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Transformation temperatures, elastic and anelastic properties of Cu-Al-Ni crystals subjected to impact loading

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Abstract. Experimental investigations of the influence of impact loading on properties of Cu-Al-Ni single crystals have been performed. Crystals in the β_1 phase were impacted with pulses of a uniaxial plane strain wave with a duration of about 2×10^{-6} s. A normal component of stress in the direction of the pulse propagation ranged from 0.5 to 5.4 GPa. For as-quenched and impacted crystals martensitic transformation temperatures were determined, the Young's modulus (YM), strain amplitude-independent and strain amplitude-dependent internal friction were measured at a frequency of about 100 kHz over the temperature range of 300-90 K for strain amplitudes of 10^{-7}-2×10^{-4}. Experimental results indicate that $\beta_1\rightarrow\gamma_1'$ martensitic transformation (MT) and plastic deformation of the martensite are induced by the impact. The impact loading generates a «structure memory effect»: the YM in the austenite is not sensitive to the impact, but the consequent temperature-induced MT reveals a dramatic influence of the impact on the YM of the γ_1' martensite. The conclusion is drawn that the observed effect is fundamentally similar to the two-way memory effect, but is extremely sensitive to the impact stress. The origin of this phenomenon is attributed to the internal stresses, created by impact, which control the nucleation of preferentially oriented anisotropic martensitic variants during temperature-induced MT in impacted crystals. No influence of the impact loading on the transformation temperatures was detected for $\beta_1\rightarrow\gamma_1'$ MT, in contrast to elastic properties of the martensitic phase, indicating that structural changes due to the high-velocity impact do not affect appreciably the thermoelastic equilibrium and hysteretic motion of parent – martensite boundaries during the MT.

1. INTRODUCTION

Performance and properties of materials exhibiting a thermoelastic martensitic transformation (TMT) are closely related to the stability of their defect structure [1,2]. From the engineering standpoint, the properties of TMT materials under the ultimate conditions of high-energy impact loading are of a great importance. Recently, detailed investigations have been performed of the influence of the high-velocity impact loading on the performance and properties of Cu-Al-Ni single crystals of different compositions, both in the β_1' martensite [3-5] and in the β_1 phase [4,6]. An acoustic technique has been used extensively to detect the structural changes induced by the shock-wave loading of Cu-Al-Ni crystals. The present paper reports the influence of high-velocity impact on the elastic and anelastic properties of the β_1 and γ_1' phases and on the $\beta_1\rightarrow\gamma_1'$ transformation temperatures. An estimate of the upper time limit to induce the TMT and plastic deformation of the martensitic phase is also obtained.

2. EXPERIMENTAL

Samples for the investigations were prepared from Cu-14.4wt%Al-5.5wt%Ni single crystalline rods with [100] orientation in the β_1 phase. Crystals were quenched into water at room temperature after homogenization at 1173 K for 15 min. The $\beta_1\rightarrow\gamma_1'$ transformation was temperature-induced on cooling of crystals and stress-induced during deformation at room temperature. For impact loading, rod-shaped samples with dimensions of about $1\times3\times30$ mm^3 were spark-cut along the crystals.

Shock-wave loading was performed by means of a striker accelerated in a gas gun to velocities in the range of 35-500 m/s [7]. Samples were embedded in a massive brass holder and a uniaxial plane compressive strain wave was induced in the holder with the sample. The uniaxial plane strain wave propagated along the shortest axis of the rod-shaped samples. The amplitude of the impact wave was

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characterized by the normal stress component in the direction of wave propagation, and was registered by means of tensometers and laser interferometer [7]. This stress component had a magnitude of 0.4-5.4 GPa with a pulse duration of about 2×10^{-6} s. The samples were impact loaded at room temperature.

