FRACTURE OF Cu-Al-Ni SHAPE MEMORY ALLOYS

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It is shown that V-like temperature dependence of the fracture toughness in Cu-Al-Ni SMA alloy single crystals is governed by the formation of stress-induced martensite. The main regularities of the formation of the fracture surfaces in threee-point bending test are described. The main conclusions about the temperature dependence of the fracture toughness are shown to be also applicable for powder metallurgy Cu-Al-Ni SMA alloys.

Fracture processes in Cu-based shape memory (SM) alloys have become of interest in the past few years. There exists in the literature a number of papers devoted to this problem (1-4). Nevertheless, up to present time no results were reported concerning the fracture toughness parameters of the SM alloys, especially in connection with the possibility of stress-induced martensite (SIM) appearance. In the present investigation an intensive study was conducted, both on the single crystals and on the powder metallurgy (PM) samples, to clarify the influence of SIM on the temperature dependence of the fracture toughness in Cu-Al-Ni SM alloys.

Single crystals used have had $[100]\beta_1$ orientation and $M_s=$ -155°C. Their characteristic temperatures together with σ-T diagrams were described in detail elsewhere (Koval (5)). Specimens for bending tests were cut from the single crystal along its axis making the special efforts to maintain the crystallographic orientation of the specimens unchanged within 5°. The prepared samples were slightly mechanically ground, quenched into water and electropolished. Some PM alloys were also prepared by hot extrusion

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of rapidly solidified pre-alloyed powders, posessing either β_1 matrix or martensitic phase structures at room temperature. Tensile specimens were made from these alloys and their surface preparation was conducted in a similar way as that for the single crystals. Fracture toughness K_{Ic} was determined in three-point bending (TPB) test of the notched samples in the temperature range -196...+100°C. Fracture surfaces were studied in SEM. Also in situ observations were carried out using special apparatus for TPB loading in SEM.

Test temperature T dependences of K_{1c} values, transition stress σ_t and fracture stress σ_f are shown in Fig. 1. As is clearly seen from Fig. 1, the whole temperature interval studied may be subdivided into three regions according to different trends in K_{1c}-vs-T behaviour. Typical load-deflection curves for each region are presented in Fig. 2.

Let us consider the K_{1c}-vs-T dependence starting from the region 3. The single crystals used posess in this region β_1 matrix phase structure (5). Upon loading, stress-induced plates of martensitic β_1' phase might appear, leading to some stress relaxation (curve 3, Fig. 2). Region 2 contains the intervals of the forward and reverse transformations (5). As the flexure strain needed for the appearance of SIM is low in this region, even two successive transformations may take place. Note, that the first one leads to appreciable stress relaxation due to interphase boundaries movement (curve 2, Fig. 2). Region 1 corresponds to γ_1' martensitic phase of the alloy used (5). Due to thermal $\beta_1 \rightarrow \gamma_1'$ transformation on cooling, different crystallographic variants of martensite may form. During bending, reorientation of the martensite takes place, which becomes irreversible after some definite deformation, converting the central part of the sample into γ_1' single crystal. After unloading such a sample remains single crystalline one, so that during the succesive loading no modes of easy deformation may act. Such samples exhibit higher strength properties, and so only the points corresponding to two-stage loading process were taken into consideration in Fig. 1.

As is clearly seen from Fig. 1, trends in fracture toughness K_{1c}-vs-T dependence correlate closely with changes in σ_t and σ_f vs T. Such an unusual V-like K_{1c} temperature dependence is not observed in other materials in which SIM may appear, e.g. in TRIP steel (Antolovich (6)). To clarify the reasons for this disagreement, an extensive study of the fracture surfaces (FS) was performed.

