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EFFECT OF DEFORMATION TWINNING ON THE FATIGUE PROPERTIES OF Cu-8 AT.%Al SINGLE CRYSTALS

This study concerns the effect of deformation twinning on the fatigue properties of single phase Cu-8 at.% Al single crystals. The analysis was performed for two different physical states, i.e.: (i) material pre-deformed plastically to the stage just before the activation of deformation twinning, which corresponds to a true strain level of approximately 0.8 and (ii) material pre-deformed to the stage after activation of deformation twinning, which is characterised by a layered T/M microstructure with a large number of Σ3 twin boundaries and a dislocation density comparable to that of material just before the twinning process. In the first case, the material did not fracture even after 100,000 cycles. However, in the second case, the material has fractured after approximately 61,000 cycles. Three different stages of fatigue testing were identified. At first, the very initial stage up to 20 cycles characterized by a significant increase in the recorded strain. Second, the stabilisation stage of very slight changes of strain, and at last, the failure stage, again of significant increase of strain at different cycles leading to the final stage of material failure.

Keywords: Deformation twinning; fatigue properties; single crystals

1. Introduction

Deformation twinning may significantly affect the mechanical properties of face-centred cubic (FCC) metallic materials. This can be demonstrated analysing the properties of these materials during plastic deformation in uniaxial tensile test, e.g. high tensile strength and, at the same time, a high degree of plasticity. Twinning-induced plasticity (TWIP) steels [1-6], Cu-Al alloys [7] or other FCC alloys of medium and high configurational entropy [8,9] are well-known examples of such materials. Structural changes caused by deformation twinning are mostly limited to the interior of the grains of the polycrystalline material. They involve the transformation of the crystal microstructure of the matrix (M) into a multilayer twin/matrix structure (T/M) [10]. The T/M structure, induced by deformation twinning, are in fact nanolayers situated within the grains of polycrystalline material [10-14]. Takin the above into consideration, it is obvious that the deformation-induced T/M layered structure 'embedded' inside the grains of polycrystalline materials must play a key role in the mechanical properties of many FCC materials. In this context, the question arises: does the layered T/M arrangement affect not only the plastic properties, but also the fatigue properties under elastic loads? Therefore, the main objective of this research is to focus on assessing the effect of mechanical twinning on the fatigue properties of a pre-twinned Cu-8at.%Al single crystal, which is free of grain boundaries and consists of the multilayer T/M structure induced by deformation twinning, only. The Cu-8at.%Al alloy was selected for testing because the plasticity of the T/M structure generated in this material has been intensively studied before [15]. The scope of the research concerns the analysis of the fatigue process for materials exhibiting two physically different states of plastically deformed Cu-8%at.Al single crystals: (i) material pre-deformed plastically to the stage just before the activation of the twinning mechanism, which corresponds to a level of approximately 0.8 of true strain. This type of material is characterised by a high dislocation density, state 1 in Fig. 1, and (ii) material pre-deformed to the stage after activation of deformation twinning. This type of material is characterised by a layered T/M microstructure with a large number of Σ3 twin boundaries and a dislocation density comparable to that of material just before the twinning process, state 2 in Fig. 1.

Several phenomena that may critically affect the cyclic response of the T/M layered structure have been previously identified for Cu-8at.%Al single crystals. Three distinct detwinning modes have been recognised [17-19]: the reverse twinning mode (denoted π), associated with a shear strictly opposite to that of primary twinning, and two pseudo-reverse modes (±π/3) inclined symmetrically by ±π/3 from η_1. The critical resolved

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shear stress of the π mode (approximately 58 MPa at room temperature) is markedly lower than that of the ±π/3 modes (approximately 105 MPa), and even lower than the critical stress of primary deformation twinning (approximately 90 MPa) [17,19]. This difference is attributed to an internal stress field Δτ, of approximately 33 MPa at room temperature, originating from extended cube dislocation configurations within the twin lamellae – the so-called cube dislocation stress (CDS) effect [15]. The CDS effect is also responsible for the giant yield stress anisotropy and the strong tension/compression asymmetry of the T/M structure [15]. Recent investigations of the temperature dependence of these phenomena have shown that the internal stress field is irreversibly annihilated upon heating, with complete vanishing of Δτ near 530°C [16]. These features – the inherent presence of internal stresses, the very low critical stress for the π detwinning mode, and the strong stress anisotropy of the T/M structure – provide a relevant physical context for interpreting the present fatigue results.

