Vapor-Condensed Composite Materials $Ni–Al_2O_3$, $NiCr–Al_2O_3$ with Oxide Nanophase

V. Grechanyuk, M. Grechanyuk, V. Chornovol, A. Kozyrev, and Kovalchuk Yu

Abstract The structure and mechanical properties of $Ni–Al_2O_3$ and $NiCr–Al_2O_3$ dispersion-strengthened materials condensed from the vapor phase were investigated. It was shown that nanoparticles are uniformly distributed throughout the volume of the condensates. The factor affecting the structure is the contact interaction at the particle–matrix interphase boundary. The studied mechanical properties at temperatures of 700 and 1000 ± 20 °C show that small concentrations of dispersed Al_2O_3 particles (0.25–0.4%) in $Ni–Al_2O_3$ condensates and up to 1% Al_2O_3 in $NiCr–Al_2O_3$ condensates lead to an increase in strength characteristics and non-monotonic decrease in plasticity. Based on the obtained data, the optimal concentration of the strengthening Al_2O_3 nanophase in condensed dispersion-strengthened $Ni–Al_2O_3$ and $NiCr–Al_2O_3$ materials was determined, which ensures a high level of strength and plasticity.

1 Introduction

Dispersion-reinforced materials (DRM) were obtained exclusively by powder metallurgy methods until recently. The authors of [1] conducted detailed studies of a wide range of properties of these materials. Many of them have found practical application. Obtaining DRM is a multi-stage technological process that requires strict adherence to technological discipline at all stages of their production.

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High-speed electron beam evaporation–condensation as a new technological process has found wide application for the deposition of various protective coatings on products, primarily on the blades of gas turbines. The rate of vapor flow deposition on substrates of various configurations can reach 150 μm/min, which allows to deposit quite a lot of material on the substrates. Therefore, it is of scientific and practical interest to use the specified technological process, controlled at the atomic-molecular level, to obtain massive (separated from the substrate) composite materials.

Fundamental studies to establish the basic physical and mechanical laws of the formation of thick (0.01–2 mm) condensates were carried out at the Paton's Institute of Electric Welding under the leadership of Academician Movchan [2, 3]. The main physico-chemical regularities of the formation of thick vacuum condensates of some pure metals, alloys, oxides, carbides, borides were determined, and their physico-mechanical characteristics were studied depending on the composition and condensation parameters.

Composite dispersion-reinforced porous and layered (microlayer) materials should be included in the new materials obtained by vapor deposition in a vacuum.

Currently, intensive research is being conducted on new composite materials condensed from the vapor phase with a reinforcing nanophase (oxides, carbides, borides, refractory metals). Dispersion-strengthened composite materials that condense from the vapor phase (condensates) consist of a polycrystalline metal or ceramic matrix with nanodisperse particles of the second phase uniformly distributed by volume. By varying the substrate temperature and cooling rate, the average crystallite size of the matrix can be varied from several hundred microns to several hundred nanometers, and the particle size of the master phase can be varied from several nanometers to several microns. As a result of the influence on the morphology, dispersion and nature of the distribution of the strengthening phase, it is possible to obtain in dispersion-strengthened materials a combination of properties that are unattainable in ordinary alloys [4, 5].

The use of stable refractory compounds as strengthening phases, e.g., oxides that do not actively interact with the base metal and do not dissolve in it up to its melting temperature, ensures the preservation of the microheterogeneous structure and dislocation substructure up to pre-melting temperatures. This allows you to preserve long-term operational characteristics of materials (0.9–0.95 T_{mel}).

2 Results and Discussions

Condensed from the vapor phase dispersion-strengthened materials Ni–Al_2O_3 (KDSM) were obtained on laboratory and industrial equipment manufactured at the IES named after Paton of the National Academy of Sciences of Ukraine. Sheet rectangular condensates (220 × 320 × 0.8–2) mm with a concentration gradient of dispersed oxide nanophase were obtained for research.