Samples with dimensions of about $1\times1\times9.5$ mm^3 were spark cut from the central parts of the impacted samples for measurements of the internal friction (IF) and the Young's modulus (YM) by means of the resonant piezoelectric composite oscillator technique at a frequency of about 100 kHz. The experimental setup [8] enabled us to measure the strain amplitude dependence (strain amplitude ranged from 2×10^{-7} to 2×10^{-4}) and temperature dependence (for temperatures of 90-300 K) of the IF and YM of the samples. More details of the technique have been published elsewhere [9].

The transformation temperatures of the crystals as determined by Differential Scanning Calorimetry are summarized in Table 1.

Table 1. Transformation temperatures of samples

Crystal	State	M_s, K	M_f, K	A_s, K	A_f, K
Cu-14.4wt%Al-5.5wt%Ni	as-quenched	178	176	≈ 217	232
	impacted, 0.5 GPa	180	179	≈ 220	232
	impacted, 3.1 GPa	179	177	≈ 218	232
	impacted, 5.3 GPa	178	177		

3. RESULTS

The temperature dependence of the YM for the as-quenched and impacted samples is represented in fig.1. A drastic virtually step-like change of the YM occurred during the direct $\beta_1\rightarrow\gamma_1'$ TMT. A detailed analysis [6] allowed us to attribute this effect to the variation of elastic properties of the material rather than to the change of the geometry of samples due to the two-way memory effect.

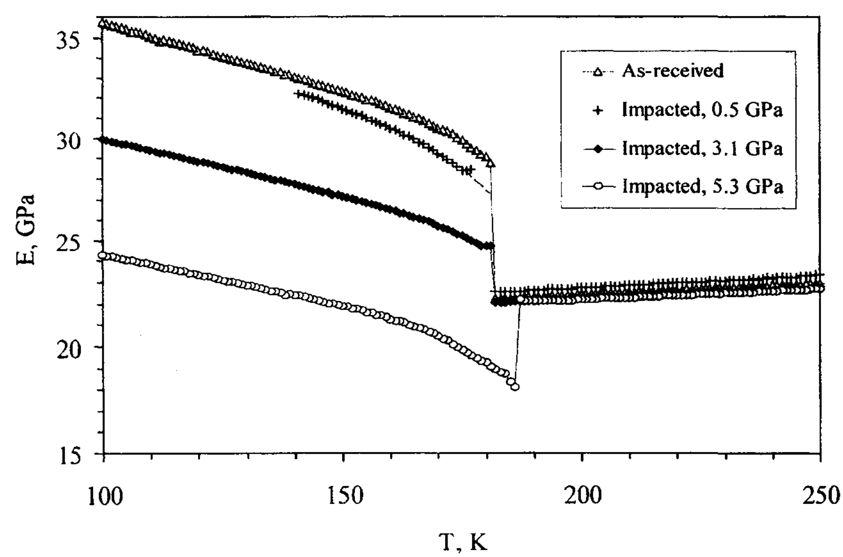


Figure 1: Temperature dependence of the Young's modulus of as-quenched and impacted samples of Cu-14.4wt%Al-5.5wt%Ni alloy measured during cooling at an oscillatory strain amplitude of 5×10^{-7}.

A number of other details are worth mentioning. First, impact loading of crystals in the β_1 phase does not lead to a detectable change of the YM in the austenite. Second, in line with the DSC measurements, the impact loading has only a marginal influence on the M_s temperature as detected by acoustic measurements, within a few degrees. Third, despite the dramatic shift of the YM in the martensite to lower values with the increase of the impact amplitude, the temperature trend is preserved. In contrast to the β_1' martensite [3-5,8], no anomaly is detected in the YM temperature dependence.

Figure 2 shows the IF stress amplitude dependence measured for as-quenched and impacted samples in the β_1 phase at room temperature and in the γ_1' martensite at ~ 100 K. The stress amplitude σ_m was recalculated from the strain amplitude ε_m measured experimentally: $\sigma_m = E(\varepsilon_m) \times \varepsilon_m$. The IF in the β_1 phase is very low and no strain amplitude dependence can be detected both for as-quenched and for impacted samples. In the martensitic state, a pronounced stress amplitude dependence is observed for as-quenched and impacted samples. The possible effect of the impact loading on the ADIF cannot be discerned reliably, fig. 2. The fact that the IF does not exhibit a significant change after the impact loading suggests that the anelastic contribution to the change of the YM after impact loading is not the controlling factor for the γ_1' martensite.

