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Structure and mechanical properties of nickel aluminide-rhenium eutectic alloys

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Ni-Al-Re phase diagram has been studied and rhenium influence on the structure and phase equilibriums of Ni-Al-Re system alloys has been investigated. Concentration restrictions have been found for optimum compositions having the maximum melting temperature (about 1665 °C). Such alloys consist of a NiAl metal matrix and γ-Re fibers arranged within the main matrix at a high ordering degree.

Исследована диаграмма состояния Ni-Al-Re, определено влияние рения на структуру и фазовые равновесия в сплавах системы Ni-Al-Re. Установлены концентрационные пределы для оптимальных составов сплавов, которые имеют максимальную температуру плавления (1665 °C). Структура этих сплавов образована металлической матрицей NiAl и волокнами γ-Re, которые расположены с высокой степенью упорядочения в основной матрице.

High physical and mechanical properties intrinsic in nickel-aluminum materials make them rather promising in manufacturing the heat-loaded parts of gas turbines and a number of other articles used in modern engineering. The intermetallic NiAl compound has a number of advantages important for aerospace engineering due to its high melting point (1640 °C), high electric conductivity and high resistance to oxidation [1]. Improvement of its mechanical properties may be achieved by doping, which affects the level of structure perfection and morphology of eutectic compositions and allows to develop a number of composite eutectic alloyed materials with high mechanical characteristics. However, increase of ductility and high-temperature strength of nickel aluminides still remains a topical problem [2-6]. Ternary Ni-Al-Re alloys that form eutectic two-phase β-NiAl+γ-Re systems are of interest, because they make it possible to achieve a favorable combination of strength properties characteristic both for intermetallic NiAl compound and rhenium [1]. The Ni-Al-Re system was studied in part before. The phase equilibrium states in the rhenium content range from 0.1 to 33 at.% were studied and the liquidus surface of the Ni-Al-Re system phase diagram was built in the plane of the concentration triangle. It has been shown that introduction of rhenium into nickel super-alloys allows to provide increased ductility and high-temperature creep resistance.

The area under consideration is peculiar for its rather wide range of β-NiAl homogeneity, which allows to vary the Ni-Al concentration ratio without any change in phase composition of the alloys. In this connection, the purpose of this work aimed at determination of the region where two-phase (β-NiAl+γ-Re) alloys do exist at crystal-

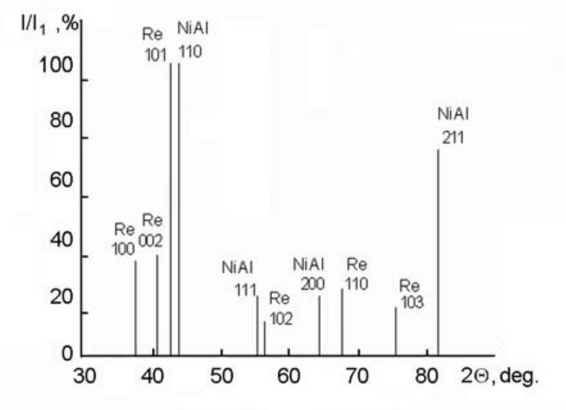

Fig. 1. Diffraction pattern of the 43 at.% Ni-43 at.% Al-14 at.% Re alloy.

lization, and at finding location of the quasi-binary sectional view within the said region, seems to be quite topical. Besides, the precise location of the said region at the state diagram was not found by far.

The Ni-Al-Re alloys were studied using the differential thermal analysis and metallographic examination. 99.999% pure aluminum, at least 99.9% pure nickel and 99.85% pure powdered rhenium were used as starting materials. The alloys were prepared in the arc furnace with a tungsten nonconsumable electrode placed at a brass water-cooled bottom, in the atmosphere of purified argon. The differential thermal analysis was carried out in corundum Al_2O_3 crucibles using a VDTA-3 thermal analyzer with symmetrical arrangement of thermocouples. Such construction allowed to receive high-quality thermograms at heating up to 2500 °C. The heating and cooling rate was 60 K/min. The X-ray phase analysis was done in Cu K_α emission using a DRON 2.0 diffractometer. The structures of alloys were studied by optical and electronic spectroscopy using Nejphot-32 and JSXA-733 microscopes.

