EFFECT OF TENSILE TEST SPECIMEN SIZE ON DUCTILITY OF R7T STEEL

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Abstract

The size and shape of test specimens, their microstructure and non-homogeneity, significantly influence the strength properties and plasticity of tested steels. Efforts to characterize small-scale tensile properties are driven by the need to reliably predict the performance of engineering parts during service. In this study it is clearly demonstrated that the tensile properties of the tested R7T steel depend on specimen size. Both the yield stress and ultimate tensile strength of cylindrical tested specimens with diameter between 2 and 10 mm and plate specimens with thickness of 1 to 5 mm are independent of size. The results show that the uniform elongation is independent of specimen size but post-necking elongation increases dramatically as specimen size increases. This is caused by localized stress distribution in the neck region. The stress localization around the neck was characterized by means of the Weibull stress, which is a measure of material resistance against hardening and fracture. The Weibull stress is determined by the sample volume and the shape parameter. Numerically calculated Weibull stress using FEM is given in relation to the uniform deformation of the sample. It has been proved that Weibull stress for a constant deformation grows with increasing sample size. Increasing the shape parameter, e.g. narrowing the local strength distribution, increases the Weibull stress. The flat specimens are much more sensitive to the change of tensile behaviors with increasing size than the cylindrical specimens. It has been clearly proved that the Weibull stress is a convenient parameter for describing the size effect of steels in both brittle and ductile regimes.

Keywords: Size effect, Weibull stress, ductility, R7T steel, tensile test specimen

1. INTRODUCTION

The size effect in brittle materials is related to the evaluation of the probability of fracture initiated by defects in the microstructure, most frequently by microcracks. The failure probability of a homogenously stressed volume V of brittle ceramics or metals with low plasticity is controlled by the Weibull distribution in the form [16] to [20]

\[ P_f(\sigma, V) = 1 - \exp \left[ -\frac{V}{V_0} \left( \frac{\sigma}{\sigma_u} \right)^m \right] \]  \hspace{1cm} (1)

where \( \sigma_u \) is the characteristic strength value, m is the Weibull modulus (which is a measure of the scatter of fracture strength \( \sigma_f \)), and \( V_0 \) is the normalizing volume (which can be arbitrarily chosen). The Weibull distribution \( P_f(\sigma, V) \) expresses the probability that the fracture strength \( \sigma_f \) of a material with volume V is lower than the given value \( \sigma \). The validity of this distribution has been confirmed both for miniaturized tension specimens [21] and [22] and for standard-size test specimens [18] and [20].

Minami et al. [20], using the Beremin concept [18], calculated the failure probability for a non-homogenously stressed volume by integrating Eq. (1) for \( V \to dV \) and using the weakest link model in the form of

\[ P_f(\sigma, V) = 1 - \exp \left\{ -\frac{1}{V_0} \int \left( \frac{\sigma}{\sigma_u} \right)^m dV \right\} = 1 - \exp \left\{ -\frac{\sigma}{\sigma_u}^m \right\} \]  \hspace{1cm} (2)

and defined Weibull stress in the form,
\[ \sigma_w = \left[ \frac{1}{V_0} \int \frac{\sigma^m dV}{\rho} \right]^{1/m} \]  

(3)

The Weibull stress \( \sigma_w \) expresses a form of mean stress in a non-homogenously stressed volume, which is a measure of material resistance against brittle fracture. However, it may also be used in the evaluation of plastic deformation propagation in the area of stress concentrators or in the initiation of a non-homogenous plastic stress deformation field. Weibull stress is a suitable tool for evaluating the overall stress state of any structural component, however complex its shape may be. Although Weibull stress was originally developed to evaluate the overall probability of brittle fracture in steels, including in the transition region where cleavage fracture is preceded by ductile tearing, this method can also be used to determine fracture probability [23]. Since the nucleation of cleavage microcracks by a dislocation slip mechanism depends on the localized plastic deformation, which is controlled by the grain size, the scale parameter \( \sigma_w \) depends on the grain size as well [18]. The effect of the normalized elementary volume \( V_0 \) on the Weibull stress can be demonstrated by the ratio between Weibull stresses for two different reference volumes \( V_{01} \) and \( V_{02} \) using Eq. (4)

\[ \frac{\sigma_w(V_{01})}{\sigma_w(V_{02})} = \left( \frac{V_{02}}{V_{01}} \right)^{1/m} \]  

(4)

Since \( m > 1 \), the growth of the normalized elementary volume \( V_0 \) lowers the Weibull stress.

