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Effects of grain size on tensile property and fracture morphology of 316L stainless steel

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ABSTRACT

The aim of this work is to understand the relationship among average grain size, dimple size and tensile properties of 316L stainless steel via directly experimental results. We have successfully prepared samples with the average grain size from a few microns to tens of microns through cold rolling and annealing processes. Uniaxial tensile tests were performed to confirm the Hall-Petch relationship between the grain size and yield strength. In order to uncover the grain size dependence of ductility, the fracture morphologies in details were observed. It revealed that the dimple size is positively related to the value of $D^{1/2}$ (D is the average diameter of grain size). A larger grain size was believed to result in a larger dimple so as to achieve a higher ductility (uniform elongation).

1. Introduction

The strength and ductility are two kinds of crucial mechanical properties for metals, which plays an important role during its serving [1–3]. Such mechanical properties are determined by its structures and phase composition, yet, significantly influenced by the grain size. The grain size adjustment is an effective way to regulate the incompatibilities between strength and ductility [4–7]. The grain size dependence of strength mainly complies with the Hall–Petch relationship [8,9]. For 316L stainless steel, it is widely used in industrial field, due to its excellent corrosion resistance, good formability and so on [10]. Previous work has shown that the yield strength of 316L stainless steel were enhanced by regulating its grain size such as the formation of submicrocrystalline, ultrafine crystalline or nano-crystalline, which confirmed the Hall-Petch strengthening by grain refinement [1,11–17]. As the grain refinement, it can significantly enhance the strength, but the ductility of materials inevitably decreased [18,19]. As is well-known, the ductility is also very important for 316L stainless steel, which is related to the ductile/brittle fracture mechanism [5,20]. But, up to now, the detailed analyses on the relationship among average grain size, dimple size and the ductility of 316L stainless steel is deficient. The systematical elucidation on the average dimple size is beneficial for understanding the evolution of tensile fracture behavior and analyzing the intrinsic relationship between plastic deformation mechanism and grain size. Since the analyses on dimple size is critical to understanding the ductility of 316L stainless steel. Thus, the mean dimple size and uniform elongation as a function of mean grain size needs to be clarified. Consequently, in this work, we aim at establishing a relationship between average grain size and dimple size, which is of great significance to understand the matching mechanism of strength and ductility. 316L stainless steel samples with various grain sizes were successfully prepared and the systematical analyses on the evolution of fracture morphologies were performed.

2. Experimental procedures

In present work, a typical 316L austenite stainless steel sheet (chemical compositions: Cr-16.26, Ni-10.33, Mo-2.05, Mn-1.34, Co-0.98, Si-0.48, Cu-0.45, W-0.25, Nb-0.028, C-0.024, P-0.035, S-0.007, and balance Fe, wt%) were selected. The as-received sample is with an average grain size ~57 µm. The grain size adjustment was processed by conventional cold rolling and the subsequent annealing treatment. The total rolling strain is ~87%, the annealing

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temperature is 750 °C, 850 °C and 950 °C, and the annealing time is 1 h, corresponding to the average grain size ~2 µm, ~4 µm and ~12 µm, respectively. Fig. 1a-d exhibits the optical micrographs of 316L stainless steel with various average grain sizes. The possible phase transformation of samples was characterized by XRD analysis (Fig. 1e). In this work, the 316L stainless steels with different grain sizes, it is composed of single austenitic phase, which can eliminate the influence of different phase composition on fracture behavior. In order to evaluate the grain size dependence of tensile behavior, uniaxial tensile tests were performed on an electromechanical universal testing machine (LFM-20kN) with a strain rate of 2×10^{-3} s^{-1} with the dog-bone shaped specimens (gage dimension of $20 \times 3 \times 4$ mm^3). In order to ensure the stability of the data, all the tensile tests were repeated three times under the same testing condition. To analyze the possible phase transformation, the X-ray diffraction (XRD) analyses were conducted using an automated Bruker-AXS D8 Advance diffractometer with Cu Ka radiation. Furthermore, the evolution of fracture morphologies in details were observed by scanning electron microscope (FEI Nova NanoSEM 450) measurement.

3. Results and discussion

The typical tensile engineering stress–strain curves are present in Fig. 2a. It indicates that the tensile strength increases with the grain size reduction of 316L stainless steel. Based on the comparison of results reported in previous literatures and in this work, the effect of grain size on the yield strength was summarized in Fig. 2b. With the decrease of grain size, the enhanced yield strength was achieved. The decrease in grain size is accompanied by the increase of grain boundaries, which can be obstacles preventing dislocation motion with the formation of dislocation pile up [1,10,24–26]. So, it confirmed that the grain size and yield strength follows the Hall-Petch relationship [24]. However, the increase in strength will inevitably lead to a decrease in ductility. The observations on fracture surfaces are critical to revealing the differences of ductility, while previous work highlighted the Hall-Petch strengthening [1,11–17]. Thus, the mean diameter of dimples was carefully counted. Fig. 3 displays the fracture morphologies of broken samples and the dimple size distribution. With the decrease of average grain size, the average dimple size significantly decreased. For the larger grain, it becomes easier for the motion and slip of dislocation at grain boundaries, so that this large-sized dimple with the higher capacity of energy absorption is easily generated during this coordinated deformation [5,27]. The relationship among the mean diameter of dimple, uniform elongation and the average grain size was clarified in Fig. 4. Based on the fracture morphologies analysis and the comparison with previous literature [14,27,28], a straightforward relationship (the formula was inset in Fig. 4a) between the mean diameter of dimple and the average grain size was estab-

