CP-Ti YIELD SURFACE EVOLUTION AFTER PRE-DEFORMATION UNDER COMPLEX LOADING

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1. Abstract

Uniaxial testing methods to characterize materials provide only limited data that is insufficient to fully understand all aspects of their behaviour, such as initial texture or anisotropy. Therefore, this research aims to conduct complex stress loading experiments to understand the physical mechanism accountable for plastic deformation caused by monotonic tension and tension assisted by proportional cyclic torsion in the CP-Ti (Commercially Pure Titanium). The yield surface approach was applied to assess the variation of mechanical properties in the as-received and pre-deformed material. It was found, that such monotonic tension associated with cyclic torsion caused a significant decrease of the tensile stress. The initial yield surface obtained for the as-received material exhibits anisotropic behaviour, whereas, the sizes of subsequent yield surface reflecting pre-deformation were reduced in all directions with exception of the tension direction.

2. Materials and methods

The material investigated in this research was CP-Ti alloy. Complex loading tests were performed on the thin-walled tubular specimens. The wall thickness of the thin-walled tubular specimen is large enough to satisfy the thin-walled tube criterion and to avoid buckling during sequential loading.

The mechanical testing was performed on the MTS 858 biaxial testing machine at room temperature (23°C). Vishay 120Ω temperature compensated strain gauges were bonded on the outer surface of the tubular specimens to measure and control axial, shear and hoop strain. The experimental programme comprised three essential steps: determination of the initial yield surface of the as-received material; introduction of the following plastic pre-deformation in the specimens: monotonic tension up to 1% permanent strain under a constant strain rate of 5×10^{-6} s^{-1} and combination of monotonic tension up to 1% permanent strain under a constant strain rate of 5×10^{-6} s^{-1} and proportional torsion-reverse-torsion cyclic loading for two magnitudes of strain amplitude (±0.2% and ±0.4%) at two different values of frequency (0.5 Hz and 1 Hz); and determination of the subsequent yield surfaces of the pre-deformed specimen.

The yield surface concept in the two-dimensional stress space (σ, τ) was applied to identify the impact of plastic pre-deformation on the material by evaluation of the yield points. Yield points were determined by the technique of sequential probes of the single-specimen along different paths in the plane stress state. Starting from the origin, loading in each direction took place until a limited plastic strain was observed (in our case it was 2 x 10^{-4}). The limited plastic strain of 2 x 10^{-4} (0.02%) was employed for probing in individual loading paths to ensure, that the plastic offset strain falls within the appropriate range of the yield definition assumed. The loading process during probing stage was strain controlled maintaining a constant ratio of the strain components. Subsequently, the unloading was carried out under stress control until zero force and torque were reached. The experimental procedure was performed along 17 stress paths, starting with simple tension and finishing with tension in the same direction. The loading and unloading were carried out for the following strain paths 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°, 180°, 210°, 225°, 240°, 270°, 300°, 315°, 330°, 360° in the (ε_{xx}, $\sqrt{(3/(1+\nu)^2)}\varepsilon_{xy}$) strain plane. Separate specimens were utilized for each yield surface (initial and pre-deformed) following the aforementioned sequential loading paths, resulting in a total set of six thin-walled tubular specimens. It should be noted, that all specimens after pre-strain in tension or combined tension-torsion were relaxed for 1 hour, and then, subjected to the yield surface determination procedure. By incorporating the relaxation step, it was aimed to limit the effect of different strain rates during pre-deformation and probing since CP-Ti has relatively high strain rate sensitivity.

3. Results and discussion

Figure 1 depicts a cumulative representation of the initial yield surface evolution in the biaxial stress space that were obtained from experimental results following pre-deformation of the material at 0.5 Hz and 1 Hz. It can be observed, that the yield surfaces have distinct shapes on the one hand, and a size of the subsequent yield surfaces decreases in the direction opposite to the pre-deformation loading on the other. As shown in Figure 1, the subsequent yield surface after monotonic tension exhibits the largest dimensions. By examining Figure 1, it becomes evident that the pre-deformed material exhibits both: kinematic hardening towards the applied axial pre-deformation direction in comparison to the as-received material surface; and kinematic softening after monotonic tensile pre-deformation assisted by cyclic torsion in comparison to the yield surface for the material deformed by tension only.

