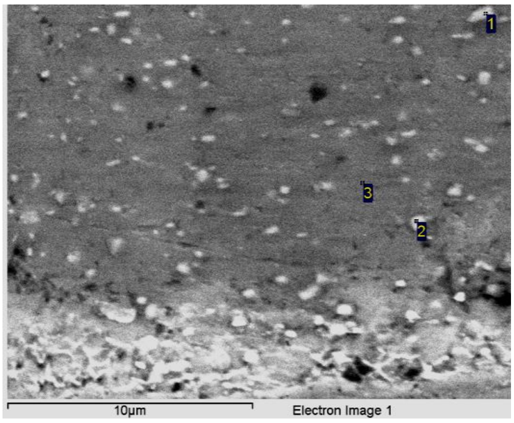


(a) (b)

Figure 4. Macrosection (a) and microstructure (b) of transition zone in alloy IN713C – steel 40X joint



(a)



(b)

	Al	Ti	Cr	Fe	Ni	Nb
1	6.91	1.22	13.55	0.00	76.99	2.33
2	6.58	0.71	12.03	0.75	77.93	2.00
10	1.86	0.67	5.48	65.74	26.25	0.00
11	0.00	0.00	1.33	98.68	0.00	0.00
12	4.28	0.79	12.12	8.85	73.97	0.00
13	4.41	0.00	10.81	16.64	68.14	0.00
14	3.68	0.00	9.97	22.90	63.45	0.00
15	6.15	1.20	10.86	2.59	76.20	3.00
16	5.54	0.83	10.23	4.07	78.30	1.03

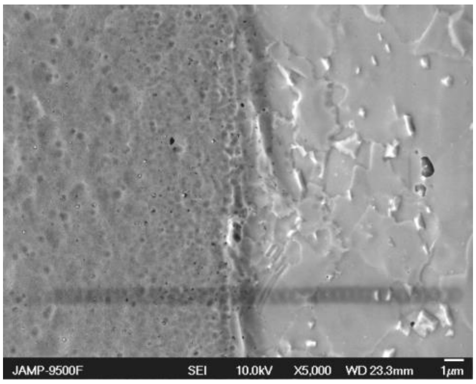
	Al	Ti	Cr	Fe	Ni	Nb
1	3.59	9.93	4.61	0.00	41.73	40.14
2	4.89	7.77	5.00	0.00	56.30	26.04
3	6.09	0.99	11.47	1.06	79.59	0.80

Figure 5. Microstructure of transition zone in alloy IN713C – steel 40X joining zone for mode 1, (a) and dispersed carbides (Nb, Ti)C in TMAZ of alloy IN713C (b)

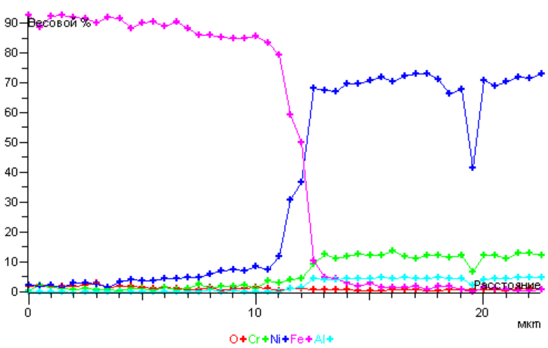
Alternate variable-composition interlayers are fixed in structure of the joints made by CFW in "soft" mode 1 (Fig. (5a)). These interlayers forming at the initial stages of the friction welding process are not fully displaced from the contact zone at the subsequent stages of heating, and persist in the 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 only radial deformation component. Only decrease in thickness of the variable-composition interlayers takes place in this case.

The joints made by hybrid friction welding with controlled deformation (mode 2) are free from the above imperfections of structure (Fig. (6a)). The joints have fine-grained, dynamically recrystallied structure with the up to 5 μm wide transition zone A substantial decrease in grain size is fixed in the thermomechanically affected zone (TMAZ) on the both sides of the joint. Size of grains of the γ-phase in alloy IN713C decreases from 20 to 2-5 μm, this being indicative of the dynamic recrystallisation process occurring in the joining zone.

The fixed dramatic change in the concentration of iron, nickel and alloying elements within the joining zone in mode 2 (Fig. (6b)) evidences both absence of melting and mixing of the materials welded in the contact zone. Size of the strengthening γ'-phase particles precipitated in cooling of the joint decreases approximately by an order of magnitude and this fact determines the microhardness distribution in the alloy IN713C – steel 40X joining zone (Fig. (7)).



(a)



(b)

Figure 6. Microstructure (a) and Fe, Ni, Cr, Al distribution (b) in alloy IN713C – steel 40X joining zone (mode 2)

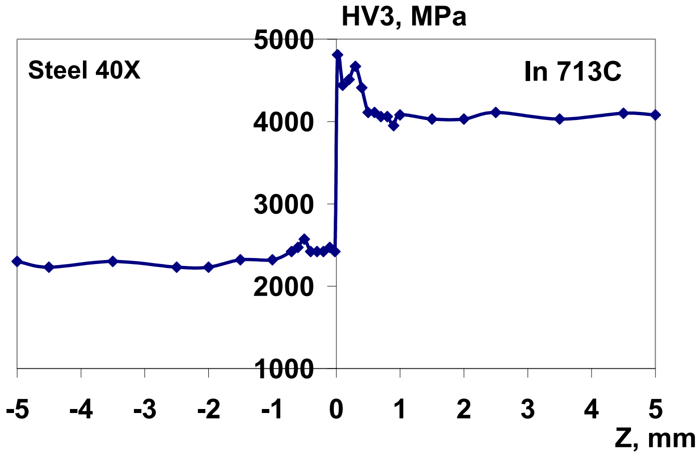


Figure 7. Microhardness distribution in the alloy IN713C – steel 40X joining zone (mode 2)

5. CONCLUSION

1. Characteristic features of the microstructure in heat-resistant alloy IN713C produced by the powder injection moulding (feedstock – "Catamold") are the equiaxed grain structure with grain size D_{90} = 20 μm and the insignificant residual porosity (individual up to 2 μm pores located along the grain boundaries). Carbide (Nb, Ti)C precipitates are distributed along the grain boundaries.
2. The up to 20 μm wide transition zone with alternate variable-composition interlayers are detected in the microstructure of the joints made by FW in "soft" mode.
3. The joints made by hybrid FW with controlled deformation have fine-grained, dynamically recrystallied structure with the up to 5 μm wide transition zone. The metal of joining zone contains no pores and no segregations of alloying elements and non-metallic inclusions. The transition zone metal is characterised by a dramatic change in the concentration of alloying elements and the absence of variable-composition interlayers.
4. The parts of the powder injection moulding materials can be applied to provide sound bimetal joints by using friction welding.

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7. ACKNOWLEDGMENTS

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