STANDARD TENSILE TEST COMPARED TO
THE SMALL PUNCH TEST OF ALUMINIUM ALLOY

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Abstract: *The paper deals with certain similarities in results of standard tensile testing and small punch tests. The study is conducted using wrought aluminium alloy 2024-T351, which is solution heat treated, stress-relieved stretched and then cold worked. This aerospace alloy has been rarely used in small punch testing, but it is well documented by standard testing techniques. Basic mechanical properties obtained by two distinct methods are compared and main consequences of the empirical estimations from the small punch testing are concluded.*

Keywords: clearance, failure, damage accumulation, finite elements, plasticity

1. Introduction

The Small Punch Test (SPT) is a miniaturized test providing the information about mechanical properties (Rouse et al., 2013). It can be used for applications where there is a shortage of material (Kubík et al., 2017) or in cases where there are very specific environmental conditions, as irradiation (Campitelli et al., 2005). It can also be used for investigation of local mechanical properties and study of microstructure (Dobeš et al., 2015). Furthermore, it can be used for elevated temperatures easily (Dymáček, 2016), while the creep is targeted (Dobeš and Dymáček, 2016). The small punch test is used for ductile fracture as well (Šebek et al., 2017).
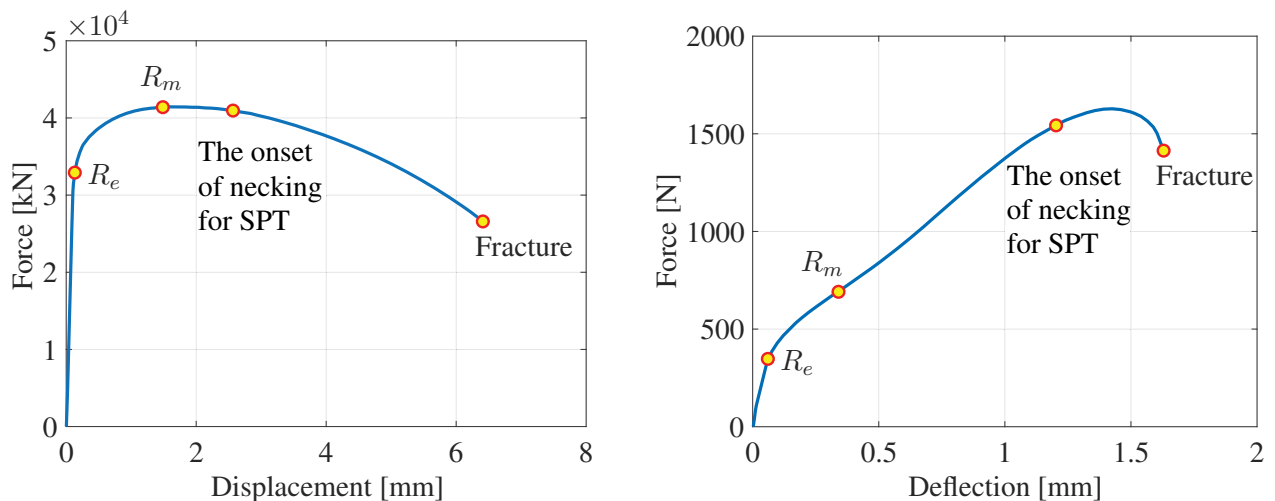

Fig. 1: The example of link between tensile (left) and small punch test (right), as proposed by Hůlka (2014).

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While simple material models are still in use with practical applications (Petruška et al., 2012), where the lack of data is typical for industry (Petruška et al., 2016), there is a demand on complex material description in academia (Šebek et al., 2014). The penetration technique is a prospective adept for that (Krčmář and Materna, 2014).

It has been suggested that here is a link between the standard tensile experiments and small punch tests in some characteristic points, as proposed by Hůlka (2014). These characteristic points are usually the yield stress (yield strength) R_e and ultimate tensile strength R_m. Furthermore, it can be the onset of necking for small punch tests and finally, the fracture itself. All the important points are depicted in Fig. 1. All the characteristics determined in small punch testing are measured in lower order values than in tensile tests, which implies high demands on precision of the measuring system. Apart from the friction, there is non-negligible influence of the clamping conditions (Andrés and Dymáček, 2016).