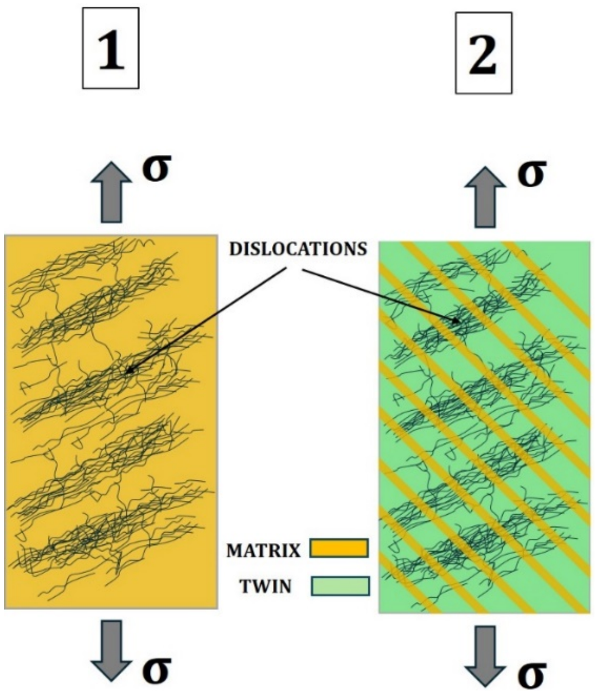

Fig. 1 Schematic representation of the tested Cu-8%at.Al single crystal in two different physical states: (1) preliminarily plastically deformed to the stage before deformation twinning, ε = 0.8, and (2) pre-deformed plastically to the stage after twinning, ε = 1.15

2. Experimental methodology

In order to carry out the planned research on how the T/M layer structure, i.e. a pre-twinned single crystal of Cu-8 at.%Al alloy, affects the fatigue properties of this type of material, the following experimental procedure was developed. A Cu-8 at.% Al single crystal with a specially designed rectangular shape measuring $3\times30\times180$ mm^3 was obtained in a furnace with a vertical temperature gradient and a vacuum better than 10^{-5} hPa. The narrow and wide side surfaces of the crystal were parallel to the $(1\bar{1}1)$ and $(\bar{3}\bar{2}1)$ planes, respectively, and the main axis of the crystal was parallel to the crystallographic direction $[\bar{1}45]$. Through the addition of aluminium, the stacking fault energy (SFE) of the Cu-8 at.% Al alloy, equal to 7.2×10^{-3} J/m^2, was low enough to induce deformation twinning in these single crystals during quasi-static tensile test at room temperature. A uniaxial tensile test was performed on the prepared single crystal at room temperature and a strain rate of 10^{-3} s^{-1}.

Fig. 2 summarises the experimental procedure used to induce the T/M system. This procedure has also been successfully used in several previous studies on the plastic deformation of these layered systems for the Cu-8 at.% Al alloy [15,17-19]. Figure 2a shows the stress-strain curve during tensile testing of a Cu-8 at.% Al single crystal. A typical two-step rotation path of the tensile axis, S-T-T/M, analysed by X-ray diffraction measurements of the (111) pole figures, is shown in Fig. 2b. The deformation twinning responsible for the M-T/M transformation process was identified based on EBSD/SEM measurements, which are illustrated in Fig. 2c. The T/M multilayer structure was recognised as consisting of twins formed in the system $(\bar{1}\bar{1}1)[\bar{1}21]$, i.e. the $(\bar{1}\bar{1}1)$ twin plane, K_1 and the $[\bar{1}21]$ twinning direction, η_1 (see Fig. 2d). The single crystal, which had been preliminarily plastically deformed, served as the base material for cutting secondary samples for fatigue testing. The secondary samples for fatigue testing were cut out from primary samples along the TD, corresponding to the T/M position in Fig. 2a and b. This was the direction of loading during the fatigue tests.

