Study of Weldability and Development of the Technology for Repair of High-Nickel Alloy Components (Ukrainian-American Partnership Project)

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Abstract

Alloys used currently to manufacture gas turbine blades of ground plants (ChS-70) and aircraft engines (JS-26) were selected for the studies.

The purpose of this study is to investigate the possibility of repair and extension of life of the blades made from nickel-base alloys of the type of ChS-70 and JS-26.

Nickel superalloys ChS-70 and JS-26 are complex materials containing a number of elements that have a limited solubility in γ-solid solution. Substantial chemical heterogeneity of metal and development of thermal-deformation processes lead to formation of hot cracks in the alloys during fusion welding.

Quantitative evaluation of weldability was done through dynamic deformation of the specimens welded using a testing machine of the Varestraint Test type.

Analysis of the curves plotted for alloy ChS-70 with the equiaxed structure shows the trend to increase in the critical deformation value in BTR. Weldability of the alloy is likely to determine behavior of the weld metal also in DTR. This effect is even more pronounced in evaluation of weldability of alloy JS-26. The threshold deformation values in BTR and DTR for alloy JS-26 are higher than for alloy ChS-70, despite the fact that alloy JS-26 has a more complicated alloying system. It is assumed that this is associated with conditions of solidification of both alloys. Alloy ChS-70, characterized by the equiaxed structure, has a conventional structure of equiaxed crystals in the weld, the grains being extended and growing from the partially melted grains of the base metal, and, therefore, the grain boundaries being of a high-angle type.

Hot cracks propagate primarily along these boundaries.

As proved by the studies, despite a limited weldability of these alloys, the manufacture or service defects in the blades made from them can be repaired by welding.

1. Introduction

Nickel-base superalloys are the main materials used to manufacture gas turbine engines, which is attributable to their high mechanical properties at high temperatures. As requirements to the service temperature of engines have substantially increased lately, modifications of the alloys led to increase of more than 45 % in the strengthening γ'-phase contained in their microstructure. Having good high-temperature properties, these materials are characterized by poor weldability. They are sensitive to hot cracking during welding and heat treatment.

In this connection, the project "Repair Welding and Brazing of Engine and Gas Turbine Components" (The project is funded by STCU – Scientific and Technical Centre of Ukraine) was developed within the framework of the International Proliferation Prevention Program, providing for collaborative work through involving the efforts of leading scientists from the CIS (Confederacy of Independent States), USA .

The industry of Ukraine and other CIS countries uses nickel-base superalloys for the manufacture of aircraft engine and ground gas turbine components. Service life of this type of the equipment is such that in some cases it may work out its specified life, while in the other cases defects of a different origin may develop in it during operation.

2. Characterization of Alloys ChS-70 and JS-26

Alloy ChS-70 is a nickel-base superalloy strengthened by the γ'-phase, the content of which amounts to 50-55 %. Casting of the alloy provides its equiaxed structure, which yields high strength mechanical properties, including at high temperatures, after appropriate heat treatment (solutionizing and aging).

Alloy JS-26 is a nickel-base alloy with a high content of elements that favor formation of the γ'-phase. The mean content of the phase is 60-65 %. The special casting technology provides directional solidification of the blades.

Heat treatment of the alloy includes solutionizing, used to eliminate inter-dendritic heterogeneity, and aging. Strengthening γ'-phases with the fcc lattice and an optimal size of 0.3-0.5 μm, mostly of a cuboidal shape, are formed after aging.

Chemical composition and mechanical properties of alloys ChS-70 and JS-26 are given in Tables 1 and 2, respectively.

3. Weldability of the Alloys

Nickel superalloys ChS-70 and JS-26 are complex materials containing a number of elements that have a limited solubility in γ-solid solution. Substantial chemical heterogeneity of metal and development of thermal-deformation processes lead to formation of defects of the type of hot cracks in the alloys during fusion welding.

