TRANSFORMATION TOUGHENING AND FRACTURE IN Cu-Al-Ni SHAPE MEMORY ALLOYS

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ABSTRACT

It is shown that the manifested fracture mechanisms and the unusual V-like temperature dependence of the fracture toughness in Cu-Al-Ni shape memory alloys are stipulated by the formation of the stress-induced martensites. This conclusion is evidenced to be the case for single crystals, and also for polycrystalline materials produced by hot extrusion.

KEYWORDS

Cu-Al-Ni, shape memory alloys, fracture toughness, fracture mechanisms, single crystals, polycrystals, temperature, stress-induced martensite.

INTRODUCTION

Cu-Al-Ni shape memory (SM) alloys attract the attention because of their unusual mechanical properties, namely the superelasticity and shape memory effect. The superelasticity arises due to the formation of the stress-induced martensites (SIM). The corresponding martensitic transformations appear to be fully reversible with respect to the deformation, what leads to unusually high deformation that may be recovered quasielastically (at the level of 10% in single crystalline specimens). Though the martensitic transformations in the Cu-Al-Ni SM alloy single and polycrystals have been carefully studied by many authors, the main regularities for the fracture processes leave practically unknown. Sakamoto et al. (1982, 1986) has discovered, that fracture of cast Cu-Al-Ni alloys in β or martensitic state is initiated by the SIM formation. Other authors (Lee and Wayman 1986, Husain and Clapp 1987, Jean et al. 1991, Roh et al. 1991) have observed the fracture mechanisms in polycrystals produced by different methods, but they gave no explanation to the observed fracture mechanisms and did not consider they connected with the test temperature. Moreover, up to present absolutely no studies have been done on the influence of SIM appearance in the concerned alloys on their fracture toughness, which serves now as one of the most useful parameters in materials characterization. The aim of the present work was to study systematically the influence of the structural state and the test temperature on the fracture toughness and the fracture mechanisms in Cu-Al-Ni SM alloys.

MATERIALS AND METHODS

Single Crystals. Single crystalline specimens were prepared from the rods with the orientation $[100]\beta_1$ possessing the different transformation temperatures. All the samples for three-point bending (TPB) tests were checked to have the same orientation of the side surfaces with respect to the crystallographic axes within the accuracy 5°. The description of the materials used and of the sample preparation procedures is given in details elsewhere (Koval et al. 1992, Cherepin et al. 1992).

Polycrystals. Polycrystalline materials were produced by hot extrusion of the rapidly solidified pre-alloyed powders. The powder chemical compositions were preliminary chosen so that the obtained materials possessed as the matrix, as also the martensitic phase state covering the set of different transformation temperatures for each of the states. The specimens for tension and TPB tests were also prepared from the obtained polycrystals. Specimen preparation was carried out following the similar procedure, as that for single crystalline samples.

The sample structures in the as-cast and in the deformed state were determined by XRD. The mechanical tests were performed in tension at the unnotched samples and in TPB at the electrospark notched ones in the temperature range -196...+100°C. Fracture surfaces were observed in SEM. The specially designed apparatus was also used for *in situ* tension and TPB tests in optical microscope or inside SEM.

EXPERIMENTAL RESULTS. SINGLE CRYSTALS

The results of the tensile tests of the single crystals have shown, that regardless the starting structures of the specimen (matrix or martensitic) the main mechanisms of their deformation and fracture are the same. Tensile fracture surfaces of both matrix or martensitic phase specimens tested at different temperatures demonstrate the characteristic V-shape with the regions of shear traces and the ductile-like dimples present at the conjugate parts of the whole fracture surface. Note, that the ductile-like dimples are clearly visible even at the samples tested at -196°C.

In our earlier paper on this subject (Koval et al. 1992) we have proposed the crystallographic model to explain the main regularities of the fracture processes in Cu-Al-Ni SM alloy single crystals. Let us briefly remind it. Consider the single crystalline specimen tensile loaded in $[100]\beta_1$ direction. As we have already shown earlier, under the loading the stress-induced martensites (SIM) are formed in the specimen and then it deforms by slip along the close-packed planes of the martensitic phases which appear to be parallel to the family of the close-packed planes $\{110\}\beta_1$ of the matrix BCC phase due to lattice correspondence in the concerned martensitic transformations. Hence, let the specimen deforms by slip along two planes, e.g., $(10\bar{1})\beta_1$ and $(101)\beta_1$. Let us resolve the complete shear deformation into two components $m\mathbf{d}=m_1\mathbf{d}_1+m_2\mathbf{d}_2$. Here m is the strain value, $\mathbf{d}$ is the unit vector along the direction of the complete strain, $\mathbf{d}_1$ and $\mathbf{d}_2$ are unit vectors, $\mathbf{d}_1 \perp \mathbf{d}_2$, and $\mathbf{d}_1$ lies in the $(101)\beta_1$ plane, while $\mathbf{d}_2$ lies in the $(10\bar{1})\beta_1$ plane.

