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EVALUATION OF DAMAGE ACCUMULATION FOR DUCTILE MATERIALS

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Abstract: *The damage accumulation is one of the issues of ductile fracture modelling. One of the potential methods for assessing the damage evolution may be the tracking of the change in Young's modulus. This contribution presents three measuring approaches to following the decrease of Young's modulus, which is related to the damage progression. Simple loading-unloading technique was compared to the two approaches using the ultrasound. In one approach utilizing the ultrasound, the test was stopped for measuring the wave velocity, while no interruption was present during the other approach. The technique employing the ultrasound without stopping yielded rather scattered results with no trend observable. Nevertheless, the loading-unloading method resulted in greater degradation of Young's modulus than in the techniques which applied the ultrasound.*

Keywords: Semi-cyclic, Failure, Plasticity, Material weakening, Non-linear damage accumulation.

1. Introduction

The ductile fracture modelling has many aspects which have to be targeted. The first one is the correct description of the stress–strain relationship, which is important to a broader range of applications than those covering only the ductile failure. The constitutive law may be obtained from the standard tensile tests or other techniques like the small punch tests. Next step is the suitable yield criterion, which may have a different form than a standard von Mieses one or it may be even employing the directionally distortional hardening. Then, the ductile fracture criterion has to be calibrated itself. Many various specimens have been designed for that purpose. Last but not least, the damage accumulation is one of the model features. The non-linear damage accumulation may be useful for better simulation of the non-proportional loadings. Nevertheless, Park et al. (2020) suggested to rather use the non-associated flow rule for that purpose. Still, many use a linear damage accumulation as there is no reliable technique for detection of the real damage evolution.

There were some attempts to estimate and quantify the damage. Lemaitre (1985) developed the concept of effective stress, which is increased by the presence of voids. It was also extended into the hypothesis of strain equivalence. Together, it gives the damage parameter as

$$D - 1 - \frac{\tilde{E}}{E}, \tag{1}$$

where $\tilde{E}$ is the degraded (actual) Young's modulus and $E$is the Young's (initial, virgin) modulus. Celentano and Chaboche (2007), and later similarly Tsiloufas and Plaut (2012), carried out the measurements of the Young's modulus degradation using a loading–unloading on two steels until failure. Ravindran (2010) used the semi-cyclic technique and measured the decrease of Young's modulus from 67.8 to 43.9 GPa on aluminum alloy 2024-T3. The deformations were assessed by means of digital image correlation, which was also done by others as Hering and Tekkaya (2020).

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2. Experiments

The experiments were conducted on the aluminum alloy 2024-T351. Zwick Z250 Allround-Line, tCII, and extensometer Zwick multiXtens with gauge length of 50 mm were used for all experiments.

At first, the loading–unloading technique is presented. It was conducted on the specimens with square cross-section (Fig. 1). Unfortunately, only one test was conducted, but it was very close to Šebek et al. (2018). Response and Young's moduli are given in Fig. 2. The test speed was 1 mm/min, which was gradually increased to 2 mm/min beyond the yield stress. The specimen was unloaded after each 2 % of total engineering strain, so that the degradation of Young's modulus could be subtracted until the necking.

