Composite Materials with a Metal Matrix Condensed from Vapor Phase: Dispersion-Strengthened Metals

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Modern scientific level of dispersion-strengthened metals condensed from the vapor phase engineering is presented. The physical and mechanical properties of these materials depend on selected matrix type (pure metal, metal alloy), particles reinforced composites (oxide, carbides, borides, refractory metals), interaction at matrix-particles boundaries, technological parameters (condensation temperature, degree level of vacuum, condensation speed of initial components and their chemical purity, roughness of substrate surface on which condensation is carried out, etc.).

Introduction

The appearance of electron beam (1956), plasma-arc (1958) and laser (1964) technology in the mid-twentieth century raise issue the question before developers of new technologies for processing and welding materials: why traditional source of energy for these purposes - free burning welding arc melts metals "superficially" (ratio of the depth of the molten zone to its width <1) while the sources listed above - "daggermaw" (ratio of the depth of the molten zone to the width of <100).

Looking at those processing brought about a new understanding of concentrated energy fluxes (CEF)[1]. It turned out, if the power source develops power density \( \geq 10^5 - 10^6 \) W/cm\(^2\) (electron beam, laser, plasma), laws of heat transfer in a heated object change sharply at excess of some threshold power density. The overcoming this threshold has opened up before technologists new opportunities.

Great scientific and technological experience with CEF showed that the most efficient source of energy at treatment is the electron beam. In the E.O. Paton Electric Welding Institute of National Academy of Sciences of Ukraine (EWI of NASU) and Production Association "Eltehmash" multipurpose two, three, five crucible electron beam installation on basis powerful electron beam guns for intense molecular beams obtaining. The intensity of these beams reaches \( 10^{20} \) particles per cm\(^3\)/s. This quasimolecular beam which is characterized, on the one hand, by the properties of the molecular beam, namely the intensity distribution in a space of approximately obeys law of cosine, and on the other hand, this beam extends as a result internal collisions of atoms, and so it has some similarity steam flows in laminar flow.

The productivity of these installations reached the level 10-15 kg of steam per hour. In other words, during 8 hours of continuous operation can be obtained masse of condensate by 100 kg or more. Fundamental researches of basic physical and chemical mechanisms of formation of thick vacuum condensates from some pure metals, metal alloys, oxides, carbides were established, and their physical properties depending...
on the composition and parameters of condensation were studied.

For new materials produced by the condensation of primarily should be attributed dispersion-strengthened materials, porous and micro-layered materials. Study of their structure and properties is the aim of this work.

**Experimental part**

Dispersion-strengthened materials consist of polycrystalline matrix with uniformly dispersed particles of second phase (Fig.1). The average dimensions of matrix crystallites and strengthened particle phase can by adjusted at wide range - from several hundred microns to several thousands angstroms by varying of substrate temperature and condensation rate.

![Fig.1. Typical structure of dispersion-strengthened material, condensed from vapor phase.](image)

The structure and physico-mechanical properties of dispersion-strengthened condensed materials for systems: iron-carbide, iron-boride, iron-oxide, nickel-carbide, nickel-oxide, copper-oxide, tungsten-oxide were investigated by A.V. Demchishin [4].

The dispersion-strengthened materials based on complex alloys of nickel, chromium, copper, titanium were studied in details by author [5]. Scientific researches in those systems currently continue [6].

Mechanical characteristics of dispersion-strengthened materials depend on following factors:
- type of selected matrix (pure metal, metal alloy);
- type of dispersed particles (oxides, carbides, borides, refractory metals);
- technological parameters of condensed materials obtaining (temperature of condensation, level of vacuum, chemical composition, condensation rate and purity of initial components, roughness of substrate on which the condensation occurs).

The main factor that determines structure and mechanical properties of dispersion-strengthened condensed materials is contact interaction at particle-matrix interface. Quantitative criterion of interaction contact between melt and refractory compounds is angle of wetting [7]. This factor depends essentially on environment in which the melt reacts with a solid substrate (particle), the purity of melt and the particles, temperature, exposure time and other factors. In the literature there are many reference data, that determine angle of wetting in systems Me (alloy) - MeO, Me-C-MeB in vacuum, inert gases, etc. [7, 8].