The complete shear deformation $m\mathbf{d}$ can now be represented as two simultaneous shears $m_1\mathbf{d}_1$ and $m_2\mathbf{d}_2$ along the mutually perpendicular planes, so that the shear along only one plane corresponds to cleavage from the other. When the SIM plate reaches the surface defect, the microcrack is formed and the slip along one of the directions, say, $\mathbf{d}_1$, becomes preferential over the slip along $\mathbf{d}_2$ direction (see Fig. 1). The thus formed fracture surface consists of the slip region with the shear traces and of the break-off region with the ductile-like dimples, whose depth corresponds to the thickness of the SIM plate. If only two planes participate in the process, then the shear traces appear perpendicular to plane intersection. If not two but three planes participate, all the above remains true with the sole exception that the shear traces are now oriented at an angle of 45° to plane intersection (Fig. 1). Thus,

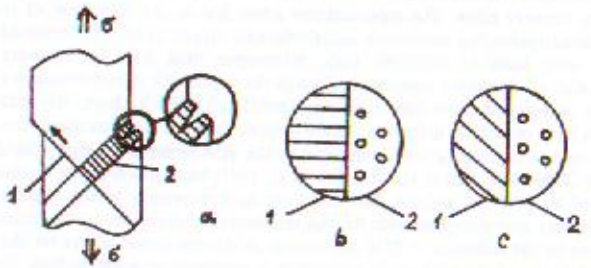

Fig. 1. The model for the fracture process under tension. 1 is the shear region, 2 is the take-off region; a is the fracture initiation at microcrack, b, c are the schematic fracture surfaces: b is the case of two planes, c is the case of three planes.

according to the model the fracture surface formed during the deformation of the SIM plates must comprise the mutually perpendicular regions of the shear traces and the ductile-like dimples.

The TPB tests have shown, that the whole temperature interval studied may be divided into 3 regions according to the main trends in fracture toughness and fracture stress behavior (Fig. 2). In the region 1 the specimen possess before loading the γ'_1 phase of the cooling-induced martensite, in the region 3 the matrix β_1 phase, and the intermediate region 2 covers the temperature interval of the forward and reverse martensitic transformations $\beta_1 \leftrightarrow \gamma'_1$. The evaluation of the validity of linear fracture mechanics criteria in all three regions have shown, that only in the region 3 the obtained stress intensity coefficient K_C values are strictly the K_{1C} values. The correlation between the values of K_C, σ_F and σ_T at different temperatures is clearly seen in Fig. 2. It follows from this observation, that on bending the fracture initiation is also connected with the SIM formation.

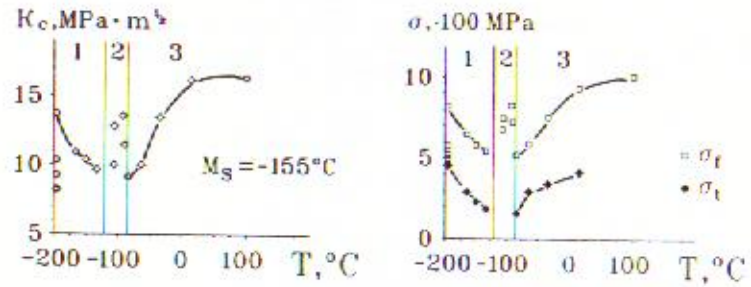

Fig. 2. The temperature dependences of K_C, σ_F and σ_T.

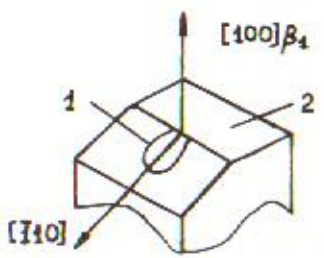

Fig. 3. Schematic view of the TPB fracture surface. 1 is the "drop", 2 is the notch.

The fractographical studies have permitted us to clarify the reasons for the observed V-like K_C and σ_F dependences on temperature, namely their diminishing on changing the test temperature toward the region 2, and their surprisingly high values in the region 2 itself. It appears, that in all three regions the fracture surfaces after TPB test demonstrate the similar overall relief, which is schematically shown in Fig. 3. The fracture is initiated at the electrospark cracks, introduced during the notch formation. The starting part of the fracture surface has the drop-like shape, the "drop" plane being the $\{110\}\beta_1$ plane and its axis being directed along the $[\bar{1}10]$. The presence of the traces of the quasi-ductile fracture at the "drop" surface are connected with the large contribution of the tension stresses at the notch tip, so that according to our scheme (Fig. 1) the break-off zone is formed there. In effect, in the concerned alloys the different martensitic phases are formed in the regions of tension and compression, so the overall surface relief appear to be rather complicated, because it is determined by the interaction of the moving crack with the plates of different SIMs. Note, that the regions with the shear traces and with the dimples are clearly visible to be perpendicular to each other, as this must follow from our model.