Table 1. Chemical composition of alloys ChS-70 and JS-26

Alloy grade	Ni	C	Cr	Co	Mo	W	Al	Ti	Nb	Ce	Fe	B
ChS-70	base	0,6-0,12	15-16,7	9,5-12,5	1,5-2,5	4,5-6,5	2,4-3,2	4,2-5,0	0,10-0,25	0,05	0,8	0,2
JS-26	base	0,13-1,18	4,3-5,6	8,0-10,0	0,8-1,4	10,9-12,5	5,5-6,2	0,8-1,2	1,1-1,8	0,025	1,0	0,015

Table 2. Properties of alloys ChS-70 and JS-26 in short-time tension

Alloy grade	Test temperature	Tensile strength	Yield stress	Elongation, δ	Reduction in area, ψ
		MPa		%	
ChS-70	20	850	750	3	-
	600	960	-	6	9,3
	900	600	500	8	-
JS-26	20	860-930	790	8-16	11-13
	800	910-1030	760-890	8-18	9-20
	900	850-880	840	16-21	19-23

Quantitative evaluation of weldability was done through dynamic deformation of the specimens welded using a testing machine of the Varestraint Test type [2]. Ductility of the weld metal can be evaluated in a temperature range from the solidification temperature to the room temperature. The generalized curve describing variations in ductility is shown in Figure 1.

Given that structural elements of the materials studied can be produced only by casting and have a limited size, the studies were conducted on composite specimens.

Appearance of a working unit of the machine used for experimental evaluation of weldability of the alloys is shown in Figure 2.

The test specimens were 1.7 mm thick.

Partial penetration of the specimens during the tests was provided by TIG welding under the following conditions:

I_w = 70 A

U_a = 10.5 V

V_w = 8.5 m/h

Argon flow rate – 10 litre/min

Based on the condition of producing cast specimens of alloy JS-26 with directional solidification, the weld region and HAZ comprised a single crystal with orientation <001> in weld direction.

High-temperature mechanical properties of metal were evaluated using the ALA-TOO testing machine, the principle of operation of which is similar to that of the "Gleeble" testing machine.

In this case the specimens are tested in a vacuum chamber. Geometry of the specimens is shown in Figure 3.

Gauge portions of the specimens of the materials studied are welded into flat clamps. Owing to this design of the specimens, it is possible, if necessary, to evaluate properties of metal of a real airfoil after operation and reconditioning heat treatment, and, thus, evaluate weldability of the used metal.

The linear thermal expansion coefficient, determining ultimate volume changes of metal during heating, is a very important characteristic that determines kinetics of the thermal-deformation state of the weld pool region.

The linear thermal expansion coefficient was measured using a specialized dilatometry machine by the non-contact method, providing a high accuracy of measurements at temperature up to the melting point.

Appearance of the machine and shape of a specimen are shown in Figures 4 and 5, respectively.

Metallography examinations were performed by optical and scanning electron microscopy.

Brittle temperature ranges for alloys ChS-70 and JS-26 were plotted as a result of the studies conducted (Figures 6 and 7).

In the case of welding alloy JS-26 characterized by a coarse oriented structure, where the weld zone is almost completely a single crystal, the weld inherits structure of the base metal. No grain boundaries acting as sources of

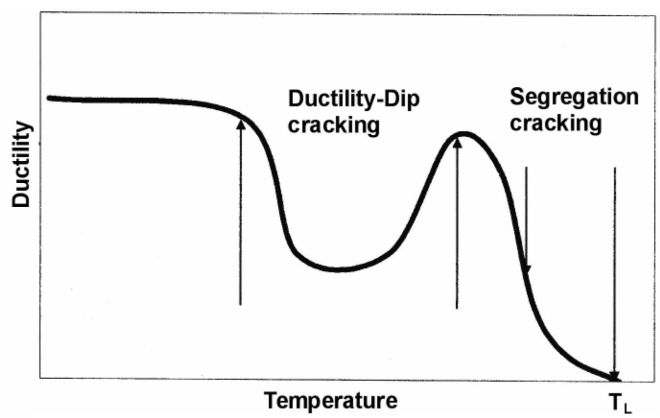


Figure 1. High-temperature ductility of the weld metal comprising zones of segregation and ductility-dip cracks