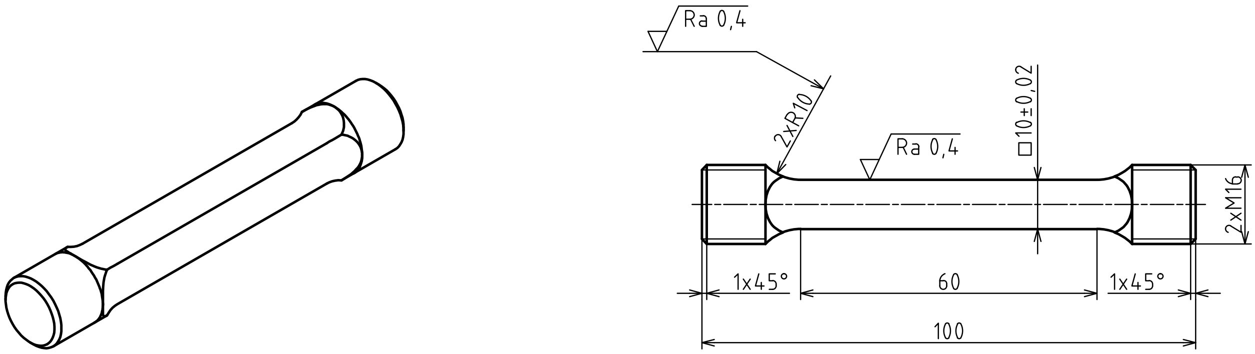

Fig. 1: Specimen with square cross-section

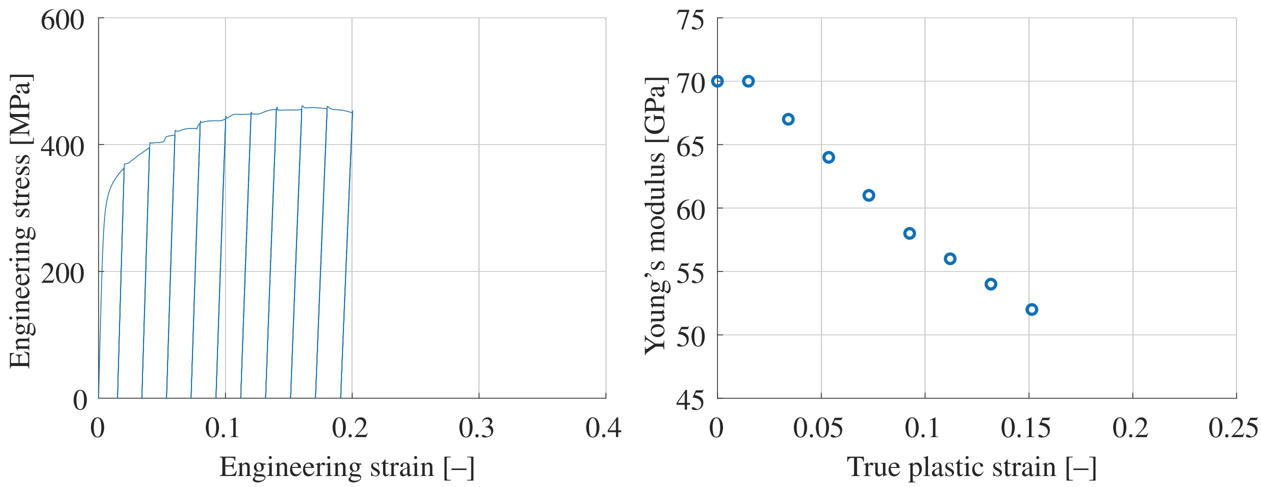

Fig. 2: Response (left) and degraded Young's moduli (right) for loading–unloading testing

Next, the measurements using the ultrasound were carried out on specimens, three to each, with square cross-section and 50 mm gauge length (Fig. 1). Two techniques were employed. The first technique was without stopping the test and the second one with interrupting the test to measure the wave velocity until the necking.

The first measurements using the ultrasound without any interruptions were conducted under the speed of 0.65 mm/min together with the thickness gauge Dakota Ultrasonics PVX with a single element delay line transducer having 6.35 mm in diameter and 15 MHz. The responses (Fig. 3) are almost identical with that obtained from the loading–unloading testing. The measured longitudinal wave velocity served for calculating the Young's modulus as

$$E = V^2 \varrho \frac{(1+\nu)(1-2\nu)}{1-\nu}, \tag{2}$$

where V is the wave velocity, ϱ is the density of 2700 kg/m^3 and ν is the Poisson's ratio of 0.34 even though the plastic deformations were present as well, which might introduce some error in the calculations. Young's moduli were estimated until the ultimate tensile strength. The first method yielded in some scatter in measured Young's moduli with no trend observable (Fig. 3).

