Materials and Design 68 (2015) 215–220

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Short Communication

Influence of microstructural parameters on damping capacity in CuAlBe shape memory alloys

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ARTICLE INFO

Article history:
Received 10 October 2014
Accepted 20 December 2014
Available online 30 December 2014

ABSTRACT

The influence of microstructural parameters on damping capacity in β CuAlBe polycrystalline shape memory alloys was studied in detail by compression tests. For higher maximum stresses, the pseudoelastic strain increases, higher values of dissipated energy are obtained, and the specific damping capacity increases to reach a stable value. As the grain size of the samples increases, the dissipated energy decreases, but higher values of the specific damping capacity are obtained and at lower strains. A similar behavior is observed as the test temperature decreases in the range of 278–340 K.

Stress-grain size and stress–temperature diagrams were constructed, indicating the areas where it is possible to obtain the PE effect, and the optimal working zones. A quantification of the dissipated energy and the specific damping capacity as a function of σ_{max}, grain size, and temperature was realized.

1. Introduction

The CuAlBe alloys exhibit shape memory properties because of a thermoelastic martensitic transformation (MT). The MT can be induced by cooling or by the application of mechanical stress. On cooling, the spontaneous transformation occurs without a macroscopic change of shape with the formation of 24 self-accommodated martensite variants, and it begins at a temperature Ms. Martensite can be also induced by the application of mechanical stress, tension or compression, to the β phase, producing a macroscopical change of shape [1,2]. On removing the load, a hysteretic loop is formed, and the strain can be almost fully recovered leading to the pseudoelastic (PE) behavior. The PE cycles exhibit hysteresis in tension, due to the dissipation of mechanical energy into heat. Previous studies on Cu–11.4Al (wt.%) alloys with small additions of beryllium have demonstrated that they exhibit the PE behavior at room temperature, associated to the β → 18R martensite transformation, with high strain recoverability and higher stability ranges of the β phase respect to others Cu-based shape memory alloys [3–6]. For these reasons, CuAlBe alloys are promising for applications as passive dampers, especially for civil engineering applications in damping and vibration control [3,4,7–9].

Some studies about the thermomechanical and PE behavior induced by tension and compression tests in CuAlBe alloys have been previously reported [1,5,6,10,11]. The beginning of the stress-induced transformation is mainly dependent on the alloy composition and the test temperature [12–14]. However, they are also influenced by the presence of microstructural defects [15–17]. The study of polycrystalline CuAlBe shape memory alloys is of great interest in view of practical applications. The effect of the grain size on the pseudoelastic behavior in CuAlBe alloys has been studied previously [6,10]. The starting stress of the stress-induced transformation (σ_s), the PE slope and the stress hysteresis decrease as the grain size increases [6]. The test temperature also influences the shape memory behavior of these alloys, σ_s increases for higher temperatures, with a linear σ_s–T relationship and a slope which depends on the grain size [10]. Nevertheless, a detailed study of the influence of the grain size or the test temperature on the damping behavior has not been reported.

The aim of this work is to study the influence of different microstructural parameters on damping capacity in two polycrystalline β CuAlBe shape memory alloys. The PE cycles are induced by compression tests in samples with different grain sizes up to increasing loading at temperatures in the range of 278–340 K, with a flash heating after each cycle. To study the damping capacity of the material, the dissipated energy and the specific damping capacity are analysed under each condition.

2. Experimental procedure

Two polycrystalline alloys, β Cu–11.41Al–0.50Be (wt.%) (A1) and β Cu–11.40Al–0.55Be (wt.%) (A2), were used in the present