For simple two-phase condensed system Me-MeO, where as a matrix were used commercially pure iron, nickel, copper, and as a second (hardening) phase - aluminum, yttrium, stabilized zirconium, can be achieved sufficiently high level of mechanical properties at narrow concentration range of second phase (to 0,6% mass.).

Fig. 2a, b, as an example, shows tensile strength ($\sigma_B$), yield strength ($\sigma_{0.2}$), elongation ($\delta$) versus $\text{Al}_2\text{O}_3$ concentration in condensates Ni-$\text{Al}_2\text{O}_3$, obtained at temperatures of substrate 700 and 1000 ± 20 °C.

![Fig.2. Tensile strength, yield strength and elongation versus $\text{Al}_2\text{O}_3$ concentration in dispersion-strengthened material Ni-$\text{Al}_2\text{O}_3$, obtained by condensation at substrate temperatures 700 (a) and 1000 °C (b).](image)
Analysis of these data shows dispersed particles Al$_2$O$_3$ particles at low concentrations leads to increase strength and to non monotonic decreasing of ductility. Maximum ductility is observed over a relatively narrow concentration range- 0.25÷ 0.4%wt Al$_2$O$_3$. Increase in plasticity takes place when the structural conditions have performed: average grain size of metallic matrix is equal to average distance between dispersed particles [2]. It should be noted that a maximum of curves $\delta = f$ (% mass. Al$_2$O$_3$) is shifted towards higher concentration of Al$_2$O$_3$ with increasing temperature. Plasticity of two-phase materials Me-MeO with optimum concentration of dispersed particles increase with increasing of condensation temperature. For example, at condensation temperature 1000 °C dispersion-strengthened materials Ni - (0.35 - 0.4 % mass.) Al$_2$O$_3$ have an elongation greater than that of pure nickel.

Similar changes of mechanical characteristics have observed for more complex condensed-phase systems based on solid solutions of MeCr, MeCrAl, MeCrY, where Me - Fe, Ni, Cu, qualitatively (Fig. 3, a, b).

Increase in strength is observed in a range of Al$_2$O$_3$ concentration up to 1 % mass. However, condensates with these concentrations of dispersed refractory particles have low ductility. Similar changes of mechanical characteristics caused by absence of interaction at particle-matrix interface. Contact angle between Al$_2$O$_3$ and liquid Ni consist up 115 to 150 degrees, depending on experimental conditions [7]. The absence of interaction due to formation of pores in the condensates, what leads to loss of strength and ductility.

The improvement of interfacial interaction in system Cr-Ni-Al$_2$O$_3$ [7] (the contact angle is 85 degrees) leads to a certain increase of strength and ductility in a wider range of Al$_2$O$_3$ concentration compared with composites Ni-Al$_2$O$_3$.

The inflection on strength curves of two-phase systems metal (alloy – carbide (boride) shifts to higher concentrations of dispersed phase relative position on curves in system with oxide phase 3-7 % mass. Similar regularities are typical for condensed materials on nickel, iron or copper based, in which as dispersed particles were used titanium carbide (TiC), niobium carbide (NbC), zirconium carbide (ZrC), titanium diboride (TiV$_2$), zirconium diboride (ZrV$_2$) [5].

The regularities of mechanical characteristics change in composition Cu-ZrV$_2$ show in Fig.4 for illustration. The increasing of ZrV$_2$ concentration up to 0.8 % mass. leads to increase of yield strength and strength to 550 and 600 MPa, respectively, and when zirconium diboride content in condensate is 2.4 % mass., tensile strength reaches to 950 MPa.

![Fig.3. Tensile strength, yield strength and elongation versus Al$_2$O$_3$ concentration in dispersion-strengthened materials N i - 20 % mass. Cr-Al$_2$O$_3$ obtained by condensation at substrate temperature 700 (a) and 1000 °C (b).](image1)

![Fig. 4. Tensile strength, yield strength and elongation versus ZrB$_2$ concentration in dispersion-strengthened materials Cu-ZrB$_2$ obtained by condensation at substrate temperature 700°C.](image2)
The plasticity of condensed materials Cu-ZrV₂ sharply decreases at low concentrations ZrV₂, but is retained satisfactory (≈6%) in dispersed phase concentration range up to 1%. Condensed materials with an oxide-dispersed phase, in particular the system Cu-ZrV₂, are characterized by peak on the plasticity curve at the concentration ZrV₂ ≈ 0.1%.