2. Experiments

There were conducted 5 tensile tests of standard specimens with 6 mm diameter and 30 mm gauge length. The testing was performed using Zwick Z250 Allround-Line, tCII, and extensometer Zwick multiXtens. Force–displacement curves with the averaged one are in Fig. 2 (left) with minimum scatter. The test speed was 1 mm/min until the yield point and then it was smoothly shifted to 2 mm/min.
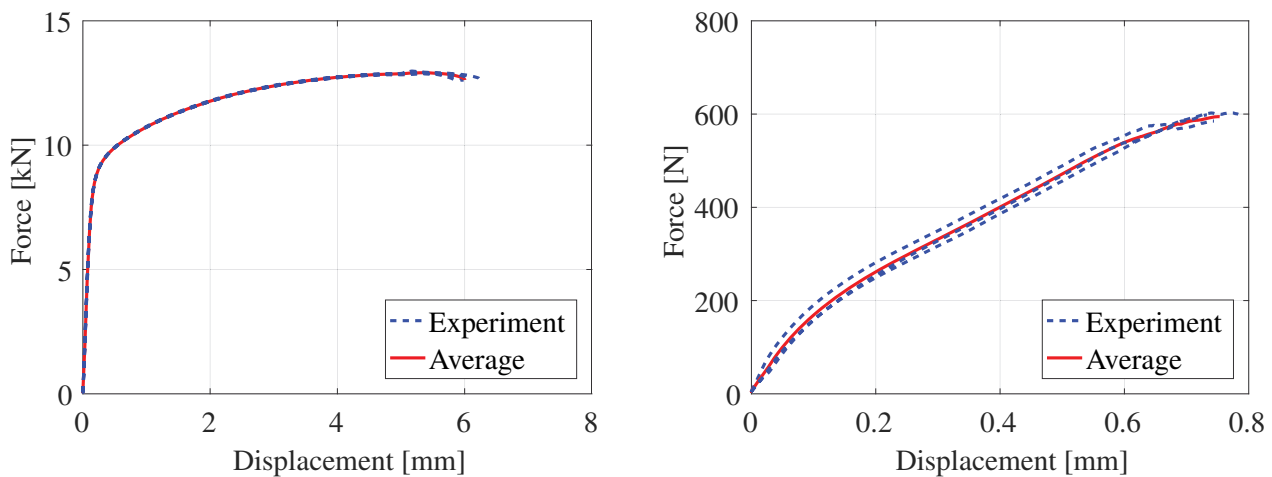

Fig. 2: Force–displacement curves from standard tensile tests (left) and small punch tests (right).

There were carried out 3 small punch tests of discs with 8 mm diameter and initial thickness $h_0 = 0.5$ mm on the same testing machine as standard tensile experiments. Results are depicted with the averaged force–displacement curve in Fig. 2 (right). The test speed was constantly 1 mm/min.

The loading was quasi-static at room temperature for all tests.

3. Calculations

The yield stress can be calculated as follows

$$R_e = \beta \frac{F_e}{h_0^2}$$

where β is the dimensionless material constant and F_e is the elastic–plastic transition load. Mao and Takahashi (1987) proposed that $\beta = 0.360$. The F_e can be estimated by the secant method.

The ultimate tensile strength can be estimated as

$$R_m = \beta_1 \frac{F_m}{h_0^2} + \beta_2$$

where β_1 and β_2 are two material constants and F_m is the maximum load. Mao and Takahashi (1987) suggested that $\beta_1 = 0.130$, which is dimensionless, and $\beta_2 = 320$ MPa.