The main fractographic features are generally the same for specimens tested in all three regions. Fracture process is initiated when the SIM plate reaches one of the electrospark cracks, which are present at the notch tip. The starting part of the FS looks like drop, its plane being parallel to $\{110\}\beta_1$ family of planes and the projection of its longitudinal axis being directed along the cubic axis (see Fig. 3). Thus, the starting part of the FS is parallel to the close-packed plane of the matrix crystal, the whole FS being very complicated. In effect, this arises from the fact that SIMs with different structures are formed in the regions of tension and compression. The overall relief is governed by the interaction of the moving crack with the plates of different SIMs. We have found out that the crack moves inside the martensitic plates and the crystallography of the fracture surfaces corresponds to the model for fracture processes in Cu-Al-Ni SM alloys (5). This model have been earlier proposed by the present authors and according to it, the regions with shear traces at the FS of the bending samples correspond to slip zones, and the ones with ductile-like dimples correspond to the take-off zones. Final part of the deformation process and the fracture itself is localized at the interphase boundaries. As the SIM formation promotes the fracture initiation, fracture stress appears to be close to the higher transition stress σ_t^2, which in turn exhibits a well-known V-like temperature dependence (1,5).

Fracture toughness K_{1c} values were compared with the fracture energy ones estimated from the tensile tests (data taken from (5)), following the approach proposed by Panasyuk et al for TRIP steel (7). The parameter S in Fig. 4 was defined as an area under the tensile stress-strain curves. The results obtained were found to agree excellently with one another, thus proving the validity of the above approach also for the Cu-based SM alloys. The main conclusion to be made is that strength and fracture toughness characteristics of Cu-Al-Ni SM alloy single crystals decrease on both heating or cooling toward the transformation temperatures interval, that is the bending strength and the fracture toughness are the higher, the farer is the test temperature from, say, M_s. Brief inspection of the results already obtained at PM samples shows, that the considerations about K_{1c}-vs-T dependence in single crystals are applicable also for PM processed Cu-Al-Ni SM alloys.

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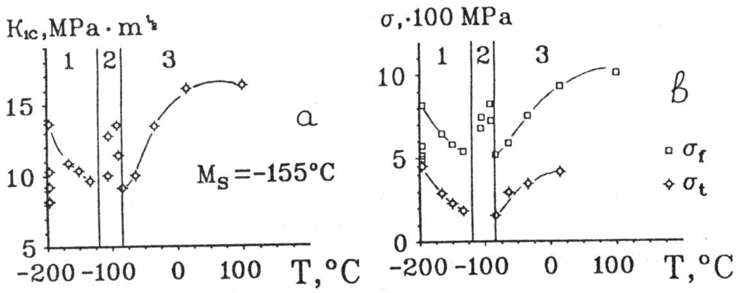


Figure 1 Temperature dependence of K_{1c} (a), σ_t and σ_f (b).

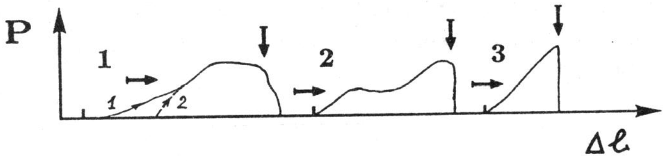
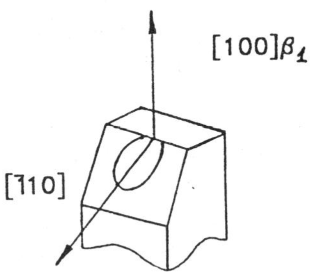


Figure 2 Typical load-deflection curves for each region from Fig. 1. → denotes σ_t, ↓ shows fracture point (stress σ_f).



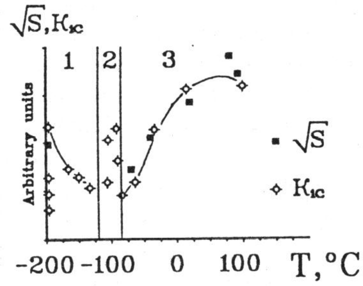


Figure 3 Schematic drawing of fracture surface after TPB test.

Figure 4 Comparison of K_{1c} and $\sqrt{S}$ values for different temperatures.