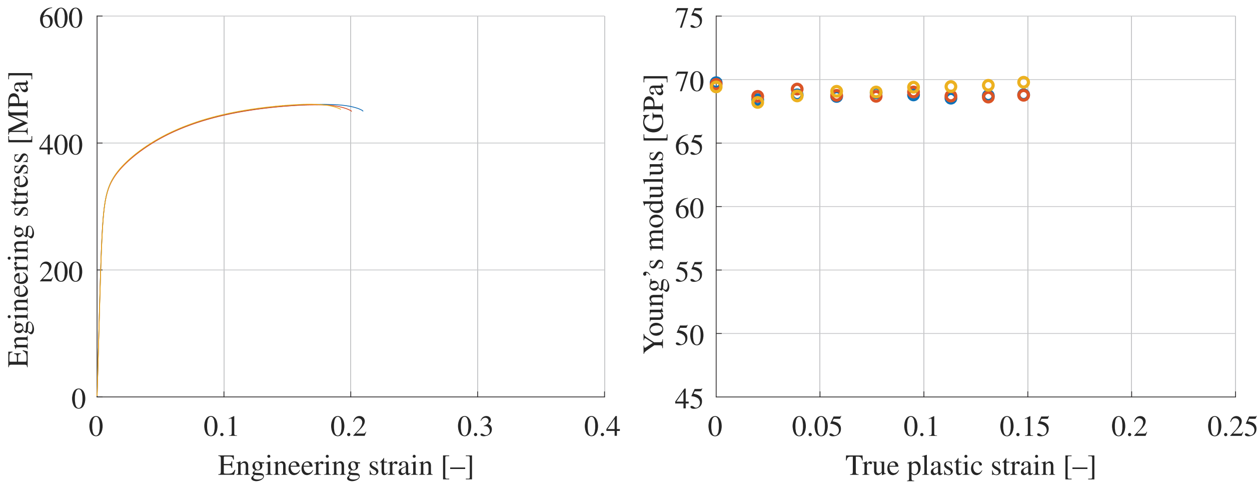

Fig. 3: Responses (left) and degraded Young's moduli (right) for continuous tests with ultrasound

The second technique using ultrasound incorporated the interruptions in order to read the wave velocity using the thickness gauge OLYMPUS 38DL PLUS with contact transducer M110 of 5 MHz. Slight decrease of Young's modulus was observed (Fig. 4). No restrictions were applied during the pauses. The same loading rate was applied as in the case of loading–unloading testing and the same assessment was applied as in the case of the first technique using the ultrasound described earlier.