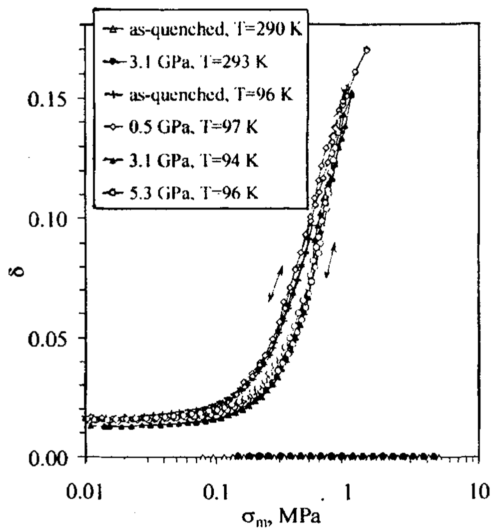


Figure 2: Stress amplitude dependence of the decrement at temperatures of about 95 K for as-quenched and impacted samples in the γ_1' phase.

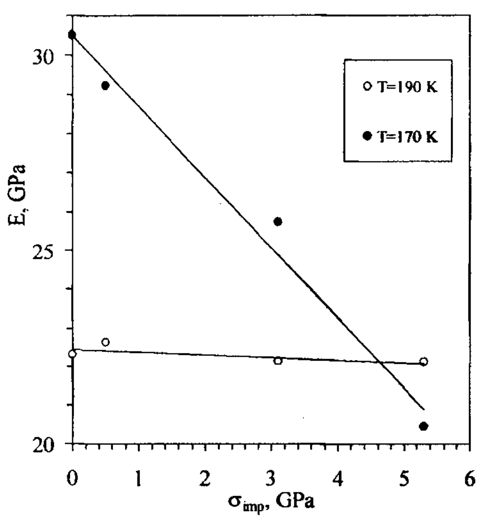


Figure 3: Influence of the impact stress on the Young's modulus of samples in the austenite (T=190 K) and in the martensite (T=170 K).

Another conspicuous detail is the absence of the amplitude hysteresis in the stress anmplitude dependence of the IF. This is contrary to what has been observed for the β_1' martensite in Cu-Al-Ni [9,10] and Cu-Al-Be systems [11], and points to the absence of mobile pinning points in the Cu-Al-Ni γ_1' martensite at a temperature of about 100 K.

The dependence of the YM in the austenite and in the martensite close to M_s and M_f, respectively, on the stress pulse magnitude is depicted in fig. 3. The YM in the martensite exhibits a nearly linear dependence on the impact stress amplitude, whereas, as mentioned before, the YM in the austenite is practically insensitive to the impact loading. It is worthwhile to note that the effect of the impact on the YM emerges at impact amplitudes with the stress components comparable with the static stress required to initiate the reorientation of martensitic variants (0.25 GPa).

4. DISCUSSION

For all impact amplitudes, the effect of the shock-wave loading on the transformation temperatures cannot be detected reliably, being comparable with the precision of the DSC measurements. The transformation temperatures determined by DSC correlate well with the results of the acoustic measurements. A discrepancy of about a few degrees between the data of calorimetry tests and acoustic measurements can be discerned in the M_s and M_f temperatures. This difference can be attributed to the difference in the geometry and size of the samples for calorimetry and acoustic measurements. We should also mention that the interval of the direct transformation is very narrow, typically about 2 degrees, see Table 1. This is an indication that only a few martensitic variants are formed during the direct TMT. The stability of the temperatures, interval and hysteresis of the transformation indicates that the impact does not alter significantly the thermoelastic equilibrium during the TMT and hysteretic effects impeding motion of parent-martensite boundaries. Thus, we conclude that the structure of the temperature-induced martensitic variants (number of variants and their accomodation) as well as basic defects, impeding the motion of parent-martensite boundaries, are not influenced significantly by the impact loading.