The chemical composition of phases was determined using the electron probe X-ray analysis. The metallographic examination of the alloys falling in the equiatomic NiAl-Re section of the ternary fusibility curve of Ni-Al-Re system has shown that the alloy structure successively changes with Re content increase from a typical solid solution to a pre-eutectic-eutectic and eutectic structure. The metallographic examination has shown that metal matrix in the eutectic state is a solid NiAl solution containing 0.2 at.% of rhenium, where rhenium provides eutectic crystallization and forms a

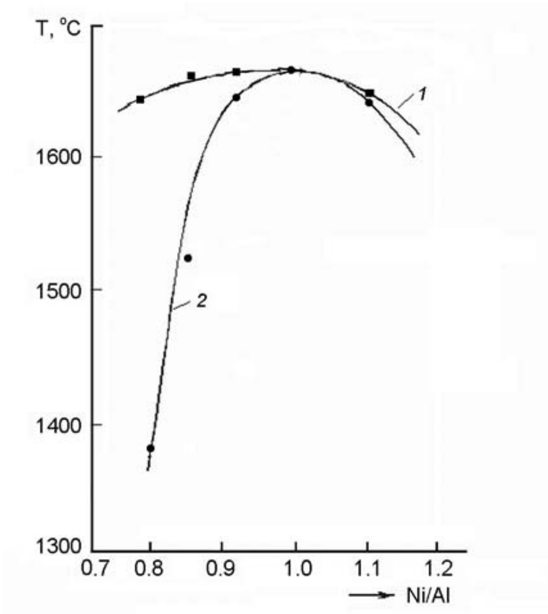

Fig. 2. Temperature and concentration parameters of L<196>β+γ eutectic equilibrium in Ni-Al-Re system: *1* — temperature began of melting monovariant eutectic L"b-NiAl+g-Re; *2* — temperature of the ending melting monovariant eutectic L"b-NiAl+g-Re

matrix with about 0.2 at.% of NiAl dissolved therein. These results were confirmed by X-ray phase analysis of alloys with equiatomic Ni/Al ratio and Re content exceeding 14 at.%. Fig. 1 shows a diffraction pattern for 43 at.% Ni – 43 at.% Al – 14 at.% Re alloy. The lattice parameter of the NiAl lattice having a ScCl type structure is a = 0.2880±0.003 nm. Parameters of the rhenium lattice having a hexagonal close-packed structure of Mg type, are a = 0.27609 nm and c = 0.4458 nm, thus coincident, within the error limits, with literature data for pure rhenium [10]. This evidences the rather low Ni and Al solubility in Re, which does not exceed 0.2 at.%.

The eutectic region of the alloy increases with Re concentration. At Re content of 2 at.% first crystals of refractory rhenium γ-phase appear. Here, rings created by NiAl may be seen around the γ-phase grains. Existence of such rings is typical of eutectics of faceted-nonfaceted class. According to DTA data, eutectics in all the alloys of NiAl-Re section are melted at the constant temperature 1665 °C. Fig. 2 can be interpreted as an evidence of the quasi-binary character of this NiAl-Re section. As it follows from this Fig. 3, the melting point is maximum at the Ni/Al concentration ratio

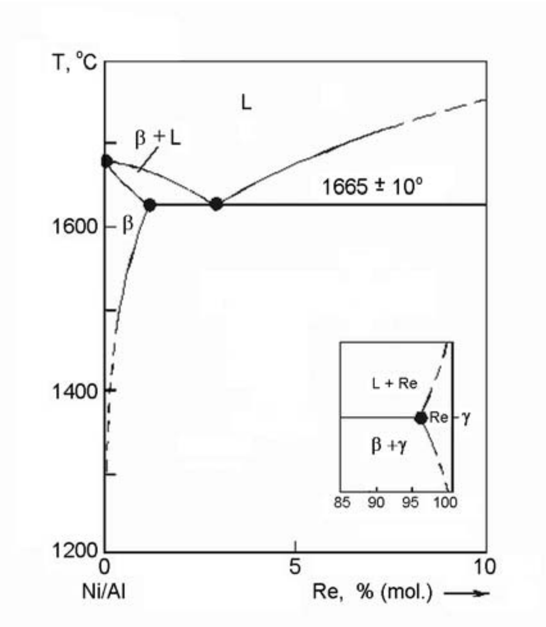

Fig. 3. Quasi-binary NiAl-Re section of the phase diagram of Ni-Al-Re system: *1*, starting melting temperature of the monovariant eutectic L – (β-NiAl + γ-Re); *2*, end melting temperature of the monovariant eutectic L – β-NiAl + γ-Re.