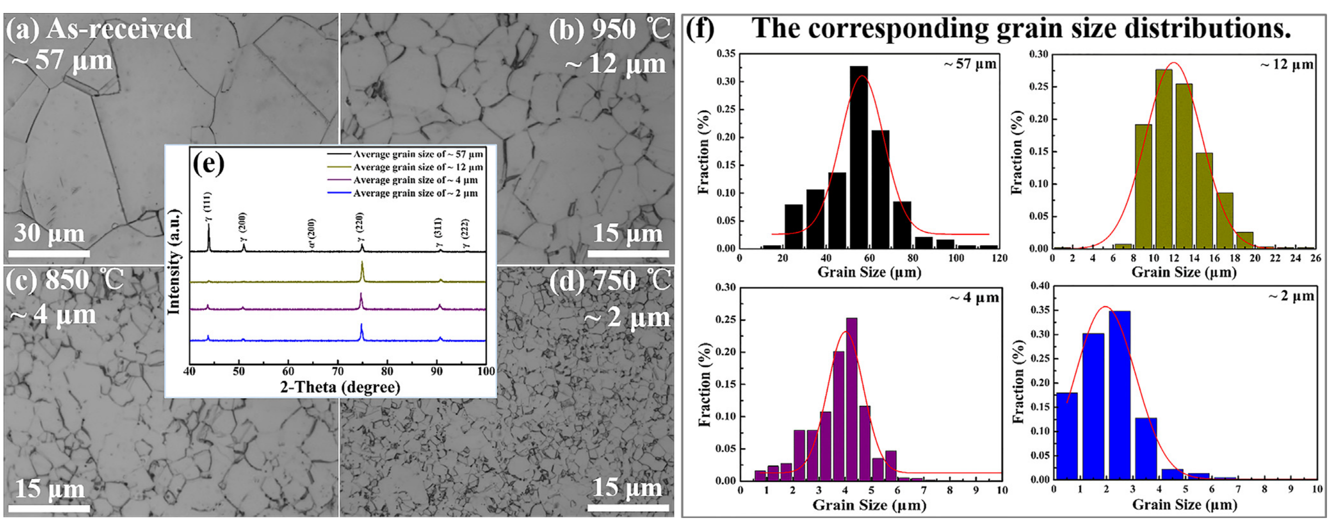

Fig. 1. (a)–(d) The optical micrographs of 316L stainless steel with different average grain sizes; (e) XRD patterns of 316L stainless steel with different average grain sizes; (f) the corresponding grain size distributions highlighting the average grain size.

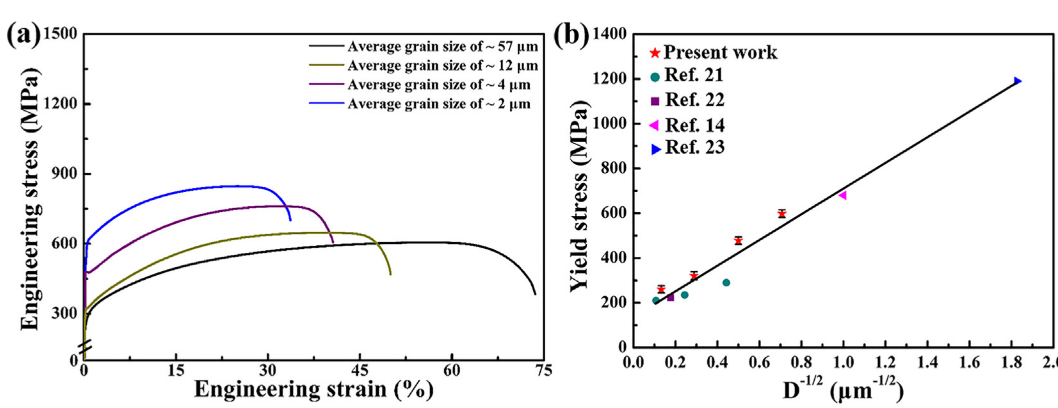

Fig. 2. (a) The engineering stress-strain curves of 316L stainless steels with different average grain sizes; (b) the effect of grain size on the yield strength: yield strength as a function of the D$^{-1/2}$, based on the results reported in previous literature [14,21–23] and in this work.