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http://dx.doi.org/10.1016/j.matdes.2014.12.034
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work. The chemical composition was determined by atomic absorption spectrophotometry. The martensitic transformation temperature (Ms) was determined from the slope change in temperature–time cooling rumps at 10 K/s using a Cole-Parmer data acquisition module as 261 K in A1 and 252 K in A2, on samples with a grain size of ≈ 0.5 mm [10]. Cylindrical samples around 5.1 mm diameter and 14.3 mm length of A1 were prepared to study the influence of the grain size on the PE cycles induced by compression. Samples were kept in a resistance furnace at 1073 K for different times and water quenched at room temperature to obtain different grain sizes. Mean grain sizes (d) were determined from micrographs obtained by optical microscopy at room temperature following the procedure used in Ref. [6]. To compare samples with different diameters (D), the relative grain size (d/D) will be used. This parameter describes the effect of the grain constrain and has been used previously for the study of polycrystalline shape memory alloys [6,18]. To study the influence of the temperature on the PE cycles induced by compression, samples of rectangular section of 5×5 mm^2 and 15.8 mm length of A2 were prepared. Samples were kept for 10 min in a resistance furnace at 1073 K and water quenched at room temperature. A mean grain size of 0.8 mm was obtained.

Compression tests were carried out on a Shimadzu Autograph-DSS-10T deformation universal machine at a constant cross-head speed of 1 mm/min. The specimens were immersed in a liquid bath at different controlled temperatures in the range 278–340 K, and the sample temperature was measured using a chromel–alumel thermocouple. The contact surfaces between the module and the specimens were covered with a thin Teflon film and lubricated with grease in order to reduce the friction. The stress–strain curves were registered by a high-speed digital acquisitor Yokogawa MV1000. The length of the samples before and after each cycle was measured with a digital caliper with a precision of $5 \cdot 10^{-3}$. Tensile tests were carried out on an INSTRON 4465 universal testing machine at 1 mm/min.

3. Results

A representative stress–strain (σ–ε) curve obtained for a sample of A1 submitted to a compression test at 293 K, with d = 0.9 mm, is presented in Fig. 1(a). The first part in the loading curve is the linear elastic region of the β phase. The linearity deviation indicates the beginning of the martensitic transformation (β → martensite), and the stress at which occurs will be referred hereafter as σ_s. Then, the martensitic transformation continues and the PE strain produced by the stress-induced martensite will be referred as ε_{ps}. On removing the load, a hysteretic loop is formed and the retransformation of martensite to β phase occurs. However, some retained strain (ε_{ret}) can be observed on unloading. In polycrystalline CuAlBe alloys, the strain ε_{ps} increases for higher maximum stresses (σ_{max}). In a previous work [5] carried out on samples with d = 0.5 mm submitted to compression tests at room temperature, it was reported that for cycles up to around 3% of ε_{ps}, the strain is almost fully recovered on unloading leading to the PE behavior. For therein more, the induced martensite could not completely revert to the β phase, leaving increasingly retained martensite on unloading. However, that retained martensite retransforms to β phase with a flash heating of 30 s in a furnace at 1073 K up to around 8% of ε_{ps} (and $\sigma_{max} \approx 600$ MPa). For higher stresses, irreversible processes occur in the material, and part of the retained strain on unloading is not recovered after the flash heating. The irreversible deformation introduced in the material under these conditions would be plastic deformation of martensite [5].

One parameter which characterizes the damping capacity in a PE cycle is the dissipated energy (E_{diss}), which can be estimated as the area enclosed by the cycle in the σ–ε curve (ΔW in Fig. 1(a)) [8]. E_{diss} increases for cycles with higher ε_{ps}, as is shown in Fig. 1(b). Another factor that affects the damping capacity is the retained strain on unloading. High values of ε_{ret} would affect the shape memory properties of the next cycles and their repeatability. Even though the retained martensite could be retransformed by a flash heating, it could be difficult to carry out for some damping applications. For ε_{ps} higher than around 4%, ε_{ret} increases (see Fig. 1(b)). No significant differences were observed between both alloys and for samples submitted to tension and compression tests. It is worth noting that in polycrystalline CuAlBe alloys, σ_s in compression tests is higher than that required in tension tests for similar samples. This asymmetry occurs due to the low symmetry of the martensitic phase and to the fact that, in some stress states, there are more martensite variants available for the transformation [19,20]. However, the variation of the dissipated energy with ε_{ps} or σ_{max} presents the same behavior in specimens submitted to both stress states. A value of E_{diss} reported for a NiTi alloy submitted to tension tests at room temperature with $\varepsilon_{ps} \approx 7\%$ [21] (d is not indicated) is similar to that obtained for CuAlBe alloys with $\varepsilon_{ps} \approx 4\%$ under similar conditions (Fig. 1(b)).