The present results show that, as usually [12,13], the anelasticity of the austenite is very low compared to that of the martensite. Since neither elastic nor anelastic properties of the β_1 phase are influenced notably by the impact loading, the behaviour of the martensite is of a prime interest. Figure 2 shows that the impact loading does not have a pronounced effect on the anelastic properties of the γ_1' martensite, in contrast to the YM. A high contribution of anelastic strain to the measured YM of the β_1' martensitic phase was detected as an anomaly of its temperature dependence [3-5,9]. Figure 1 demonstrates that, in line with the relative stability of the strain amplitude dependence of the IF, the anomaly of the YM temperature dependence is not observed in the as-quenched and impacted γ_1' martensite. Moreover, the trend of the YM temperature dependence is not influenced by the impact. Therefore, it is reasonable to suggest that a possible contribution of anelastic effects to the YM does not change appreciably with impact amplitude. This conclusion is contrary to what has been reported for the β_1' martensite [4,5]. This difference can be associated with the presence and the absence of mobile quenched-in pinning points in the β_1' and γ_1' martensites, respectively. The absence of mobile pinning points in the γ_1' martensite (at least at temperatures of about 100 K) is evidenced by the absence of the amplitude hysteresis, see fig. 2. As has been shown, interaction of mobile partial dislocations with atmospheres of quenched-in defects controls to a great extent the anelasticity of the β_1' martensite for the Cu-Al-Ni [3-5,9,10,14] and Cu-Al-Be [11] systems. Most likely, quenched-in defects for the present alloy composition are annealed out in the β_1 phase at room temperature. The stability of the anelastic properties of the γ_1' martensite after the impact enables us to ascribe the influence of the impact on the YM mostly to elastic effects.

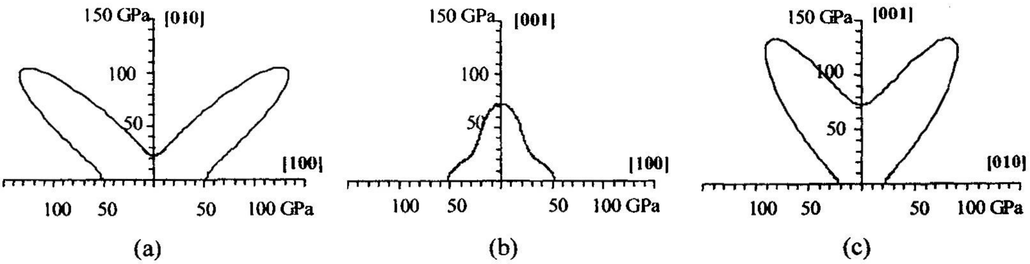
The effect of the impact on elastic properties of martensite can be interpreted based on the concept of internal stresses, which are known to influence strongly the YM and anelastic properties of martensitic phases [3-5]. We propose the following sequence of events, leading to the sensitivity of the YM in the martensite to the impact loading of the β_1 phase.

- The stress-induced TMT occurs under the action of the impact with a duration of about 2×10^{-6} s.
- In addition to the TMT, the impact induces plastic deformation of the γ_1' martensitic phase through the motion of intervariant boundaries. Just as in the case of impact loading of the β_1' martensite [3-5], high internal stresses are generated by the plastic deformation of the polyvariant martensitic structure due to high elastic anisotropy of the martensitic phase.
- The reverse TMT occurs with the completion of the action of the stress pulse. However, a change of the pattern of structural defects and internal stresses, induced in the martensite, is inherited by the single crystal of austenite, most likely through its dislocation structure.
- During subsequent direct TMT under thermal cycling, the internal stress pattern created by the impact loading governs the structure of martenitic variants nucleated during the TMT. The formation of variants with a preferred orientation leads to a significant change of the effective YM of samples, due to the high elastic anisotropy of the γ_1' phase.