The presented results of the fractography permit to explain the unusual trends in the dependences shown in Fig. 2. In the region 3 the sample initially possesses the matrix phase structure. On loading, the SIM plates are formed in it in the compression zone and in the tension one (near the notch tip). When the SIM plate reaches the electrospark crack, then the fracture process begins, which is at first localized inside the SIM plate, forming the "drop". In the region 1 the sample is in the martensitic γ'_1 phase, and furthermore, the whole number of the crystallographically equivalent variants are present in it. On loading, the reorientation of the variants takes

place at first. When this channel of the strain accommodation is exhausted, the SIM plates are formed and on further loading the situation is the same, as in the region 3.

In the region 2 the deformations to induce the SIM formation are very low, so the plates of the first SIM phase are formed near the notch tip, leading to some stress relaxation. On continuing the loading process the measured stress increases again, the plates of the second SIM appear and at last the fracture is initiated. The higher values of the fracture stress determine the higher values of the stress intensity coefficient K_C. Thus, in the region 2 the transformation toughening effect takes place, that is the toughening of the material due to proceeding of the martensitic transformations(s). Since the fracture process is initiated by the SIM formation, and the temperature dependence of the transition stress is known to demonstrate the V-like behavior in the regions 1 and 3 (see Fig. 2), then outside the region 2 the fracture stress σ_F and the stress intensity coefficient K_C are envisaged to manifest also V-like behavior. This effect of SIM on K_C may be additionally explained in view of thermodynamics of the martensitic transformations. The amount of the mechanical energy needed to be additionally supplied to the sample by the testing machine for SIM formation is evidently determined by the driving force of the transformation. This additional energy in turn determines the increment in K_C due to the transformation. As the driving force for the transformation decreases when the temperature approaches the transformation temperature interval, then the increment in K_C will also decrease.

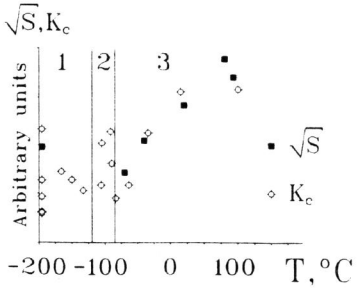

Fig. 4. Comparison of K_C and $\sqrt{S}$ values at different temperatures.

We have also compared the results of the tension and bending tests carried out at the single crystals through the estimation of the temperature dependence of the specific fracture energy. This dependence has been constructed by the value of the parameter S defined as the area under the tensile σ–ε curve. According to the approach developed by Panasyuk et al. (1977) for TRIP steels, in the wide temperature region the values of $\sqrt{S}$ must coincide with the ones of K_{1C} multiplied by the constant temperature-independent coefficient. The results of this comparison are plotted in Fig. 4 in arbitrary units to show the qualitative trends only. As is clearly seen from Fig. 4, in Cu-Al-Ni SM alloy single crystals the temperature dependence of K_C closely correlate with the one of $\sqrt{S}$, that is the estimations of the trends in fracture toughness (usually measured in TPB tests) might be carried out for the concerned alloys by the results of the tensile tests only.

EXPERIMENTAL RESULTS. POLYCRYSTALS

The effect of the granular structure on the mechanical properties of the materials is the circumstance one must take into account during the investigation of polycrystalline SM alloys. The account for the presence of the grain boundaries is needed in this case, since they serve as the obstacles for the quasielastic deformation of the SM alloys which is usually accomplished by the movement of the interphase boundaries dividing the SIM plates and the untransformed material. The interaction with the grain boundaries is possible also in the course of the stress-induced reorientation of the variants of the cooling-induced martensite. Some authors (Sure and Brown 1984) have investigated the concerned problem without going into details of SIM behavior. They have shown, that the Cu-Al-Ni SM alloys obeyed the well-known dependence of fracture and transition stresses on average grain size expressed as the Hall-Petch law corrected for the specimen thickness effect. Nevertheless, our analysis of the data from different papers quoted in the reference list clearly shows the large scatter in the respective dependences plotted according to Sure and Brown by the data found in the literature. The reason for this scatter may be as follows. Since it is well-known, that the chemical composition and the method of material preparation effect the characteristic temperatures of the SM alloys, then it evidently follows in view of the results of the SIM studies (Sakamoto et al. 1982, 1986), that the condition for the SIM formation must always be taken into consideration during the comparison of the data from different sources. This condition has been proposed to be characterized by the value of $\Delta T = T_{test} - M_s$, where T_{test} is the test temperature. Thus, when studying the polycrystalline SM alloys, either two distinctly different parameters, namely, the average grain size