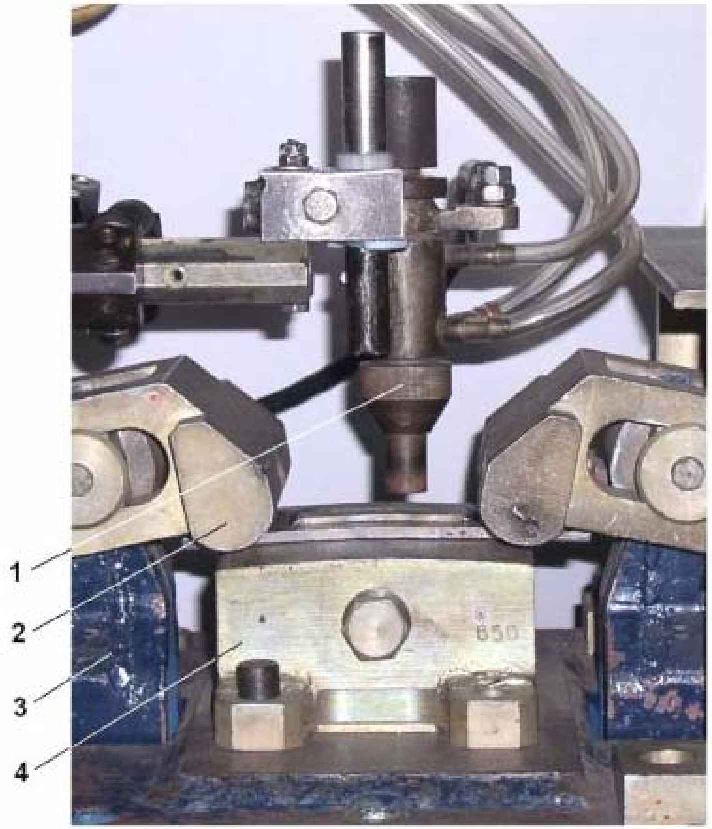


Figure 2. Appearance of a composite specimen for testing using the Varestraint Test machine:
1- TIG torch; 2- yoke; 3 – specimen; 4 – bending block