A similar technological technique makes it possible to obtain a significant number of samples of different composition. Alternating vapor flow deposition was carried out on a substrate with Art. 3, processed to a purity class of 0.63 at two condensation temperatures of 700 and 1000 ± 20 °C. For easy separation of condensates from the substrate, a separating layer of calcium fluoride (CaF_2) with a thickness of 20–40 microns was previously applied to the surface on which condensation was carried out. For industrial applying, condensates were formed in the form of cylindrical sheet blanks with a thickness of 1–4 mm and a diameter of 800 mm.

In the work, the structure, chemical, phase composition and mechanical properties were investigated according to known standard methods [4].

According to the Fig. 1 of the Ni–Al_2O_3 KDSM structure that dispersed aluminum oxide nanoparticles are evenly distributed throughout the volume of the condensate. The determining factor that affects the structure and, as a result, the mechanical properties of KDSM is the contact interaction at the particle–matrix interphase boundary. The quantitative criterion of such contact interaction is the wetting angle. It is largely influenced by the environment in which the crystallizing liquid phase interacts with the solid oxide particle, the purity of the metal and oxide phases, the condensation temperature, and other factors. Currently, a sufficient number of studies have been conducted, which are based on their contact interaction when obtaining new materials in metal (alloy)—MeO systems in a vacuum [6]. KDSM Ni–Al_2O_3 with an acceptable set of mechanical characteristics can be obtained in a narrow interval of oxide phase concentration (up to 0.6 wt.%).

Using the methods of electron microscopic and X-ray phase analysis, it was established that only nickel and aluminum oxide are present in the material.

Figure 2a, b shows the dependences of strength limits (σ), yield strength ($\sigma_{0,2}$) and relative elongation (δ) of Ni–Al_2O_3 condensates obtained at substrate temperatures (T_s) of 700 and 1000 ± 20 °C.

The analysis of obtained data shows that small concentrations of dispersed Al_2O_3 particles lead to an increase in strength characteristics and a non-monotonic decrease in plasticity in a relatively narrow range of Al_2O_3 concentrations (0.25–0.4 wt.%).

Fig. 1 Structure of KDSM Ni–Al_2O_3 (×30,000)

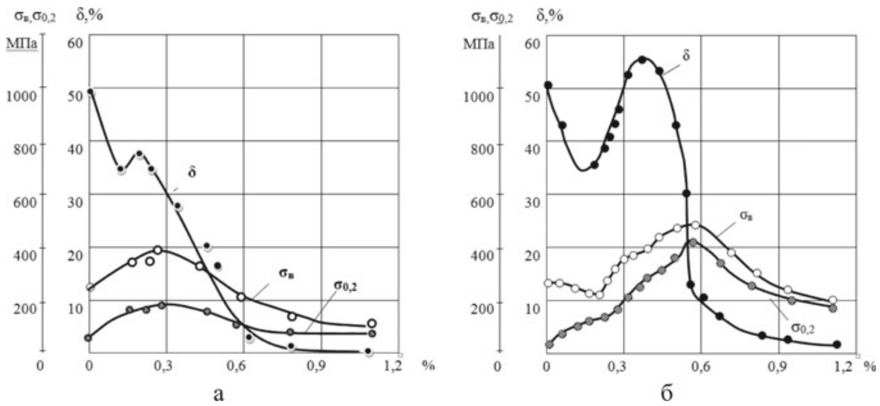

Fig. 2 Dependencies of strength, yield strength and relative elongation on the content of Al_2O_3 in Ni–Al_2O_3 KDSM obtained at temperatures: **a**—700 °C; **b**—1000 °C

The increase in plasticity is explained by the fulfillment of the structural condition: the average grain size of the metal matrix (D_3) is equal to the average distance between dispersed particles of the strengthening phase (Λ) [2].

It should be emphasized that the maximum of the curves of the dependence of plasticity on the content of Al_2O_3 shifts toward a higher content of aluminum oxide with an increase in the temperature of the substrate. The absolute values of the plasticity of two-phase Ni–Al_2O_3 materials with an optimal content of dispersed particles increase with an increase in the condensation temperature. For example, at $T_s = 1000$ °C, KDSM Ni–(0.35–0.4) mass % Al_2O_3 has a value of relative elongation greater than that of pure nickel (Fig. 2b).

In terms of strength characteristics, Ni–Al_2O_3 KDSM is not inferior to industrial VDU-2 DUM (98% Ni + 2% HfO_2), obtained by powder metallurgy methods.