and the value of ΔT must be taken into account simultaneously, or the more important one is to be selected as the main. In some of the materials prepared by novel technique, which possess the textured microstructure, even the definition what is to be treated as the "grain size" is strongly complicated. We consider it not fatal, because the actual grain sizes of the SM alloys reported in the literature does not vary significantly, usually from about 50 to 400 μm or even less, so in the first approximation the ΔT parameter may be regarded as more critical. Since the materials used in the given work have demonstrated the whole set of grain sizes, even wider than that present in the literature, we have decided to divide our materials into the groups with close grain sizes and to characterize the influence of ΔT on the mechanical properties separately within each group. Thus, in this paper only the effect of the temperature on SIM formation is considered, whilst the detailed studies on the effect of polycrystallinity on the alloy properties has been left beyond the scope of the paper.

The data on the tensile strength of the polycrystalline samples are briefly presented in Fig. 5. Despite the scatter, one may observe, that the general trends in the plotted dependence are similar to those plotted in Fig. 2 for single crystals. This means, that the SIM formation is to be regarded as the governing factor which influence the strength of the hot-extruded Cu-Al-Ni SM alloys regardless their phase composition, that is both in matrix phase or martensitic phase states. This statement is supported also by the results of the extensive fractographic studies conducted on the samples tested in tension and bending at different ΔT values. The obtained data show, that the specimens possessing the martensitic phase structure may accommodate the incompatibility stresses at the grain boundaries arising due to the SIM formation easier, than the matrix phase specimens. In fact, the matrix phase samples begin to break practically immediately after the formation of the first SIM plates. Though the transgranular fracture mechanism is prevailing for the matrix phase, the very few number of grains with the traces of the SIM deformation is observed at the fracture surfaces. On the contrary, the martensitic phase samples accommodate the deformation at first by the reorientation of the already present intragranular martensitic variants. On further loading SIM plates also appear, whose deformation again determines the fracture stress and so the fracture surfaces are formed with the clearly observed V-shaped regions inside the fractured grains. These regions evidence, that despite the effect of the neighboring grains, inside each specific grain the SIM deformation and its fracture proceeds according to the scheme shown in Fig. 1.

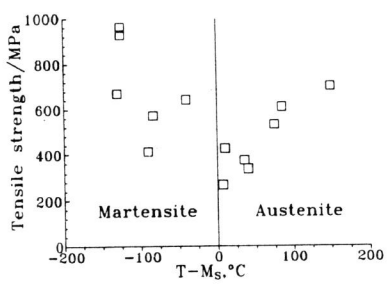

Fig. 5. Tensile strength of the polycrystals at different ΔT parameter values.

Due to complex stress state in bending tests which significantly influence the conditions for the SIM formation, the data on the fracture toughness K_C of the polycrystalline materials show large scatter. Nevertheless, the general trends over the different alloys studied are similar to the results on the tensile strength, namely the increase in K_C on departing by the temperature outwards the interval of the characteristic transformation temperatures. The results of the mechanical tests also permit to claim, that the influence of the grain size on the mechanical properties in the martensitic state is less critical, than in the matrix one, what is well explicable in view of different conditions for the SIM formation in different states. Since the number of variants of the cooling-induced martensitic plates appear weakly dependent on the grain size, the larger grain will mean the larger length and the thickness of the variants in it, that is the higher value of the deformation which may be accommodated by the intragranular reorientation of the variants. Thus, our preliminary conclusion on this subject is that the matrix phase alloys must have the smallest grain size possible to lower the incompatibility deformations at the grain boundaries, whereas the martensitic phase materials should better have the grain size at the level of about 200 μm or even more, to improve the intragranular reorientation of the martensitic variants.

CONCLUSIONS

The results of our extensive studies on the mechanical properties of Cu-Al-Ni SM alloys in different phase and structural states evidence, that they manifest the transformation toughening effect, which comprise in the increase of strength and fracture toughness due to proceeding of the martensitic transformation. Since the amount of the mechanical energy which is to be additionally supplied for the proceeding of the transformation

is the larger, the farer is the temperature from the transformation interval, then the resulting transformation dependence of fracture stress and fracture toughness appears to show the V-like behavior. We also propose for the very first time the model for explaining the main regularities of the fracture surface formation in Cu-Al-Ni SM alloys.

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