While the effect of size on the mechanical behaviour of brittle specimens can be very satisfactorily modelled using Weibull’s weakest link theory, very little is known about the effect of specimen size on the plastic characteristics of high toughness materials. Likewise, little is known about the sensitivity of material structural non-homogeneities to the size effect [14]. In an attempt to determine directly the effect of microvolume plastic deformation on material stress deformation behaviour in large specimens, methods of in situ testing of miniaturized tension specimens were developed [21], [24] and [25]. The stress deformation of these specimens is very strongly affected by the aspect ratio, defined as the ratio of gauge length to specimen thickness. Whereas at higher aspect ratios, for values of 5 and higher, strengthening of the tested single crystal copper tension specimens is low and flow stress grows only slightly with a decrease in cross section area, at low aspect ratios the material strengthens more rapidly, with strong growth of flow stress in small-diameter specimens (below 2 \( \mu \)m) [24]. At very high aspect ratios (higher than 17 or 40 respectively, when testing specimens of very thin Ti alloy sheets or Fe metallic glass with gauge length from 2 up to 40 mm), strength is almost independent on aspect ratio [3]. Yuan et al. [5] investigated tensile test specimens of varying thickness prepared from FH 550 marine structural steel and \( \times \)80 pipeline steel, finding that yield stress and tensile strength are independent on the thickness of the tested specimens. However, ductility was found to grow very rapidly with increasing thickness of test specimens between 1 and 6 mm in both investigated steels. Similarly, testing pure copper specimens, Zhao et al. [4] found an increase in ductility with increasing thickness and with decreasing gauge length. Sergueeva et al. [3], testing thin Ti alloy sheets and Fe metallic glass, clearly demonstrated an increase in ductility with decreasing gauge length. Tests of robust specimens (cylindrical specimens with diameter up to 10 mm) also show that ductility increases with increasing diameter, though it stabilizes at large diameters [1]. All these results clearly indicate that ductility decreases with increasing aspect ratio (i.e. the ratio of gauge length to specimen thickness).

Three different areas of mechanical behaviour of polycrystalline Ni test specimens dependent on size were identified by Keller et al. [12]. For miniaturized tension specimens of very low thickness, when the ratio of thickness \( t \) to grain size \( d \), \( t/d < 1 \), the above study, like Kiener et al. [24], found that the true stress for a given strain level increases with decreasing specimen thickness. In the range \( 1 < t/d < 4 \), true stress increases very rapidly with increasing specimen thickness, and at values above \( t/d = 4 \) the true stress becomes saturated and shows only weak dependence on thickness. When the number of grains in the specimen cross section is lower than 1 and \( t/d < 1 \), the slip mechanism of plastic deformation occurs only at
levels affecting the entire cross section of the specimen, interaction between mobile dislocations and grain boundaries is very limited, and strengthening is very low [12] and [24]. With increasing cross section area there is multiplication of activated glide systems and the Hall-Petch grain strengthening mechanism operates. Janssen et al. [26], testing high-purity aluminium, identified a rapid increase in true stress with increasing ratio \( t/d \) in the range \( 1 < t/d < t_c/d = 3 \). Similarly, Kohyama et al. [9], testing austenitic 316 SS steel and 10Cr2Mo dual phase steel, found a very weak dependence of yield strength on specimen thickness above the critical value \( t_c \), which approximately corresponds with the size of 6 grains. For values \( t_c/d < 6 \) it is indeed true that yield stress \( \sigma_y \) grows with increasing specimen thickness according to the relationship

\[
\sigma_y(t) = \sigma_y(b) - \alpha (1/t - 1/t_c) k_d^{1/2}
\]

where \( \sigma_y(b) \) is the yield strength of a robust bulk specimen, \( d \) is mean grain size, \( k \) is the Hall-Petch constant, and \( \alpha \) is the shape parameter characterizing the speed of growth. A very gradual increase in yield stress and tensile strength with increasing ratio \( t/d \) in the range \( 1.2 < t/d < 14 \), with a low critical value \( t_c \), was found for thin Al sheets [27]. Suh et al. [28], testing aluminium sheets with thickness from 0.40 to 1.58 mm, found a clear increase in both yield strength and strength with increasing thickness / grain size ratio up to the value \( t/d = 26 \). However, as in [21], at higher values of \( t/d \) there was a slight decrease in strength, while yield strength continued to grow. Zhao et al. [4], testing pure copper with grain size 50 μm (around one-fifth of the lowest thickness of the specimens tested), revealed almost no effect of specimen thickness on true stress up to ultimate tensile strength. For all tested specimens it was evident that \( t/d > 5 > t_c/d \) and that true stress was always under critical specimen thickness \( t_c \). At lower thicknesses, and thus also at lower specimen thickness / grain size ratios \( t/d \), surface grains are predominant. This modifies the plastic deformation mechanism and stages of strengthening, giving a stronger dependence of yield strength on grain size [12], [26] and [29].