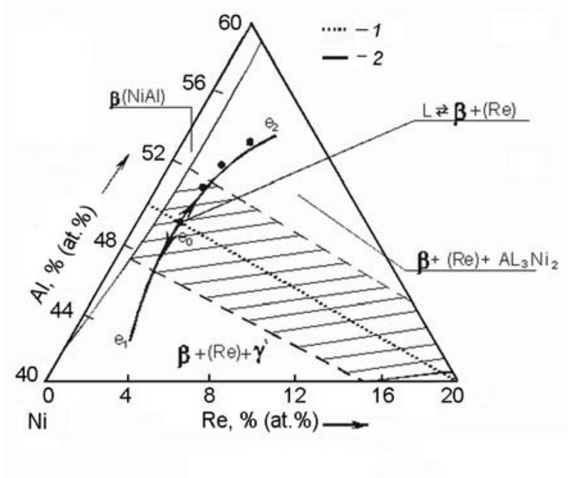

Fig. 4. A fragment of projection of the monovariant eutectic NiAl-Re on the concentration triangle for ternary NiAl-Re system: *1*, location of the quasi-binary section; *2*, monovariant eutectic transformation line.

equal to 1. The relevant NiAl-Re section is shown in Fig. 3.

Results of metallographic examination allow to discern the range of alloy compositions (2–2.5 at.% Re) where the eutectic should exist. The eutectic structure of (NiAl+Re) alloys may be classified as an anomalous. The detailed morphology study of the eutectic colony using the scanning electron microscope allowed to find out that it has a fibrous structure. Further studies of the alloy microstructure at various values of Re/Al ratio allowed to determine the width (from 46 at.% to 53 at.% of NiAl) of the two-phase equilibrium region between the solid solution formed by Intel-metallic NiAl compound (β-phase) and Re (γ-phase), as well as to construct a fragment of projection of the monovariant eutectic NiAl-Re on the concentration triangular of a ternary system (Fig. 4). It should be noted that any deviation from Ni/Al = 1 towards any side results in decrease of the eutectic equilibrium temperature and is accompanied by an extension of its melting range.

Thus, near the area of intermetallic NiAl compound, there exists a binary monovariant eutectic formed by nickel aluminide (β-phase) and Re (γ-phase). The starting melting temperature point of the monovariant (NiAl+Re) eutectic has a maximum at Ni/Al = 1. The zero eutectic melting range corresponds to Re content about 2%, i.e., the saddle point at the quasi-binary NiAl-Re section corresponds to the following composition: 99 at.% Ni, 99 at.% Al, 2 at.% Re.

In this work, the indention of a rigid Vickers indenter has been used to measure the microhardness and characterize the mechanical properties. Such indenter allows to determine mechanical properties of brittle materials, including especially hard and superhard ones, in a wide range of loadings. At microhardness measurements, the introduction of the indenter into a flat sample surface has viscoelastic character. Using the local loading method (MLL), the microhardness of cast alloys NiAl-Re was studied. In the method, an indentor shaped as a tetrahedral pyramid with the dihedral angle $2\theta = 136^{\circ}$ is pressed into the sample. Exposure time $t = 20$ sec. Loading made $P_{\max} = 100$ cN. The loading rate $v = 20$ cN/sec. The maximal depth of indention $h = 25$ μm. The data obtained are presented in the Table 1.

