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Size effect criteria on the small punch test for AISI 316L austenitic stainless steel

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ABSTRACT

The miniature specimen test technique has been extensively studied for quantifying the properties of bulk materials with greatly reduced volume recently. In this paper small punch test (SPT) is used to evaluate effects of specimen thickness, grain size and thickness-to-grain size ratio (TGR) on mechanical properties of 25 samples of type 316L austenitic stainless steel with nearly the same crystallographic texture. Effective SPT yield and maximum loads were measured and correlated with yield and ultimate strengths of conventional tensile test. The results show that SPT is sensitive not only to grain size, but also to thickness and TGR. Size effects exist between SPT and standard-sized samples. The present work gives a size effect criterion of SPT for engineering application. In addition, the underlying mechanisms of these size effects are provided.

1. Introduction

It is well-known that the strength of polycrystalline metals is inversely proportional to grain size according to the Hall–Petch relation [1,2], though the inverse relationship is found for nanometer size grains [3]. Recently, many tests on miniature, sub-millimeter and sub-micron specimens have been performed to study the interplay of grain size, specimen thickness and shape on the mechanical properties [4–7]. The miniature specimen test technique has the potential to be used in lifetime prediction of in-service components [8] and creep testing at elevated temperature [9–11], especially in the nuclear industry where neutron irradiation space is limited and irradiation cost increases with the volume of specimens [8]. Small punch test (SPT) is one of the most promising techniques of miniature specimen test, which was originally applied in testing irradiated materials in nuclear engineering [12–15] and then introduced to other fields as an almost nondestructive method to measure the local mechanical properties that are difficult to be obtained using conventional mechanical tests, for example, weld heat-affected zone of steel, in-service high Cr ferritic steel, P92 steel, and other engineering materials [16–20]. Despite much effort to correlate these miniature specimen tests with the conventional tests, the size effects on the extraction of mechanical behavior of materials by using greatly reduced volume of materials are still unclear. At present, there are some reports that seem to contradict each other. Toloczko et al. [21] used miniature shear punch test to measure the yield strength and ultimate tensile strength of stainless steel 316L and did not observe any dependence of strength on the thickness and grain size of specimens, based on which they drew a conclusion that shear punch test did not have the same sensitivity to specimen thicknesses and grain sizes as the other miniature tensile tests. Chen et al. [7] reported that micron-sized Ag wire exhibited significant dependence of strength on grain size and specimen size in the micro-tensile test. The similar results are also reported by Miyahara [22] and Igata [23] in the tensile test of foil specimen of steels. So far, there is still a lack of comprehensive understanding on the specimen size effect on mechanical behaviors of SPT and its underlying mechanism. Generally speaking, the grain size plays a role of internal microscopic scale to affect strength through Hall–Petch effect in polycrystalline materials, while the specimen size may play another role of external macroscopic scale affecting strength. However, very few studies have been devoted to the correlation between specimen size, grain size and their effects on mechanical properties in SPT so far. In addition, in the engineering application of SPT, a critical thickness-to-grain size ratio (TGR) is urgently needed for thin sample testing due to the breakdown of classical law of mechanics (e.g., Schmid's law [24]) and the observed mechanical size effect (smaller-is-stronger) in small scaled materials [25]. When the TGR is larger than the critical value, the data extracted from SPT may be appropriately

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Table 1
Chemical composition of as-received AISI 316L stainless steel (wt%).

C	Mn	P	S	Si	Ni	Cr	N	Mo	Fe
0.03 Max	2.0 Max	0.045 Max	0.03 Max	1.0 Max	10.0–14.0	16.0–18.0	0.10 Max	2.0–3.0	Balance

Table 2
Solution treatment temperature and obtained grain sizes of SS 316L specimens.

Solution treatment temperature (K)	As-received	1223	1323	1323	1373	1473
Holding time in furnace (h)	Nil	1.0	1.0	2.0	1.5	2.0
Grain size (μm)	5.2 ± 1.5	10.5 ± 2.0	24 ± 4.0	32.5 ± 3.0	42 ± 3.0	65 ± 6.0