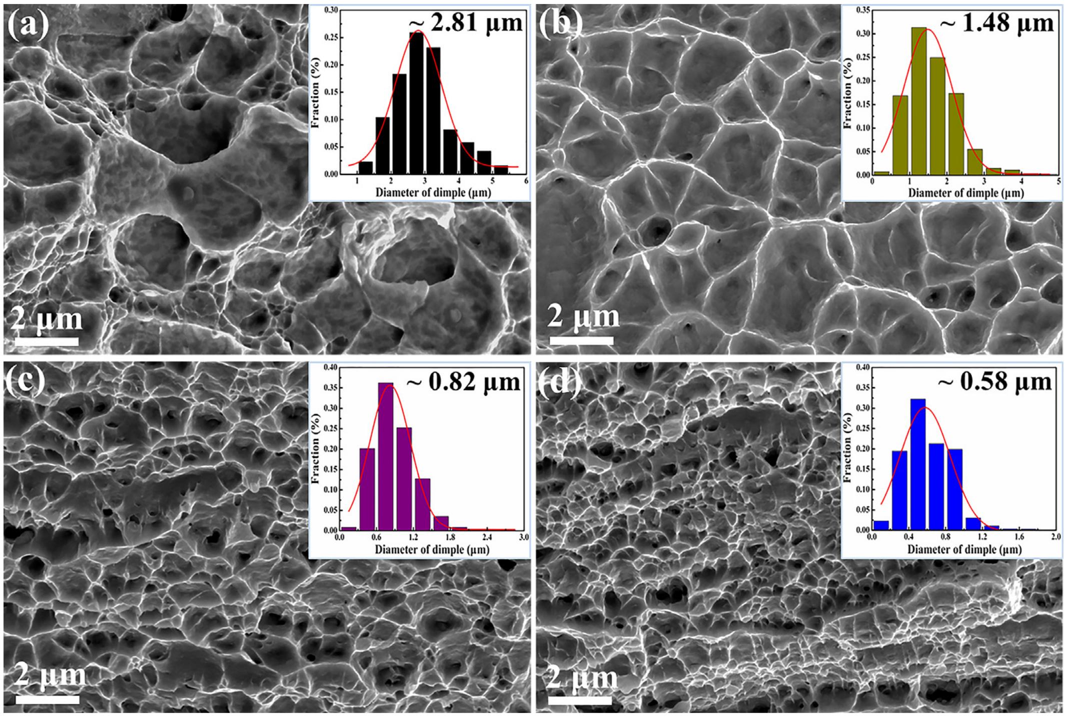

Fig. 3. The typical SEM fracture morphologies of 316L stainless steels with different average grain sizes: (a) ~57 μm, (b) ~12 μm, (c) ~4 μm, (d) ~2 μm; all the illustrations describe the dimple size distribution obtained from SEM observations.

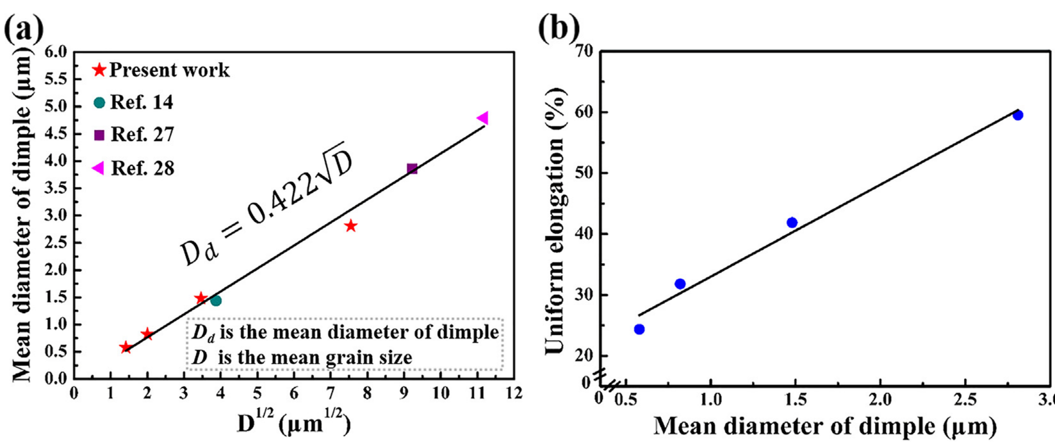

Fig.4. (a) Plot of the mean diameter of dimple as a function of the $D^{1/2}$ [14,27,28]; (b) plot of the uniform elongation as a function of the mean diameter of dimple.

lished, which could be clearer to exhibit the grain size dependence of fracture morphologies. It indicates that the mean diameter of dimple is positively related to $D^{1/2}$ and the uniform elongation is directly proportional to the mean diameter of dimple, which may be clearer for understanding such internal relationships.

4. Conclusion

In this work, the relationship among average grain size, average dimple size, strength and ductility for 316L stainless steels were carefully revealed. The results indicated that the grain size and yield strength follows the Hall-Petch relationship. The mean diameter of dimple was positively related to the $D^{1/2}$ for such grain size range. As the grain size increases, the average diameter of dimple gradually increases. These large-sized dimples are generally caused by severe plastic deformation during the fracture process, indicating an enhanced ductility.

Declaration of Competing Interest

The authors declare no competing financial interest.

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