In more complex two-phase condensed systems that form solid solutions, e.g., NiCr-Al_2O_3, qualitatively similar changes in mechanical characteristics are observed (Fig. 3a, b). The strength limit and yield strength increase in a wider range of Al_2O_3 concentrations (up to 1%). However, with this content of dispersed refractory particles, condensates have low plasticity. A similar change of the mechanical characteristics in the KDSM is caused by the almost complete absence of particle–matrix interphase interface interaction. The marginal wetting angle of Al_2O_3 with liquid nickel ranges from 150 to 1150. Due to the lack of mutual action in the condensates, pores are formed, which leads to a loss of strength and plasticity. Improvement of interphase interaction in the NiCr–Al_2O_3 system (up to 85o) leads to some increase in strength and plasticity in a wide range of Al_2O_3 concentrations compared to Ni–Al_2O_3 composites.

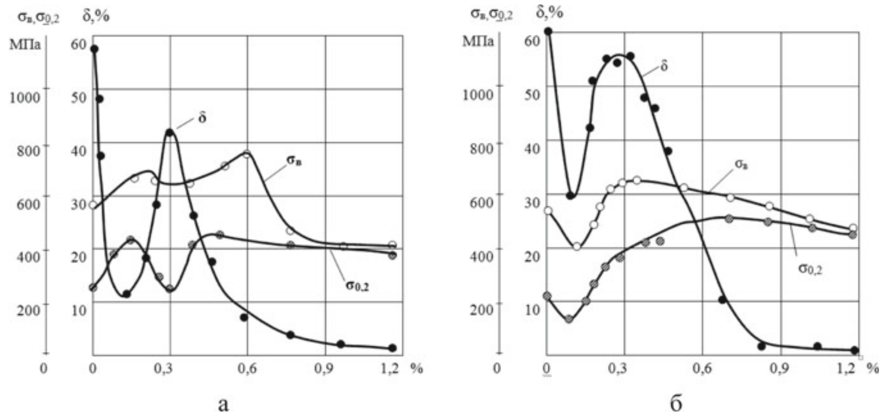

Fig. 3 Dependencies of strength, yield strength and relative elongation on the content of Al_2O_3 in NiCr–Al_2O_3 KDSM obtained at temperatures: **a**—700 °C; **b**—1000 °C

3 Conclusion

Thus, as a result of the research of the mechanical properties of condensed dispersion-strengthened materials (KDSM) Ni–Al_2O_3, NiCr–Al_2O_3, the optimal concentration of the reinforcing nanophase Al_2O_3 in KDSM Ni–Al_2O_3 and NiCr–Al_2O_3 was determined, which ensures a high level of strength and plasticity.

References

1. E. Khomenko, N. Grechanyuk, V. Zatovskiy, Modern composite materials for switching and welding equipment. Message 1. Powder composite materials. Autom. Weld. **10**, 38–44 2015. (In Russian)
2. B. Movchan, K. Yakovchuk, Electron-beam installations for the deposition of inorganic materials and coatings. Spec. Electrometallurgy **2**, 10–15 (2004)
3. B. Movchan, S. Firsov, Yu. Lugovskoy, in *Structure, Strength and Resistance to Fatigue of Microcrystalline and Microlayer Materials* (Naukova Dumka, Kyiv, 2016)
4. I. Grechanyuk, Scientific and technological principles of creating new composite materials based on nickel, cobalt, titanium and copper and the latest industrial radiation equipment for their production. Abstract of the dissertation of Ph.D. Kyiv, 2021, 42 p.
5. N. Grecyanyuk, G. Baglyuk, P. Kucherenko, A. Melnik, I. Grechanyuk, V. Grechanyuk, Y. Smashnyuk, Laboratory electron-beam multipurpose installation L-2 for producing alloys, composites, coatings, and powders. Powder Metall. Metal Ceram. **56**(1–2), 113–121 (2017)
6. N. Grechanyuk, V. Konoval, V. Grechanyuk, G. Bagliuk, D. Myroniuk, Properties of Cu–Mo materials produced by physical vapor deposition for electrical contacts. Powder Metall. Met. Ceram. **60**(3–4), 183–190 (2021)