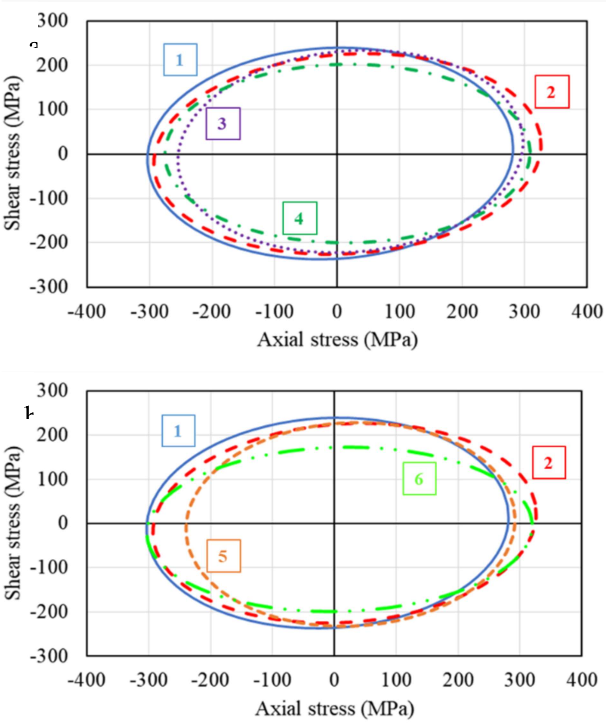

Fig. 1. Evolution of the initial yield surface (1) of CP-Ti due to pre-deformation caused by monotonic tension (2); monotonic tension assisted by cyclic torsion of strain amplitudes equal to: ±0.2% (3 , 5) and ±0.4% (4 , 6) at frequency values equal to 0.5 Hz (a) and 1 Hz (b).

This is demonstrated by a decrease of the subsequent yield loci compared to those for monotonic tensile pre-deformation. For example, the yield surface obtained after combined tension-cyclic torsion with a strain amplitude of ±0.2% pre-deformation exhibits a similar shear yield strength but a decrease of axial yield strength compared to that obtained for the monotonic tensile deformation. Conversely, in the case of combined tension-cyclic torsion with a strain amplitude of ±0.4% pre-deformation, the opposite trend is observed. Similar tendencies can be observed for both values of frequency taken into account. The shape analysis of these subsequent yield surfaces reveals that the dimensions of the yield surface are dependent on the preloading direction. The detailed discussion of the reported results was presented in [1].

4. Conclusions

In this paper, an experimental approach was performed to investigate the effect of monotonic tension and combined monotonic tension-proportional cyclic torsion on the pure titanium behaviour using the yield surface concept. The 0.01% plastic offset strain was adopted as yield definition. Such approach was found to be suitable for sequential probing paths during the yield surface determination. The initial yield surface and its evolution reflecting the pre-deformation history were identified. It was found, that under complex stress states (tension + cyclic torsion), restructurization of the material is responsible for significant decrease of the axial stress. This reduction of the axial stress becomes more prominent with an increase in cyclic torsion strain amplitude and frequency. Furthermore, the size of subsequent yield surfaces after pre-deformation of the material were reduced in all directions, except of that representing the simple tension. This indicates, that the introduction of plastic anisotropy due to the complex loading leads to significant softening in the direction opposite to axial loading. CP-Ti exhibits both, kinematic hardening towards the direction of tensile pre-deformation in comparison to the initial yield surface, and kinematic softening after pre-deformation due to combination of tension and cyclic torsion in the direction of tensile pre-deformation in comparison to the yield surface determined after monotonic tension only.

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References

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