3. Results and discussion

The first experimental measurements were performed on a sample without the T/M microstructure (state 1), but is characterised by a relatively high dislocation density that reflects the true strain level of around 0.8 (please see point T on the stress-strain curve in Fig. 2). For this sample, 100,000 cycles were performed at an oscillating stress ranging from 20.5 MPa to 205 MPa, which gives a 10:1 ratio. The maximum stress in fatigue tests was selected so that the process was carried out only within the elastic range of the material. Therefore, the upper range of the cycle was selected to be approximately 95% of the yield strength for sample of state 1. The yield strength in this case was 215 MPa. Fig. 3a shows the relationship between the oscillating stress and the resulting deformation as a function of time. The test was carried out in such a way that the stress oscillated without change as a function of time between the originally set threshold values. Fig. 3b shows the response of the material in terms of plastic deformation during the fatigue process, which also oscillates according to the specified stress cycles. So, it shows the strain response of the material subjected to the stress amplitude varying from 20.5 MPa to 205 MPa. A more detailed analysis of these data showed that the upper strain limit vs. the cycle number was approximately 2% and the lower limit was approximately 1.3% (Fig. 4a). At the same time, a very stable deformation effect can be observed across

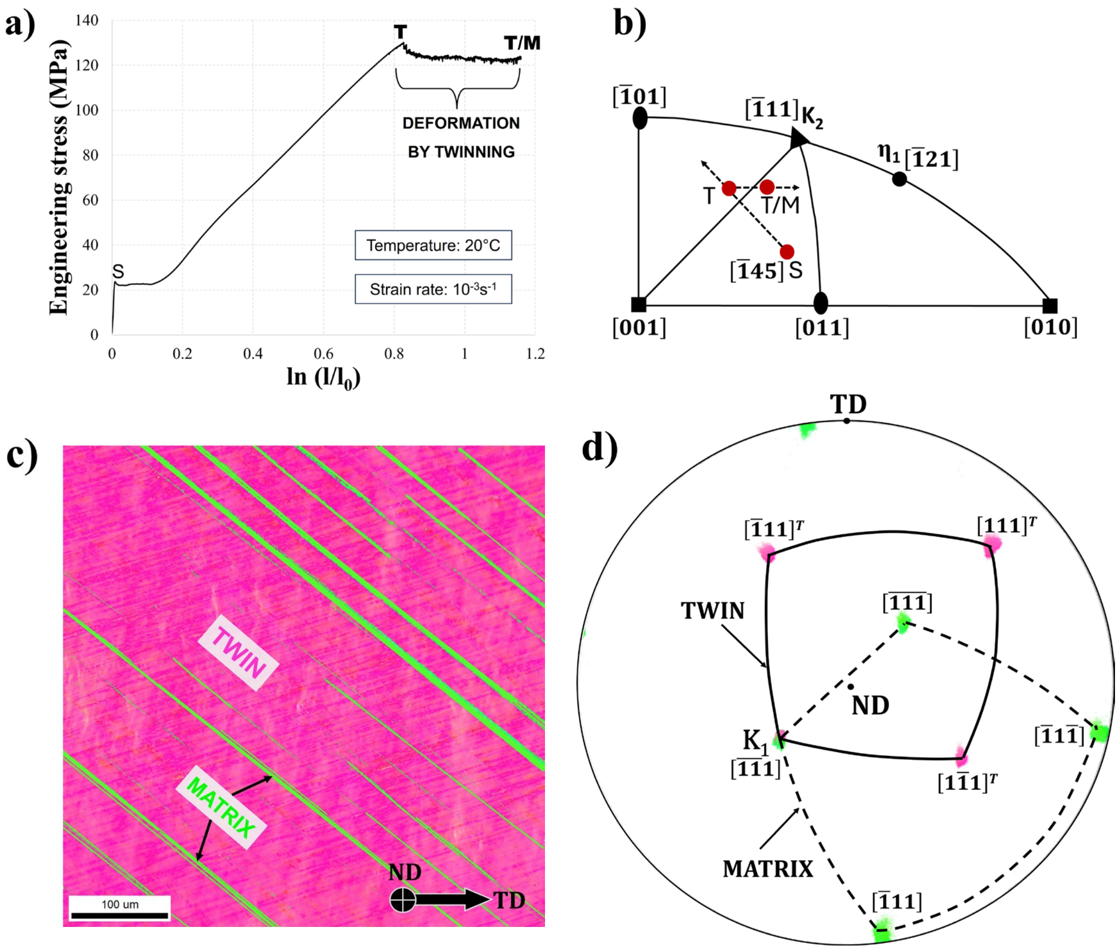

Fig. 2. Stress-strain curve of a Cu-8 at.% Al single crystal in a uniaxial tensile test with marked areas of slip system and twinning system dominance a). The rotation path of the tensile direction S-T-T/M during plastic deformation shown on the stereographic projection b). EBSD map of the sample surface with marked areas of the lattice and twin c) and the corresponding pole figure (111) with marked matrix and twin lattices (d)

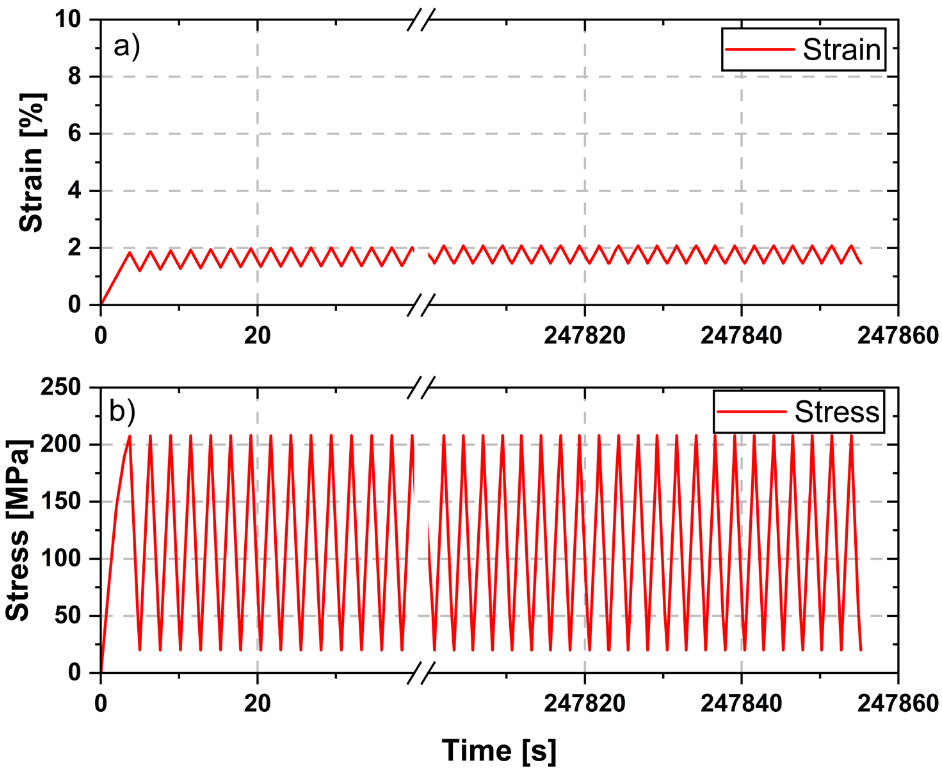

Fig. 3. Strain-time (a) and stress-time (b) curves for the tested material in state 1, obtained in a uniaxial tensile fatigue cycle test