The code of practise (CEN, 2007) defines a bilinear function that goes from the origin through two points, A and B, as

$$f(u) = \begin{cases} \frac{f_A}{u_A} u & \text{for } 0 \leq u < u_A \\ \frac{f_B - f_A}{u_B - u_A}(u - u_A) + f_A & \text{for } u_A \leq u \leq u_B \end{cases}$$

where f_A is the load at point A, u is the displacement, u_A is the displacement at point A, f_B is the load at point B and u_B is the displacement at point B. When $u_B = h_0$, then u_A, f_A and f_B can be varied so the following error is minimized

$$e = \int_0^{u_B} [F(u) - f(u)]^2 \, du$$

where $F(u)$ is the load punch displacement curve.

The testing machine with its extensometer was in accuracy class 0.5 according to EN ISO 9513. This corresponds to the relative error of the nominal full scale reading in percentage. Then, 0.5 % should be precise enough.

The fitting was done within MATLAB R2016b using non-linear least square method with the result of $u_A = 0.095$ mm, $f_A = 176$ N and $f_B = 477$ N for $u_B = 0.499$ mm, which is approximately equal to the initial thickness. The fit is depicted in Fig. 3. Then, $F_e = F(u_A) = 163$ N, which corresponds to the yield stress $R_e = 235$ MPa according to one of the above equations.
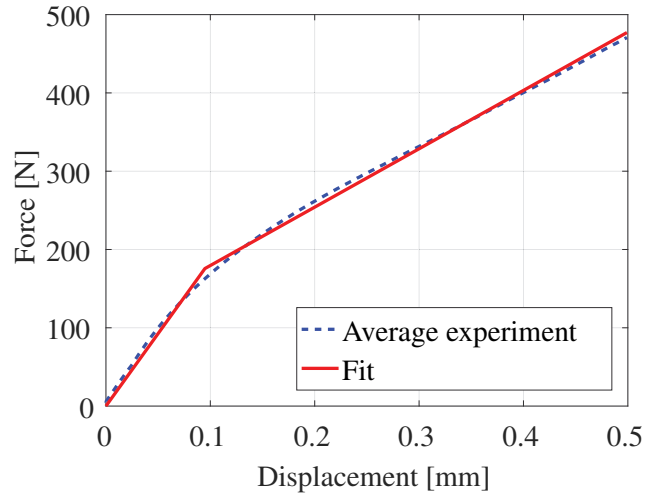

Fig. 3: The load punch displacement curve with least square fit.

The maximum load from small punch testing was $F_m = 595$ N. Accordingly, the estimated ultimate tensile strength is $R_m = 629$ MPa with respect to the above equation. It should be noted that the aluminium alloy 2024-T351 is quite brittle, so maximum load corresponds to the fracture in the same moment.

Both results from small punch tests are compared to the standard tensile testing in Tab. 1. It should also be noted that the yield stress is the proof stress in the case of tensile test in Tab. 1, because this aluminium alloy does not exhibit a yield point.

Tab. 1: Comparison of results from tensile and small punch testing.

	Yield stress [MPa]	Ultimate tensile strength [MPa]
Standard tensile test	300	741
Small punch test	235	629
Difference [%]	−22	−15

4. Conclusions

There is a big boom in miniaturized testing in recent years, as small punch test, shear punch test or disc bend test, despite it has not been standardized yet. There are several reasons for using that technique, which mainly include investigating the local properties of microstructures, such as the weldments, heat affected zones or transition layers. Small punch test can be used for determining the R-curves in fracture mechanics (Kumar et al., 2016). It can also perspectively contribute to the more accurate life assessment and extend the service life of components in industry.

Several experiments were done with aluminium alloy 2024-T351 to see the correlation between standard tensile test and SPT. It can be seen that used approximations underestimate the results obtained by standard tensile tests. Difference can be probably contributed to the different geometry of SPT. Then, the ultimate tensile strength is reached way before the maximum load on the circumference of the bottom surface, but not through the thickness, where the stresses are not homogeneously distributed. The onset of necking occurs when the stress reaches ultimate tensile strength through the thickness, as it can be computationally investigated. This point can still be before the maximum load, because this can happen only in location on the circumference where the weakest material point is. Then, the global force response can still increase slightly until the stress, which equals or exceeds the ultimate tensile strength, is developed through the thickness along the whole circumference.

Acknowledgments

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