The obtained results are in good agreement with data on wetting of zirconium diboride by liquid copper. The contact angle varies in the range from 123 to 36 degrees at a temperature range 1100-1400°C [8].

Qualitatively similar changes of mechanical characteristics are also typical for condensed composites Cu-Mo with dispersed molybdenum particles (Fig. 5). The increase of Mo concentration to 2% mass. leads to a decrease of copper matrix ductility up 45 to 15%, and high yield strength and strength up to 270 and 380 MPa respectively. Increase of Mo content to 6% mass. contributes to increase of tensile strength to 500 MPa, which is more than 5 times higher than the tensile strength of pure copper, and the yield strength to 410 MPa, which exceeds those of copper, is more than 8 times. The elongation of material remains at a sufficiently high level – 10-12%, and is almost independent of Mo in concentration range 2-6% mass.

Gradual reduction of mechanical characteristics of dispersion-strengthened materials Cu-Mo has observed where dispersed particle concentration was above 12% mass. Absolute wetting molybdenum by liquid copper (contact angle is 0 [7]) ensure high mechanical properties of composites in wide concentration range of Mo.

Mechanical properties of discussed above materials are determined by real structure, i.e. by size of matrix grains and dispersed articles, the magnitude of which, in turn, were determined by substrate temperature. Decrease of substrate temperature on obtaining of condensate Cu-1% mass. Mo, from 700 to 500 °C leads to significant dispergation of structural parameters: grain size decrease from 3.2 to 1.45 microns, the average particle diameter - from 25 to 12 nm. At the same time, strength characteristics greatly increase: yield strength - from 140 to 400 MPa; yield strength - from 270 to 428 MPa; elongation is 7%.

Additional cold rolling at reduction ratio 30% leads to increase in mechanical properties of dispersion-strengthened materials with Cu-1% mass. Mo, obtained at substrate temperature 500 °C. Moreover, tensile strength increases from 428 to 498 MPa, a yield strength - of 400 to 420 MPa, elongation increase from 7 to 9%. The deformation contributes to further grain dispergation of copper matrix from 1.45 to 1 micron. Increase in condensation temperature leads to decrease in strength and to increase of ductility in all cases. As an example, Figure 6 shows the correlation between mechanical properties for Mo-Cu condensates and Mo concentration, when substrate temperature is 900 °C.

These data shows that increase of Mo concentration increase strength until to 25% mass. and then this characteristic is constant up to 50% mass., next mechanical characteristics decrease when Mo concentration is above 50%. The plasticity of these materials decreases rapidly with Mo concentration increasing up to 17%, and then there is a tendency to further decreasing of this parameter with increasing dispersed refractory particles concentration.

Degree of vacuum, chemical purity of initial components, the condensation rate, and roughness of substrate on which condensation is carried out - these factors have action upon mechanical properties of dispersion-strengthened condensates. At a low degree
of vacuum in the chamber, wherein the condensation is carried out, oxygen and nitrogen atoms interact with the metal atoms, that leads to oxides and nitrides formation. Thus, the mechanical properties of composites increase, but simultaneously ductility, conductivity and heat conductivity decrease.

The quantity of defects (microdroplets, nonmetallic inclusions) depends on purity of vaporized materials. The most rational for obtaining composites to use as initial metal ingots metal alloys after electron beam melting. This process reduces the amount of low-melting impurities, oxygen, nitrogen and hydrogen as compared to commercially pure metals and metal alloys.

The evaporation rate increase removal of impurities of liquid or solid phases during metal evaporation from the bath. Electron-beam remelting of leads to increase of pure metals and metal alloys condensation rate up 3.5 to 60 microns/min and dispersed phase – up 0.5 to 10 micron/min. In obtaining of composites to make the most efficient use the substrate surface roughness 0.63-1.2 Ra.

**Conclusions**

It has been established that obtaining of dispersion-strengthened materials, condensed from vapor phase, have suitable physical and mechanical properties, primarily depend on type of metal matrix and dispersed particles, substrate temperature, interfacial interaction between matrix - dispersed particles, substrate roughness, purity initial materials and evaporation speed and etc.

Method of high-speed evaporation of metals and non-metals in vacuum permit easy to construct new perspective dispersion-strengthened materials with predetermined physico-mechanical properties using estimation criterion of interaction at the matrix – particle boundary.

**REFERENCE**