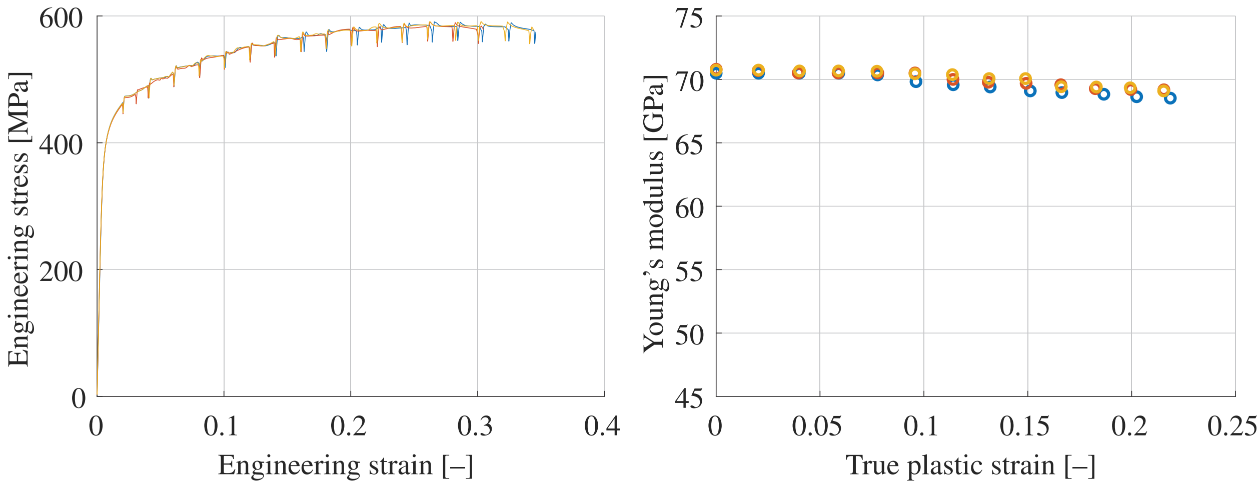

Fig. 4: Responses (left) and degraded Young's moduli (right) for interrupted tests with ultrasound

3. Results and discussion

The damage parameters were calculated for respective testing techniques and plotted in Fig. 5 after averaging. It is clear that the loading–unloading testing and the one with non-stop ultrasound produced similar responses up to approximately 0.15 of true plastic strain. On the contrary, the technique with ultrasound and interrupting the test resulted in larger ductility, which was probably due to the low temperature creep and stress relaxation. In the view of damage parameter, the loading–unloading testing gave some significant damage evolution, while both the ultrasound methods showed almost no damage. It is probably due to the difference in loading, as both ultrasound tests were not done with a full unloading. Therefore, some pretension (tensile stress) was present in the direction transverse to the measurements, which may influence the wave velocity propagation through the thickness and introduce another errors in the calculations.

Such results may be used for calibrating the damage laws, which have been proposed to capture various evolution of damage parameter as in the case of (Šebek et al., 2018) or (Xue, 2007). Further, it may be employed for more accurate numerical simulations covering the ductile fracture, especially when the non-proportionality is present.

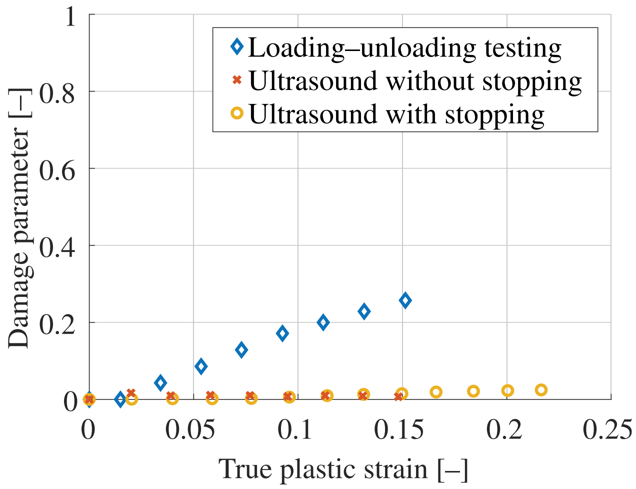

Fig. 5: Evolution of damage parameter for all methods

4. Conclusions

The possibilities of damage evolution measurements were investigated. Two major techniques were applied. One covered the loading–unloading technique and direct observation of Young's moduli degradation, the other consisted of utilizing the ultrasound which served for indirect measurement of Young's moduli. The evolution of Young's moduli is related to the damage accumulation dependent on the true plastic strain. Both methods revealed distinct results. Nevertheless, it is probable that the damage accumulation is non-linear, because the measurements were done until the ultimate tensile strength so that the true plastic strain was equal to the equivalent plastic strain, which was very close to the fracture strain for this material, see also (Šebek et al., 2018). Therefore, if the damage parameter reaches almost the value of 0.3 and has to be 1 in a very short time, there is probably a rapid damage rate in the final stage of loading prior to the fracture, which has been observed using X-ray tomography by Fabrègue et al. (2013), for example.

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