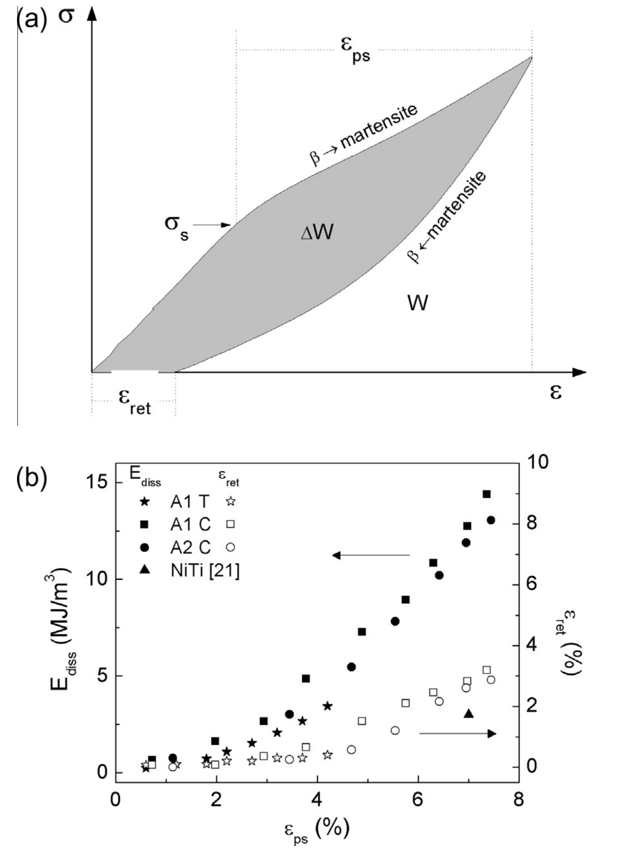

Fig. 1. (a) Stress–strain curve obtained for a sample of A1, where different parameters are indicated. See text. (b) Variation of E_{diss} and ε_{ret} with ε_{ps} for samples of A1 and A2 with $d/D \sim 0.15$ submitted to tension (T) and compression (C) tests at room temperature (~295 K).

3.1. Influence of the grain size on the damping capacity

Representative σ–ε cycles for samples of A1 with different grain sizes submitted to compression tests at room temperature (~295 K) and $\varepsilon_{ps} \sim 3.8\%$ are shown in Fig. 2(a). The grain size of the specimens modifies the shape of the PE cycles. σ_s increases for smaller grain sizes, as was reported in previous works [4–6,10]. To obtain the same value of ε_{ps}, samples with smaller grain

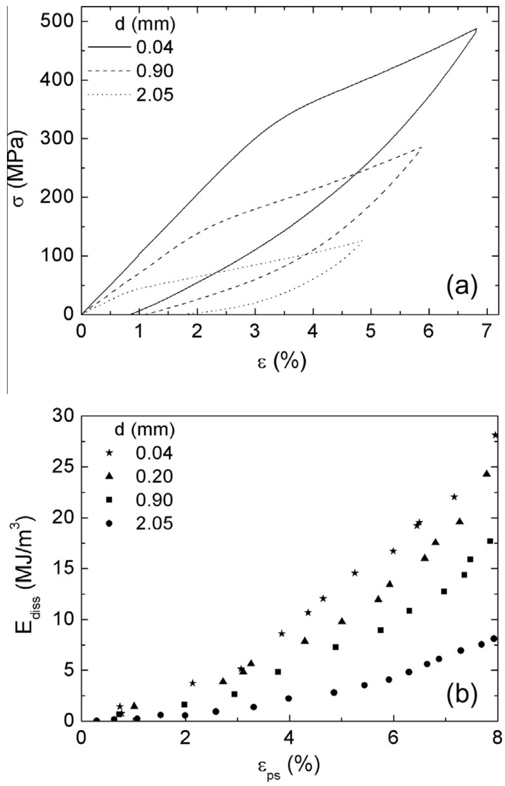

Fig. 2. (a) Representative σ–ε curves for samples of A1 with different grain sizes submitted to compression tests. (b) Variation of E_{diss} with ε_{ps} for samples with different grain sizes.

sizes require higher stresses, and the dissipated energy increases (see Fig. 2(b)). From the point of view of obtaining a higher dissipated energy, samples with smaller grain sizes present a better behavior. It is worth noting that the ε_{ret}–ε_{ps} relationship is independent of the grain size as is observed in Fig. 3, and as was previously reported in [22].