the entire specified range of 100,000 cycles. An analysis of the change in the maximum strain value obtained in individual cycles shows a slight increase from just under 2% to just over 2%. At the same time, similar changes can be observed in the case of minimum strain. The difference between these values (marked as Delta in Fig. 4a) is therefore almost constant. Subtle differences in these values can be observed when comparing cycle 5,000 with cycle 95,000, where it can be seen that the Delta value is lower for cycle 95,000 than for cycle 5,000. This is due to the fact that the lower strain limit increases faster than the upper limit. Fig. 4b illustrates the change in these values in the initial fatigue cycles (from 0 to 20 cycles), where it is clear that the changes in the upper and lower strain limits occur to the greatest extent in the initial cycles. In the later stage of fatigue (i.e. from 97,000 to 100,000 cycles), the material behaves very stably and any changes in the deformation values are practically negligible (Fig. 4a).

Very different fatigue behaviour was observed during testing carried out on sample in condition 2 (i.e. after deformation twinning with a layered T/M structure). In this case, the upper stress limit during fatigue testing was set at 95% of the yield strength, which in this case was 315MPa. The lower limit was set at 31.5 MPa so that the ratio of the maximum and the minimum stress during fatigue cycles in this case was also 10:1 as

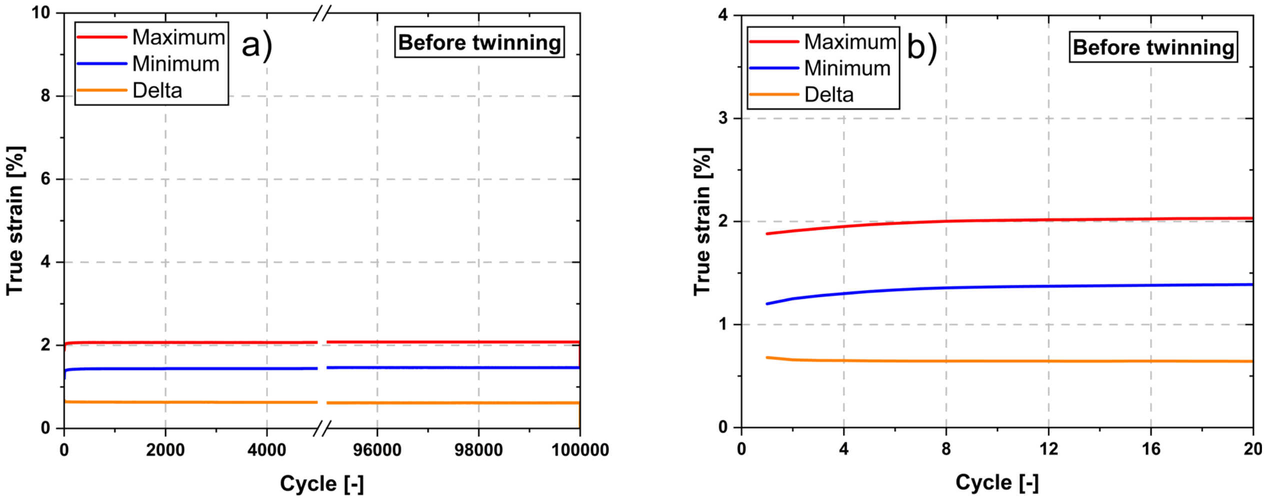

Fig. 4. True strain as a function of the number of cycles of the tested material in state 1 during the fatigue test. The graphs show the maximum and minimum strain values and their difference (delta) obtained during fatigue testing throughout the applied cycles (a) and during the first 20 cycles