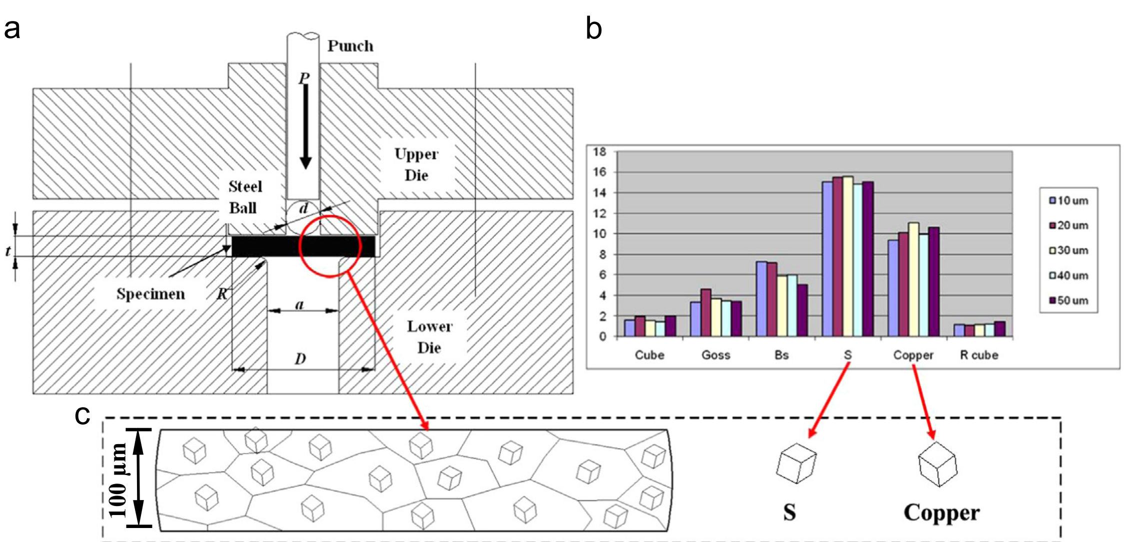

Fig. 1. Schematic representation of SPT configuration (a), different sorts of texture volume fractions comparison between samples with different grain sizes (b), and grain orientations of S and Copper texture components for the specimen with largest grain size 50 μm and minimum thickness 100 μm (c).

correlated with the data obtained by conventional mechanical tests; otherwise a strong size effect between miniature and conventional tests may lead a failure of these correlations. In this paper, type 316L austenitic stainless steel (SS 316L) is used as a model sample, as it is widely used in the nuclear power, petrochemical and fertilizer industries with excellent properties of corrosion resistance, toughness and weldability, to investigate the biaxial deformation behavior under different grain sizes (d_g) and specimen thicknesses (t), and then the effects of these two length scales (t/d_g) on SPT are clarified.

2. Experimental procedure

The material used in this study is commercial SS 316L sheet with 1.5 mm thickness. Its chemical composition is given in Table 1. The low carbon content variant was selected to ensure no strain-induced precipitation would be expected during deformation. For obtaining a series of specimens with different grain sizes and thicknesses, the SS 316L sheets were rolled until the thickness reached to 0.60 ± 0.02 mm, and then solution treatment of specimens were carried out at various temperatures between 1223 and 1473 K to obtain different grain sizes. The detailed heat-treatment parameters are given in Table 2. To determine the grain sizes of the as-received and the after-heating specimens, two different cross sections, one normal to rolling direction and the other perpendicular to rolling direction, were polished and then chemically etched with a solution of 25% nitric acid and 75% hydrochloric acid (with their highest concentration solutions) for around 15 s. Grain sizes were measured using optical microscopic (OM) images and standard linear interception method [26], in which grain sizes were obtained by averaging results at three different observed areas.

For preparing small punch test specimens, several disk-type specimens with 10 mm in diameter were cut from the after-annealing sheets using electric discharge machine (EDM), and then both surfaces of the disk specimens (thickness 0.60 ± 0.02 mm) were ground on silicon carbide papers up to 1200 grit and get different thicknesses of 500, 400, 300, 200 and 100 μm, respectively, with a typical variation of ± 10 μm. The bulk texture measurements of samples were carried out by the Bruker D8 DISCOVER with GADDS XRD and MULTEX 3 software. The oxide layer on the sample surface after heat treatment was removed by polishing before performing XRD texture measurements. The SPT was conducted on a servo-hydraulic system with central load sets which include a punch, a quenched steel ball and upper and lower dies that are used to hold the specimen. The detailed SPT configuration is shown in Fig. 1. The diameter of the steel ball (d) is 2.5 mm and the diameter of the hole in lower die (a) is 4 mm, the radius of the chamfer of lower die (R) is 0.5 mm. There are two reasons for selecting a range of the specimen