2. EXPERIMENTAL PROCEDURES

All testing was conducted on specimens cut from a rail wheel supplied by Bonatrans, a.s., Bohumín, Czech Republic. The chemical composition was determined to be, in weight percent, 0.51 C, 0.74 Mn, 0.30 Si, 0.24 Cr, 0.16 Ni, 0.04 Mo, 0.003 V, 0.005 N, 0.08 Cu, 0.009 S, 0.012 P, and the balance Fe, which conforms to the R7T designation [37]. The steel was heat treated by austenitization at 850°C then water cooling and tempering at 520°C. The final microstructure resulting from the heat treatment of the commercially produced wheel, in general terms, was a mixture of lamellar pearlite with a small quantity of ferrite. The microstructure morphology of the steel with less than 20% of the area fraction ferrite grains observed using image analysis. The ferrite grain size measured by the linear intercept method from optical microscopy micrographs of the polished and etched surfaces was approximately 7 μm. The pearlite colony size was \( D_p = 15 \) μm. The pearlite interlamellar spacing \( S_p \) was measured using a line drawn normal to the pearlite lamellae on metallography-prepared specimens heavily etched in 3 % Nital and examined in a scanning electron microscope. The minimum interlamellar spacing \( S_p \) observed in several locations varied from 0.1 to 0.2 μm. This value was assumed to be the actual true spacing.

The specimens for tensile testing were made in two shapes – cylindrical and flat. The specimens were tested in 6 sizes of different diameter \( D_0 \) or different thickness \( t_0 \), always fulfilling the similarity condition

\[
L_0 / \sqrt{S_0} = \text{const}
\]

where \( L_0 \) is the gauge length, \( S_0 \) is the cross section area and \( \text{const} = 5.56 \). Tensile tests were performed at a strain rate of \( 10^{-4} \) s\(^{-1} \) on a tensile test machine at room temperature. The obtained stress-strain characteristics were described by means of the non-linear Ramberg-Osgood relationship as follows,

\[
e = \frac{\sigma}{E} + \left( \frac{\sigma}{K} \right)^{1/n}
\]
where $\sigma_0/E$ is the elastic and $(\sigma/K)^{1/n}$ is the plastic part of the overall strain $\varepsilon$. $\sigma_0$ and $K$ are parameters, and $n$ is the strain hardening exponent. It follows from these results that there is a decreasing dependence of ductility $A$ on the specimen cross section area $S_0$, illustrated graphically in Fig. 1a.

**Fig. 1** a) Dependence of ductility of cylindrical and flat specimens of R7T steel on cross section area; b) Dependence of Weibull stress on actual deformation in cylindrical specimens of R7T steel.

The dependence of the strain hardening exponent $n$ on the cross section area was investigated for cylindrical specimens only. The decreasing trend of the strain hardening exponent with increasing specimen size is similar in character to the dependence of ductility on specimen cross section given in Fig. 1a, showing the dependence of the strain hardening exponent on specimen size, provides clear evidence that hardening processes during loading are much more intensive in smaller specimens.

The stress deformation behaviour of both flat and cylindrical specimens in all sizes was numerically simulated. By applying the finite element method (using Ansys code), the development of the stress field in
the gauged part of the test specimen was determined. Considering the mesh element as the normalizing volume $V_0$, the Weibull stress of the specimen at all times of loading was calculated.

The dependence of Weibull stress on actual deformation in cylindrical and flat R7T steel specimens for different specimen diameters or thicknesses is shown in Figs. 1b and 2a. These images clearly show that up to the onset of plastic instability, Weibull stress is almost independent on specimen size; however, beyond the point of onset of plastic instability, Weibull stress $\sigma_w$ increases with increasing specimen size. The increase of Weibull stress with increasing specimen size is more prominent in flat specimens than in cylindrical specimens, especially at higher levels of plastic deformation. Fig. 2b shows the dependence of Weibull stress on cross section area for four selected deformation values in flat specimens. While this dependence is weak at low levels of deformation, for deformation above $\varepsilon = 0.16$ Weibull stress increases dramatically with increasing cross section area.

3. CONCLUSIONS

Weibull stress has been found to be a tool for the integrated description of the stress field inside tensile test specimens. The stress field in the central part of the test specimen undergoes different changes in differently sized test specimens; this is the main reason for the different stress deformation characteristics. Experimental procedures and numerically analyzed stress-strain fields of tensile test specimens from R7T ferritic-pearlitic steel revealed the following: Increasing specimen size is accompanied by decreasing ductility and strain hardening exponent. The Weibull stress for a constant strain increases with the increasing size of the test specimen. Increasing the shape parameter $m$, e.g. by narrowing the local strength distribution, increases the Weibull stress. The Weibull stress is a convenient parameter for descriptions of the size effect of steels in both brittle and ductile regimes.

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