Other useful parameter to characterize the damping capacity of the material under different conditions is the Specific Damping Capacity (SDC), which compares the dissipated energy in a cycle ΔW with the applied energy ($\Delta W + W$), as is indicated in Fig. 1(a) [4,8]:

$$\mathrm{SDC} = \frac{\Delta W}{(\Delta W + W)} \quad (1)$$

The variation of SDC with ε_{ps} for samples with different grain sizes is presented in Fig. 3. SDC increases as ε_{ps} increases, reaching a stable value for $\varepsilon_{ps} \sim 4\%$. As the grain size increases, higher values

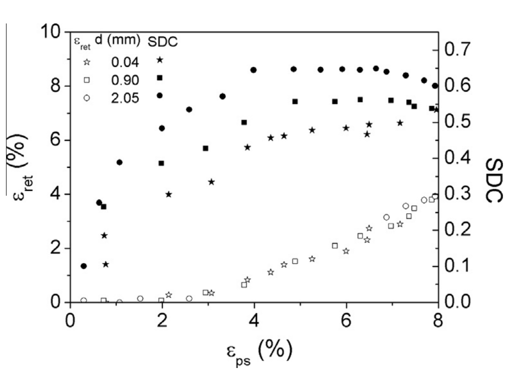

Fig. 3. Variation of ε_{ret} and the parameter SDC with ε_{ps} for representative samples with different grain sizes.

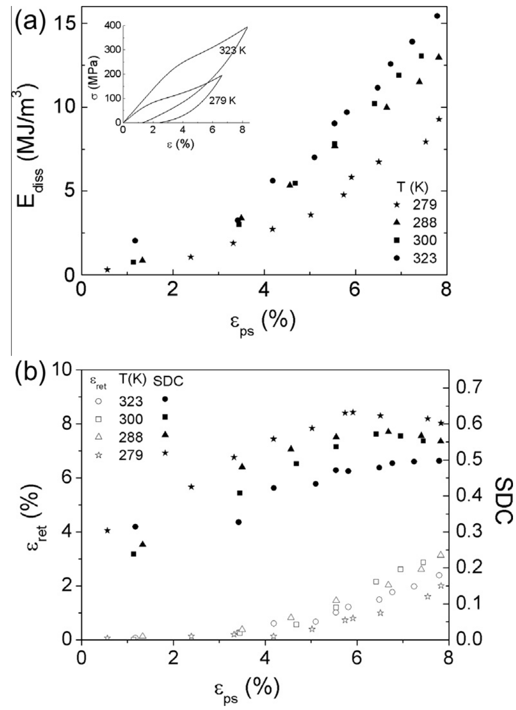

Fig. 4. (a) Variation of E_{diss} with ε_{ps} for samples of A2 with d = 0.8 mm submitted to compression tests at different temperatures. (b) Variation of ε_{ret} and SDC with ε_{ps} for samples at different tests temperatures.

of SDC are obtained and at lower pseudoelastic strains. This behavior shows an advantage for the use of samples with higher grain sizes, with a greater capacity of energy dissipation respect to the applied energy.

3.2. Influence of the test temperature on the damping capacity

The shape of the PE cycles also depends on the test temperature (T). Higher stresses are required to induce the martensitic transformation at higher temperatures, and plastic deformation could occur in the material if T is high enough. On the other hand, if T is low enough close to Ms, spontaneous transformation could be carried out. The damping capacity was studied in the range of temperatures considered as room temperature, where CuAlBe alloys exhibit the PE effect. The insert in Fig. 4(a) shows representative σ–ε cycles for samples of A2 submitted to compression tests at different temperatures and $\varepsilon_{ps} \sim 5.5\%$. The dependence of σ_s with T has been previously reported in [10]. As the test temperature increases, higher values of dissipated energy are obtained (Fig. 4(a)), however, lower values of the parameter SDC are reached (Fig. 4(b)). No clear influence of the test temperature on the ε_{ret}–ε_{ps} relationship is observed.