The Young modulus was calculated using the ratio

$$E = \frac{H}{0.13N\frac{h_e}{h_p}}$$

where H is hardness determined on size of a diagonal d of the indenter trace; h_e, h_p, traces of the elastic and plastic indenters, respectively; N parameter varying from

Table 1. Main mechanical properties of Ni-Al-ReI alloys

Alloy	H_{μ}, GPa	E, GPa	$A_{ful.}$, 10^{-6}, Dg	$A_{el.}$, 10^{-6}, Dg	$A_{pl.}$, 10^{-6}, Dg	CFL
Ni_{50} Al_{50}	3.12	212	2.05	0.68	1.37	25
$NiAlRe_{0.2}$	4.01	353	1.89	0.75	1.18	30
$NiAlRe_{2.5}$	4.83	226	2.41	0.98	1.43	35
$NiAlRe_{3.0}$	5.40	270	2.18	1.04	1.14	35

0.74 for fully plastic deformation up to 1.0 for only elastic indentor.

With the computerized test machine "CERAMTEST", equipped with automatic registration of experimental data, the mechanical tests on four-point flexure were carried out on the NiAl-Re system alloys. The values of the elasticity module and failure stress are given in the Table 2.

The mechanical tests of NiAl-Re system samples under compression were carried out using an U2-10-5212 universal test machine (NIKIMP, Moscow). Yield stresses $\sigma_{0.2}$, failure stresses, and plastic strains are given in Table 3. The alloys of the nearly eutectic structure, with 2.5–3.0 ат. % rhenium contents, show the highest values of plastic strain (3.9 to 6.1%).

To conclude, the part of plastic strain δ_n in the overall elastic-plastic strain under indenter characterizes ability of a material to change its form during deformation. Basing on the researches carried out, it is possible to note influence of the doping element on the plasticity parameter of δ_n in Ni-Al-Re system. From Table 1, it is seen that the doping changes the Young modulus and microhardness. This change has a complex character and is defined by the type of atomic interaction and strength of atomic bonding. Generally, the doping in solid solution results in a decrease of various metal plasticity characteristics, as is seen from the reduction of the plasticity parameter δ_n.

Table 2. Measurement of NiAl-Re alloy mechanical properties at four-point flexure

Alloy (BCC)	Linear dimensions of cast samples, mm		E, MPa	σ_p, MPa
	a	b		
$NiAlRe_{0.2}$	3.21	5.35	131	60
$NiAlRe_{2.0}$	2.86	5.29	151	56.5
$NiAlRe_{2.5}$	3.24	5.48	148	102
$NiAlRe_{3.0}$	3.17	5.41	157	80

As the solubility limit is attained and the compound phase changes, there is a sharp change of microhardness H_V. The same is true for the Young modulus. Therefore, the plasticity characteristic δ_n is a sensitive indicator to chemical and phase state of the alloys and thus can be used in physicochemical analysis for phase diagrams construction. It was found that polythermal NiAl-Re section of the ternary system is quasi-binary. Any deviation of compositions of the monovariant eutectic alloys from this section results in decrease of the eutectic equilibrium temperature. The existence region of the two-phase alloys (β-NiAl + γ-Re) has been found for crystallization of the ternary Ni-Al-Re system.

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Table 3. Measurement of NiAl-Re system mechanical properties under compression

Alloy (BCC)	Linear dimensions of cast samples, mm			$\sigma_{0.2}$, MPa	$\sigma_{des.}$, MPa	ε, %
	a	b	c			
NiAl	3.2	3.25	5.13	370	491	3.0
NiAl	3.25	3.47	5.20	770	814	0.78
$NiAlRe_{0.2}$	3.08	3.46	5.32	860	912	1.2
$NiAlRe_{2.0}$	3.11	3.34	5.27	555	571	0.39
$NiAlRe_{2.5}$	3.13	3.29	5.39	810	1295	6.1
$NiAlRe_{3.0}$	3.12	3.12	5.41	910	1162	3.9

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Структура і механичні властивості евтектичних сплавів NiAl з ренієм

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Досліджено діаграму стану системи Ni-Al-Re та встановлено вплив ренію на структуру і фазові рівноваги у сплавах системи Ni-Al-Re. Встановлено концентраційні обмеження для оптимальних складів сплавів, які мають максимальну температуру плавлення (1665 °C). Структуру цих сплавів утворено металічною матрицею NiAl і волокнами γ-Re, що розташовані з високим ступенем упорядкування в основній матриці.