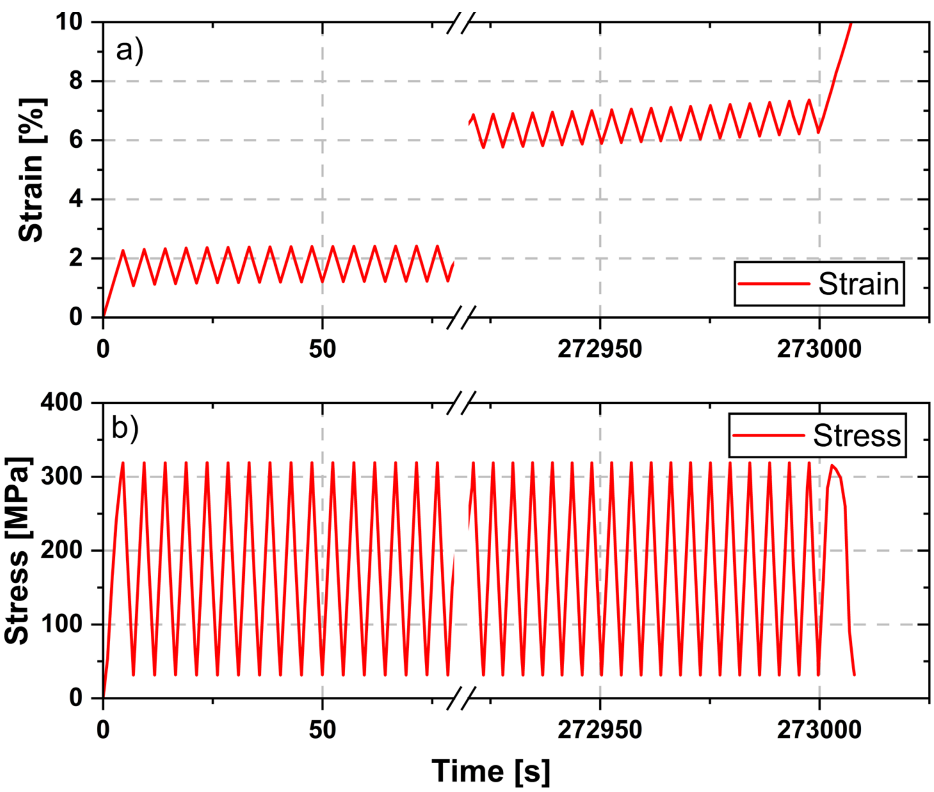

Fig. 5 Strain-time (a) and stress-time (b) curves for the tested material in state 2, obtained in a uniaxial tensile fatigue cycle test

previously (Fig. 5). The fatigue characteristics of this material were significantly different when analysing the obtained change of strain as a function of time. Comparing the initial and final stages of the process, there is a substantial change in the upper and lower limits of deformation by approximately 5% (Fig. 5). At the same time, it can be seen that the material fractured after approximately 273,000 seconds, corresponding to approximately 61,000 cycles.

Fig. 6a shows the changes in the upper and lower strain values as a function of the specified cycles. For 5,000 cycles, the upper limit was 2.5% and the lower limit was 1.4%. Comparing the 5,000 cycle with 56,000 cycle, there is a certain difference in relation to state 1, namely that in this case there is a greater increase of strain for the upper limit than for the lower limit, which causes the Delta value to become practically constant throughout the whole fatigue process. The most significant changes occur during the final fatigue cycles. As before, changes in the upper and lower limits occur in the very early stages of fatigue, from 0 to 20 cycles (Fig. 6b). This is followed by a stabilisation phase, which lasts until approximately 59,000 cycles, i.e. 2,000 cycles before the material is destroyed. At this stage (in the range from 59,000 to 61,000 cycles), the behaviour of the material is completely different, with a significant increase in the upper and lower limits of the deformation obtained at a constant stress amplitude (Fig. 6a). This effect can be interpreted as the initiation of the failure process, which apparently begins as early as 2,000 cycles before the final failure of the specimen. It is interesting to note that the Delta value at this specific stage of intense straining is approximately constant. Thus, the strain change for the lower and upper limits are constant, similarly as in the earlier cycle stages before the initiation of the failure stage. As a result of the fatigue cycles performed, the material fractured reaching almost 61,000 cycles.