4. Discussion

For the use of CuAlBe shape memory alloys as energy dissipators, is useful to have tools that help us to anticipate the damping capacity of the material and the stress levels at which the alloy exhibits the PE effect under different conditions. The range of temperatures usually used for applications as passive dampers, specifically for seismic applications is between 278 K and 308 K [4]. For that reason the pseudoelastic behavior of the studied CuAlBe alloy was analysed for different temperatures in the range of room temperature. It is also commonly considered that the fine grained alloys exhibit better mechanical properties, and some intents have

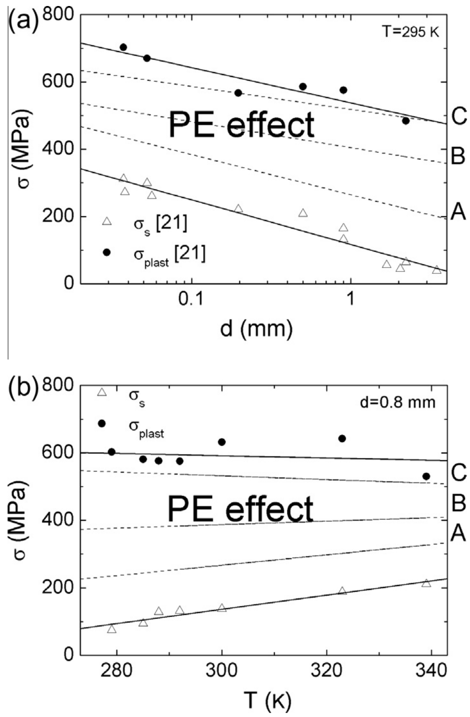

Fig. 5. σ–d (a) and σ–T (b) diagrams. The alloy exhibits the PE effect in the area between solid lines. Dotted lines A, B and C correspond to zones with E_{diss} of 5, 10 and 15 MJ/m^3, respectively.

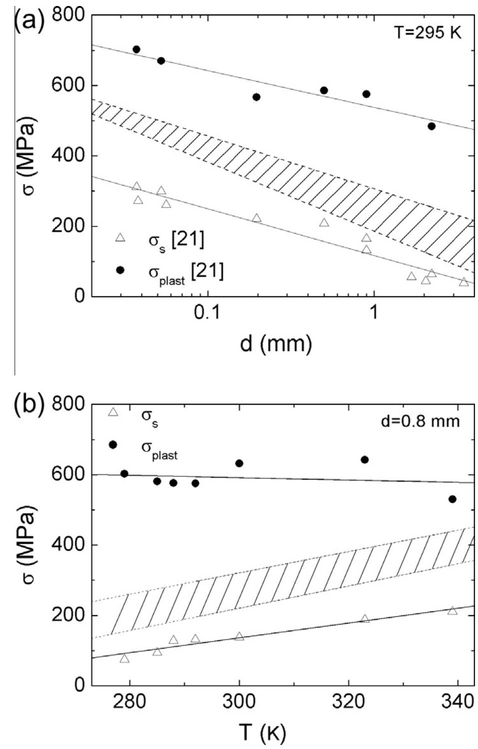

Fig. 6. Hatched zones where ε_{ret} < 1% and SDC > 0.4 in σ–d (a) and σ–T (b) diagrams.

been done on grain refinement of CuAlBe alloys [23]. The addition of grain refiners increases the stress of the alloy but causes reduction on its ductility [24]. However, the results of this work show that in samples with smaller grain sizes, higher dissipated energy but smaller capacity of energy dissipation respect to the applied energy are obtained. Previous studies in CuAlBe shape memory alloys have reported that the grain size does not have a significant influence on the strain recovery capacity [6]. Therefore, the desirable grain size of the material will depend on the application of the material and the conditions of its use.