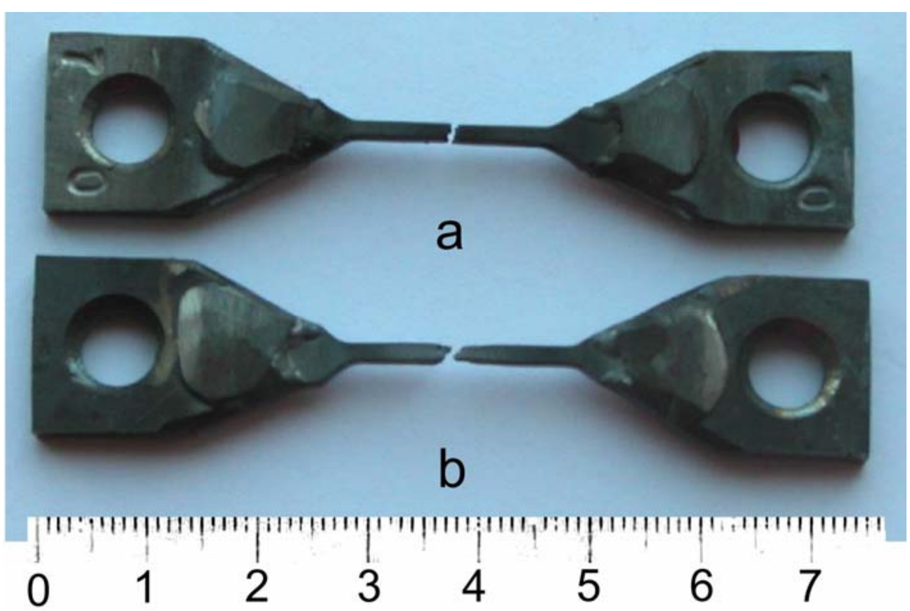


Figure 3. Appearance of the ChS-70 specimen after high-temperature tests

Figure 4. Appearance of the machine to study linear thermal expansion of metals

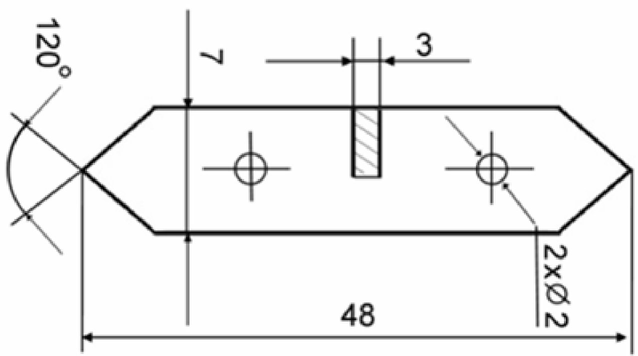


Figure 5. Size of specimen for dilatometry studies

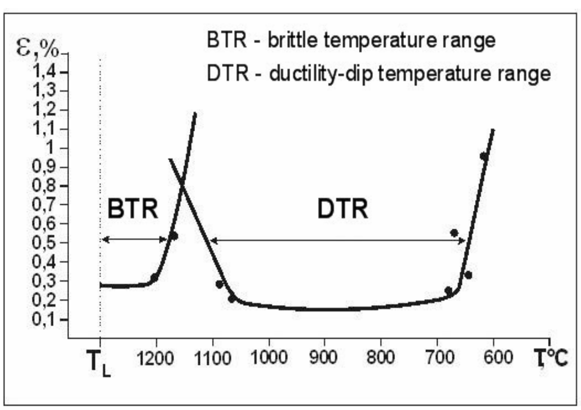


Figure 6. Brittle temperature ranges for the ChS-70 welds

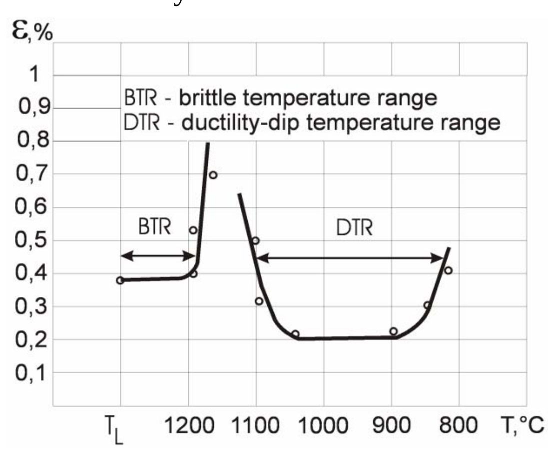


Figure 7. Brittle temperature ranges for the JS-26 welds

inter-granular fracture are present here [3, 4]. As a result, ductility of the weld metal in BTR and DTR increases. Characteristic structures of metal of the welds that confirm the above assumption are shown in Figure 8.

This assumption is also confirmed by comparative studies of high-temperature mechanical properties of superalloys ChS-70 and JS-26 using the "Gleeble"-type testing machine ALA-TOO (Figure 9). Technological tests of the alloys made by welding beads on plates 5x50x80 mm in size show that alloy JS-26 is less sensitive to hot cracking than alloy ChS-70, which proves the data on weldability of these alloys.

Computer simulation of thermal-deformation processes occurring in the weld zone during welding of nickel-base superalloys ChS-70 and JS-26, as well as contribution of structural changes in the HAZ to the dynamics of variations in these processes constitutes much scope of the studies conducted under the project. Structural examinations were performed using a high-temperature laser dilatometer.