The observation that the T/M layered structure exhibits lower fatigue properties compared with the pre-twinning state, despite its higher yield stress, is intriguing and deserves a brief physical commentary. A plausible explanation lies in the internal stress field $\Delta\tau$ (~33 MPa at room temperature) inherently present within the T/M structure due to the CDS effect [15-17,19]. Although macroscopic deformation in the present fatigue tests remained within the elastic regime, local stress concentrations at the T/M interfaces and in the vicinity of extended cube dislocation configurations [15] may locally exceed the critical resolved shear stress of the π detwinning mode, which is the lowest among all accessible plastic shear modes of the T/M structure [17-19]. Repeated cycling could thus trigger localised, low-amplitude detwinning events that, when accumulated over tens of thousands of cycles, progressively damage the T/M architecture and ultimately lead to failure.

4. Conclusions

As part of the experimental research, fatigue tests were performed on Cu-8 at.% Al single crystals characterised by different levels of strain. The material was deformed to the stage just prior deformation twinning (state 1) and to the stage after deformation twinning (state 2). In the first case, the material did not crack even after 100,000 cycles. However, in the case of state 2 characterised by the layered T/M structure induced by deformation twinning, the material has fractured after approximately 61,000 cycles. Therefore, it seems that the T/M structure has a negative effect on the fatigue properties of this type of material. From the results obtained for the analysed cases (states 1 and 2), three stages of fatigue testing can be identified: (i) a very initial stage up to 20 cycles, where there is a fairly significant increase in the obtained upper and lower strain limits, (ii) the stabilisation stage, where there were very slight changes of strain, and (iii) the failure stage, where there is again a significant increase in the recorded upper and lower strain limits at different cycles, ultimately leading to the final stage of material failure.

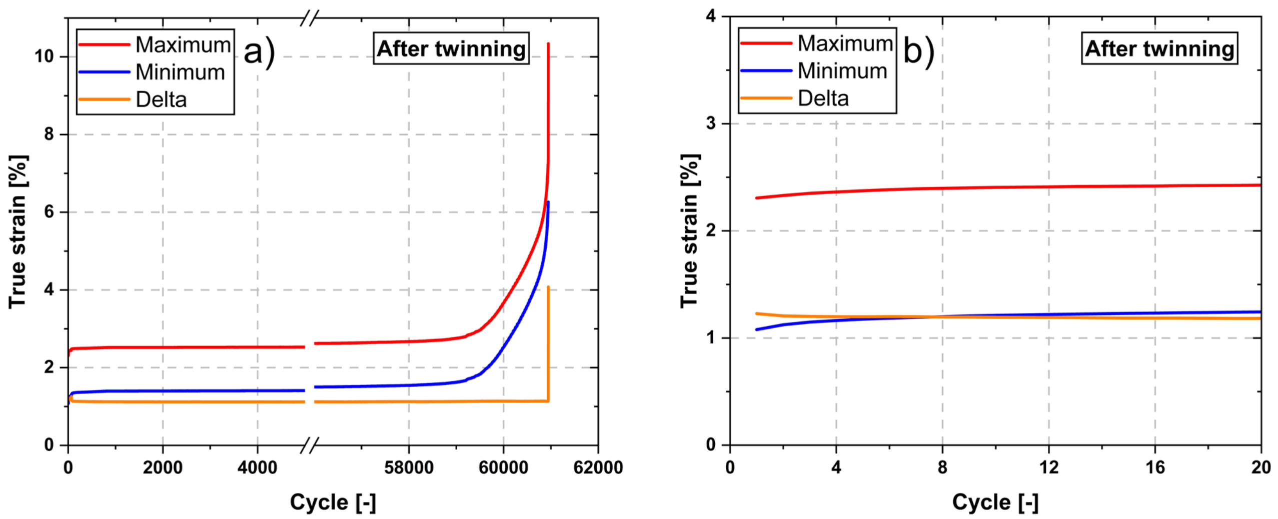

Fig. 6 Actual deformation as a function of the number of cycles of the tested material in state 2 during the fatigue test. The graphs show the maximum and minimum strain values and their difference (delta) obtained during fatigue testing throughout the applied cycles (a) and during the first 20 cycles

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