Using the results obtained for this alloy, σ–d and σ–T diagrams indicating the zones where it is possible to obtain the PE effect were constructed (Fig. 5(a) and (b)). The alloy exhibits the PE effect at stresses higher than σ_s and lower than the plastic limit (σ_{plast}). The stress values in the σ–d diagram in Fig. 5(a) were obtained from Ref. [22]. σ_s was determined as the stress at which the curve departs from linear elastic initial slope, and σ_{plast} as the stress at which it is observed an increase in the retained deformation after the flash heating of 30 s at 1073 K. To characterize the damping capacity of the material under different conditions of d, T and σ_{max}, lines A, B and C are indicated in Fig. 5(a) and (b), corresponding to zones with dissipated energy of 5, 10 and 15 MJ/m^3, respectively. For the applications of the material, higher values of dissipated energy are desirable, however, when we move to zones of higher dissipation the performance of the material is adversely affected in other aspects, like an increase of the retained martensite on unloading. When a pseudoelastic cycle is induced at stresses higher than σ_{plast}, irreversible processes occur in the material, and the presence of dislocations will difficult the beginning and the progress of the next cycle, inhibiting the pseudoelastic effect [5].

For practical applications is very useful to have diagrams where we can determinate the optimal working zones under certain conditions of temperature and grain size. The hatched zones in Fig. 6(a) and (b) show the optimal working zones in σ–d and σ–T diagrams, where the material exhibits the PE effect, with retained strains on unloading lower than 1%, SDC > 0.4 and $E_{diss} \approx 5$ MJ/m^3. These diagrams will permit to obtain in a simple way all the available information about the damping properties of the CuAlBe studied alloy in different conditions. This is an essential aspect in the design perspective for a specific application of shape memory alloys [9].

To estimate more accurately the dissipated energy in a PE cycle at a certain σ_{max}, and the dependence with the grain size, a phenomenological approach was obtained for cycles at room temperature (~295 K):

$$E_{diss}(d, \sigma_{max}) = 0.62d - 1.76 + (0.05 - 0.01d)(\sigma_{max} - \sigma_s(d)) \quad (2)$$

This approach was obtained from the variation of E_{diss} with (σ_{max}–σ_s) for samples with grain sizes between 0.04 and 2 mm, with a specimen diameter of 5.1 mm. d is expressed in mm and the stresses in MPa. σ_s depends on the grain size and can be estimated from Fig. 5(a). The influence of the test temperature on E_{diss} can be appreciated in Fig. 7. For the highest temperature, E_{diss} follows a straight line with (σ_{max}–σ_s), where σ_s also depends on the test temperature and can be estimated from Fig. 5(b). As the temperature decreases, a deviation from the straight line is observed at high stresses, and lower values of E_{diss} are obtained.

It is also important to know and anticipate the damping capacity of the material through the behavior of SDC with σ_{max} under different conditions of d and T. As the grain size increases, higher values of SDC are obtained and at lower stresses up to reach a stable value, similar to the behavior of SDC with ε_{ps} shown in Fig. 3. The same occurs as the temperature decreases. This behavior can be characterize by using two parameters: the stress at which the stable value is reached (σ_{min}), and the mean SDC when it reached a stable value (SDC_{st}). The variation of both parameters with d and T is shown in Fig. 8(a) and (b), respectively. For PE cycles at stresses higher than σ_{min}, the material dissipates the greatest amount of energy respect to the energy applied during the load, and the highest value of SDC is reached, which corresponds to

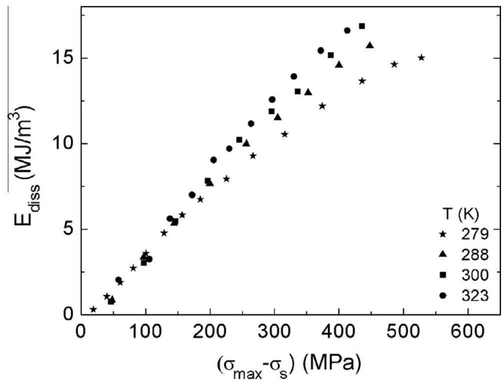

Fig. 7. Variation of E_{diss} with (σ_{max}–σ_s) for samples with d = 0.8 mm submitted to PE cycles at different temperatures.