Thus, fundamentally this effect is similar to the two-way memory effect. However, the registered effect in the elastic properties is at least an order of magnitude higher than that expected from the change of the geometry of the samples. The suggested concept implies that strong anisotropy of the YM in the γ_1' martensitic phase exists. To determine the orientation dependence of the YM we used the values of the 9 independent elastic constants c_{ij} reported in ref. [15]. First, the reciprocal matrix of the elastic compliances s_{ij} was calculated from the data of ref. [15]. Then, the inverse YM in the direction of the unit vector l_i can be calculated from the elastic compliances [16]:

$$\frac{1}{E} = l_1^4 s_{11} + 2l_1^2 l_2^2 s_{12} + 2l_1^2 l_3^2 s_{13} + l_2^4 s_{22} + 2l_2^2 l_3^2 s_{23} + l_3^4 s_{33} + l_2^2 l_3^2 s_{44} + l_1^2 l_3^2 s_{55} + l_1^2 l_2^2 s_{44}.$$

Figure 4 shows the calculated orientation dependence of the YM of the γ_1' martensitic single crystal. The YM attains the lowest value of about 20 GPa in the [010] direction. A maximum of the YM of about 160 GPa is expected in the direction [430]. The exact comparison of measured (fig. 1) and calculated values of the YM (fig. 4) is difficult since measurements in the present work and in ref. [15] were performed at different temperatures and the softening due to the TMT should be also accounted for. Nevertheless, quite



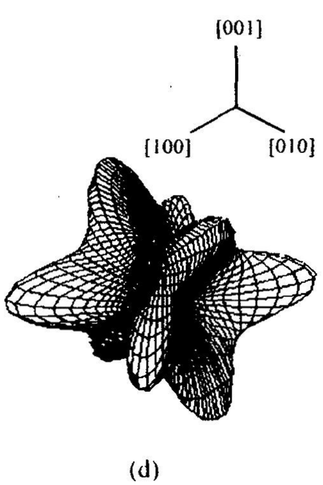


Figure 4: Orientation dependence of the Young's modulus of the γ_1' martensite: (a), (b), (c) – three cross-sections of the Young's modulus field (d).

low experimentally measured values of the YM indicate that even in the as-quenched state a preferential orientation of martensitic variants exists close to the [010] direction along the samples. It appears that after the impact loading the martensitic variants with the lowest YM are even better aligned along the impacted crystal. The high anisotropy of the the YM of the γ_1' martensite accounts thus for the virtual discrepancy in the behaviour of the YM and the transformation temperatures: minor changes in the variant structure are sufficient to change dramatically the YM, while the transformation temperatures are practically not influenced by the impact.

5. SUMMARY

1. The present results indicate that the stress-induced $\beta_1 \rightarrow \gamma_1'$ martensitic transformation occurs for a stress pulse duration of 2×10^{-6} s. This time interval appears to be sufficient also for the subsequent deformation of the γ_1' martensitic phase to occur.

2. A structure memory effect has been found: Cu-Al-Ni austenitic crystals, shock-loaded at room temperature to induce γ_1' –martensite, recall during consequent temperature-induced martensitic transformation the martensitic variant structure (elastic properties) formed under the shock loading.

3. Elastic properties of γ_1' crystals of the Cu-Al-Ni system are extremely sensitive to the shock-wave loading. Mechanisms of this effect includes the generation of internal stresses due to the high elastic anisotropy of the martensitic phase. These internal stresses govern the formation of the martensitic variant structure during the temperature-induced martensitic transformation.

4. In contrast to elastic properties, the transformation temperatures, the interval and hysteresis of the thermoelastic martensitic transformation are insensitive to the impact loading, indicating that the impact does not alter significantly the thermoelastic equilibrium during the TMT and hysteretic effects impeding the motion of parent-martensite boundaries.

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