MECHANICAL PROPERTIES AND STRUCTURE OF AGE-HARDENABLE INVAR ALLOY 40 NL

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The majority of known Fe-Ni based invar alloys possess low mechanical properties. For example, the tensile strength of alloy 36 NX does not exceed 450 N/mm². At the same time demands for ever higher mechanical properties appear each year. There is a series of well-known methods to increase the mechanical properties of Fe-Ni based austenitic alloys [1, 2], but they all require additional alloying with one or several elements (Al, Nb, Ti, or others) in appreciable quantities which, besides raising the strength, also sharply increase the temperature coefficient of linear expansion (TCLE) [3].

It has been established [4-6] that alloying Fe-Ni alloys with beryllium produces dispersion hardening without a significant increase in TCLE. The optimal combination of nickel and beryllium in the ternary Fe-Ni-Be system has been determined (~40% Ni and ~8% Be) to permit an increase in hardness upon aging while maintaining TCLE at (2.5-3)·10⁻⁶ K⁻¹. However, a detailed investigation of the mechanical properties of such an invar alloy has not yet been carried out. Hence, in the present work, an investigation was made of the influence of heat treatment on the mechanical properties, crack resistance, and elastic properties of the Fe-Ni-Be alloy 40 NL over a wide range of temperatures, with a parallel study of the fine structure in the undeformed and deformed states.

Alloy 40 NL (40% Ni, 0.75% Be, remainder Fe) was produced under industrial conditions in the Sibélectrostal' mill. Ingots of 300 kg mass were forged to 80 mm diameter billets, which were rolled into 5 mm thick sheets and rods of 10 × 10 mm cross section and 8 mm diameter. These served as stock for the production of specimens. The specimens were water-quenched from 1050-1200°C (austenitizing time = 30 minutes) and subjected to aging for up to 15 h at 500-600°C.

Tensile tests at +20 to -262°C were carried out on an "Instron-1114" test machine at a deformation velocity of 3.3·10⁻⁵ m/sec using specimens of type MEG-3 with a 30 mm gauge length. Impact bending tests were conducted on longitudinal (relative to the rolling direction) and transverse specimens of type 3 (thickness, h = 5 mm, notch radius, R = 1 mm) and type 13 (h = 5 mm, R = 0.25 mm) at temperatures of -253, -196, -90, and +20°C. Crack resistance was determined on flat specimens with preliminary initiation of fatigue cracks at 20°C. The specimens were then taken to fracture under static loading on the "Instron-1114" machine. As criterion for fracture resistance the limiting fracture resistance was used, representing the maximum load, P_max, supported by the cracked specimen:

\[ I = \frac{P_{\text{max}}}{b t} \sqrt{\frac{l}{b}} \]  

where b and t are the width and thickness, respectively, of the specimen, \( I \) is the total length of the initial notch and grown fatigue crack, \( Y(t/b) \) is a function of the relative length of the crack for a selected specimen geometry. According to [7] the function \( Y(t/b) \) is approximated by the following series:

\[ Y = 1.99 - 0.41 \left( \frac{l}{b} \right) + 18.7 \left( \frac{l}{b} \right)^2 - 38.4 \left( \frac{l}{b} \right)^3 + 53.85 \left( \frac{l}{b} \right)^4 \]  

Fig. 1. Dependence of the mechanical properties (at 20°C) of alloy 40NL on the temperature of annealing before quenching (a), and on the aging time at 500 (b), 550 (c) and 600°C (d) after quenching from 1100°C.

In correspondence with the data of [8] the tests were carried out with one length, satisfying the condition \( l = 0.5b \). The temperature dependence of the elastic modulus, \( E \), was determined at -196 to +100°C by the dynamic method under the natural frequency of longitudinal vibration of a specimen 5 × 5 mm in cross section, 180 mm in length, on the unit "Elastomat". The temperature coefficient of the elastic modulus was calculated according to the formula:

\[
\frac{\Delta E}{E_{100°C} - E_{-196°C}} = \frac{E_{100°C} - E_{-196°C}}{E_{100°C} - E_{-196°C}} \Delta T
\]

The structure of the alloy after various heat-treatments was studied with the aid of the optical microscope "Neofot-2" and the electron microscope "Tesla-540".

After quenching, the alloy possesses low strength and comparatively high plasticity, but with increase of the quenching temperature (\( t_q \)) above 1100°C the tensile strength and plasticity sharply decrease (Fig. 1a). The optimal from the point of view of elevated mechanical properties (\( \sigma_{0.2} = 350 \text{ N/mm}^2 \), \( \sigma_u = 550 \text{ N/mm}^2 \), \( \delta = 33\% \)) is \( t_q = 1100°C \). In order to clarify the reasons for the decrease on mechanical properties for \( t_q > 1100°C \) a metallographic study was carried out, which showed that increasing \( t_q \) from 1050 to 1100°C led to a growth in the average grain size of the austenite from 25 to 50 mkm (Fig. 2a), and increasing \( t_q \) from 1100 to 1200°C to a growth to 220 mkm (Fig. 2b). This change in grain size is connected with the number of particles of second phase remaining undissolved after quenching (according to the X-ray diffraction studies conducted this phase is NiBe with a BCC lattice and parameter, \( a = 0.261 \text{ nm} \), which are located mainly along the boundaries of the grains, and retard their growth. With increasing \( t_q \) the number of particles of the second phase decreases. At \( t_q = 1150°C \) only traces of the second phase are found, and at \( t_q = 1200°C \) it is completely absent, which leads to rapid grain growth. Considering the above, the sharp decrease in mechanical properties for \( t_q > 1100°C \) may be connected with an increase in grain size.