SDC_{st}. As the grain size increases, σ_{min} decreases and slightly higher values of SDC_{st} are obtained. A similar behavior is observed as the test temperature decreases.

The damping capacity of the CuAlBe studied alloy was studied for a constant rate of 1 mm/min, corresponding to a frequency around 0.001 Hz. However, it has been reported that the damping capacity of this alloy does not vary with the cycling frequency in the range of seismic applications [4].

Huang [25] reported the material properties of different shape memory alloys: NiTi, CuZnAl and CuAlNi. Even when the NiTi thermomechanic performance is the best, copper-based shape memory alloys are very attractive for applications when the material cost and the machinability are taken into consideration. The cost factor is especially important for shape memory applications in bridges and building structures as columns, beams, and connecting elements between them [9]. The studied CuAlBe alloy presents higher values of SDC respect to that reported for NiTi and CuAlNi alloys with fine grain size [25]. It was also previously reported that this alloys shows a better strain recovery capacity respect to CuAlNi, CuAlMn and CuZnSn shape memory alloys [6].

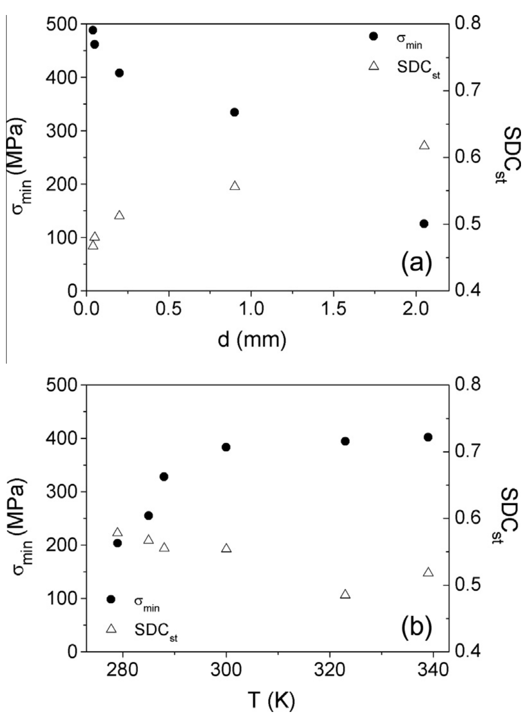

Fig. 8. Variation of σ_{min} and SDC_{st} with the grain size (a) and test temperature (b). See text.

5. Conclusions

The influence of microstructural parameters on damping capacity in two β CuAlBe polycrystalline shape memory alloys was studied in detail. The specimens were submitted to pseudoelastic cycles under compression tests at increasing stresses, with a flash heating after each cycle. For higher maximum stresses, the pseudoelastic strain increases and higher values of dissipated energy are obtained. However, for ε_{ps} higher than around 4%, ε_{ret} increases, which will produce a deterioration of the damping capacity in the material. The specific damping capacity increases for higher ε_{ps} to reach a stable value.

No significant differences were observed in the dissipated energy between both alloys and for samples submitted to tension and compression tests. As the grain size of the samples increases, the dissipated energy decreases, but higher values of SDC are obtained and at lower strains. A similar behavior is observed as the test temperature decreases in the range of 278–340 K.

To anticipate the damping capacity of the material under different conditions, σ–d and σ–T diagrams were constructed, indicating the zones where it is possible to obtain the PE effect, the areas with different levels of dissipated energy and the optimal working zones. A phenomenological approach was obtained to estimate more accurately the dissipated energy as a function of σ_{max} and the grain size, and the influence of the test temperature was quantified. To determine SDC under different conditions of grain size and tests temperature, two parameters were used: the stress at which the stable value is reached, and the mean SDC when it reached a stable value.

Acknowledgements

This work was supported by CONICET, ANPCYT, SECAT-UNCentro and CICPBA, Argentina. The author also like to thank Dr. Adela Cuniberti for readings and comments on the paper.

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