The results of measurement of the thermal expansion coefficients for the alloy specimens show that a considerable contribution to thermal expansion of metal in heating is made by the $\gamma+\gamma' \rightarrow \gamma$ transformation, involving increase in volume. This behavior is possible where the lattice parameter of the γ'-phase (inter-plane distances of the γ'-phase) is lower than the corresponding parameters of the matrix with γ-structure. Maximal values of the linear thermal expansion coefficient are $60 \cdot 10^{-6}$ T^{-1} and $44 \cdot 10^{-6}$ T^{-1} for alloys ChS-70 and JS-26, respectively.

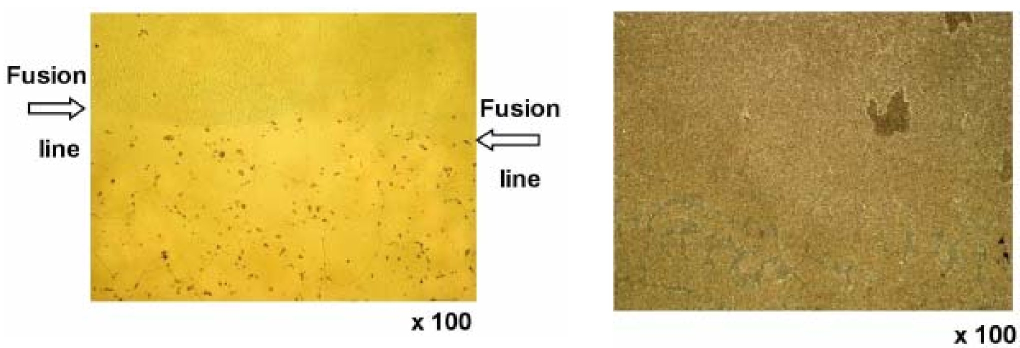
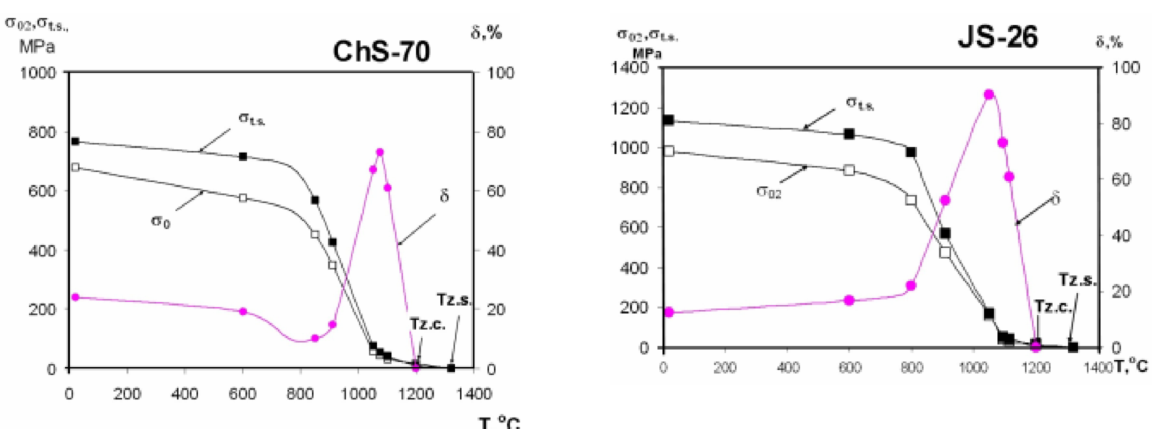


Figure 8. Weld metal microstructure: a – ChS-70; b – JS-26



a b

Figure 9. Temperature dependence of weld metal strength and ductility:
a – ChS-70; b – JS-26

These are the actual values, and they are markedly in excess of the table data. In our opinion, they determine development of substantial elasto-plastic strains.

Calculations of these strains were made using the software developed by the E.O.Paton Electric Welding Institute and actual physical properties, including the above values of the thermal expansion coefficient. The calculations were made for superalloy ChS-70 and, to compare, for stable-austenitic high-alloy steel, which is insensitive to phase transformations in heating and cooling.

As shown by analysis of the results obtained, substantial plastic strains develop in the HAZ of the alloy under the effect of the welding thermal cycle. The two-axial stressed state being taken into account, the total value of the above strains may exceed the values of ductility of the alloy and lead to cracking during welding [5].

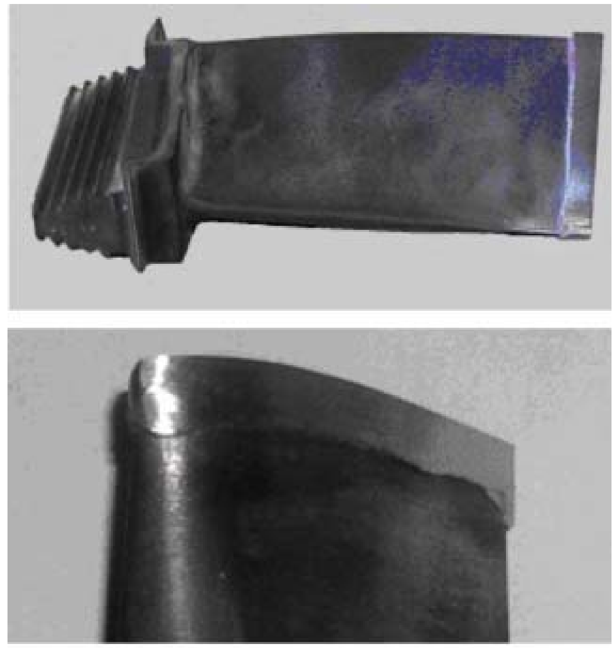


Figure 10. Appearance of gas turbine blades repaired by welding

Trials were conducted on repair welding of the ChS-70 gas turbine blades. Appearance of the repaired blades is shown in Figure 10. No defects in the deposited metal were revealed by examination of microstructure.

Mechanical properties of the repaired regions on model samples properties of the weld metal are close to those of the base metal.

Blades in a sampled batch, repaired by the developed technology, were subjected to fatigue tests using a dynamic test bench in order to evaluate fatigue limit of such blades. The fatigue tests were conducted at a resonance frequency of an airfoil. Fracture in all the blades of the batch initiated in base metal (airfoil near the root section), no fracture took place in the repaired zone.

The test results gave ground to make a decision to repair a commercial batch of the blades.

3. Conclusions

1. Studies were conducted to evaluate weldability of nickel-base superalloys with an equiaxed structure, γ'-phase content of 50-65% and oriented solidification, used to manufacture gas turbine blades.
2. As proved by the studies, despite a limited weldability of these alloys, the manufacture or service defects in the blades made from them can be repaired by welding.

Acknowledgements

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References

1. C.T. Sims, N.S. Stoloff, W.C. Hagel: "Superalloys II", *A Wiley-Interscience Publication.*
2. W.F. Savage, G.D. Lundin: *Welding Journal*, **44** (1965), p.433.
3. A.A. Bukhanova, V.N. Toloraya: *"Heat-Resistant and High-Temperature Steels and Alloys on Nickel Base"*, Moscow (1984), p. 213.
4. J.W. Park, S.S. Babu, J.M. Vitek, T.A. Kenik, S.A. David: *Journal of Applied Physics*, v. **94**, No. **6**, p.4203.
5. V.S. Savchenko, K.A. Yushchenko, V.I. Makhnenko, E.A. Velikoivanenko, N.I. Savolej, G.I. Makhneva: *Avtomaticheskaya Svarka*, **11** (1993), p. 6.