Hongxia Bian, Liang Zhu*, Hui Zhou and Peng Tu

Effect of Deformation Temperatures on High Temperature Tensile Instability of Austenitic Stainless Steel

Abstract: The characteristics of instability have been investigated on two low nickel austenite stainless steel at the temperatures of 950–1200 °C through the uniaxial tensile test and tensile unload test. The results show geometrical instability is not concurrent with load instability in high temperature tensile. The deformation of specimens are uniform before the load instability, then appear non-uniform in some local area of specimen but they do not directly lead to the geometric instability. With the increase of deformation temperature, load instability strain and strain hardening exponent *n* are both no obvious variation, and load instability true strain is close to *n* and depends on *n*. The geometric instability strain and strain rate sensitivity coefficient *m* both increase with the increase of temperature, and the strain between load instability and geometric instability depends on *m* and is the main part of the geometric instability strain.

Keywords: load instability, geometrical instability, work hardening exponent, strain rate sensitivity coefficient

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1 Introduction

The widely applied austenitic stainless steel is prone to crack when it is processed to required product shape through hot deformation such as hot rolling and hot forging [1–3]. Based on the morphology of the cracks, it has been found that there is strain localization prior to cracking for most of cracks, suggesting that the strain localization is an early indication of cracking; therefore to control strain localization can partly control the cracking of material. The strain localization in uniaxial tensile test is often typified by the necking. When the necking occurs, the cross-sectional area of the specimen in certain regions is sharply decreased and this is also known as geometrical instability. When geometrical instability occurs, the fractional decrease in cross-sectional area at a local region exactly compensates for the increase in flow strength due to the deformation strengthening, and load began to decrease. Uniaxial tensile test is the most basic method to determine the characteristics of material plastic deformation, and can be used for the study of tensile geometrical instability.

The geometrical instability of uniaxial tensile has been extensively studied from the aspects of experiment [4–7] and theory [8–12] and is considered to be closely related with material mechanical properties [4, 5, 8, 9]. Plastic deformation commences after the linear elastic deformation in tensile, after which specimens should experience load instability, geometrical instability until fracture. For ordinary metals and alloys, load instability and geometrical instability are concurrent when load reaches maximum, and the geometrical instability true strain equals to work hardening exponent *n*. This conclusion is first deduced by Considère and has been proved on many materials. For certain metallic alloys and non-crystalline polymers, especially in high temperature conditions, experiment results are evidence that load instability and geometrical instability are not concurrent in uniaxial tensile and geometrical instability. True strain not only is related with work hardening exponent *n* but also is related with strain rate sensitivity coefficient *m* [4, 5, 13]. Such as, at high temperature deformation, geometrical instability of super-plastic material and some alloy does not occur when load instability appears at the maximum [14, 15]. Specimen could be permanently uniform deformation in a period of time after load instability, and geometrical instability appears when non-uniform deformation develops in local region. The analysis of relationship of material's mechanical properties and geometrical instability indicates that both load instability strain

Table 1: Chemical composition in mass%

Composition	C	Si	Mn	P	S	Ni	Cr	Cu	N	F_e
Cr15Mn9Cu2NiN	0.09	0.30	9.20	0.03	0.001	0.99	15.26	1.54	0.12	remainder
Cr17Mn6Ni4Cu2N	0.07	0.45	5.62	0.03	0.004	3.70	17.19	2.00	0.14	remainder

and geometrical instability strain change with work hardening exponent *n* and strain rate sensitivity coefficient *m* [16].

Geometrical instability decides the forming ability of material in deformation process, and when geometrical instability occurs after load instability the forming limit increases. To analyze the nature of geometrical instability can help to improve the forming limit. The researchers have made various new variables to analyze the relation between geometrical instability and mechanical parameters. By selecting the cross-section at any instant during a deformation as a new variable, Hart considered that geometrical instability appears when the cross-section area in local region decreases faster than other regions and the instability strain is affected by strain hardening rate and strain rate sensitivity [9]. According to Hart's instability criterion, Ghosh discussed the geometrical instability by employing diffusion rate of defect and considered that the geometrical instability strain decreased with increasing of diffusion rate [8]. By selecting the local length and dislocation density as new analysis variables, it is believed that the geometrical instability is dominated by deformation gradients which include the length of local mesh, local strain and local cross-section and which were effected by material property [17].

Much attention was given to the characters of geometrical instability of material in room temperature and super-plastic material in the uniaxial tensile test. For the commonly used materials such as stainless steel, its geometrical instability affects more wide range, and there should be further investigation on the geometrical instability of stainless steel especially at high temperature. At high temperature, although stainless steel does not have the geometrical instability strain like super-plastic material, it appears the phenomena of load instability and geometrical instability is not concurrent [18]. The character of stainless steel is well worth to deeply study. The aim of this work is to use the uniaxial tensile test to investigate the character of tensile deformation and the rule of geometrical instability at high temperature, and to explore the relationship between mechanical parameters and geometrical instability strain.

2 Experimental procedures

The investigated materials were Cr15Mn9Cu2NiN and Cr17Mn6Ni14Cu2N austenite stainless steel with the main chemical composition in mass% listed in Table 1.

The dimensions of tensile specimens are shown in Figure 1 and the specimens had the thicknesses of 5 mm. The tensile tests have been carried out in thermal/ mechanical simulation testing machine, with the apparatus given in Figure 2. Specimens were drawn by the ropes made of molybdenum wires which were tied in the semicircles of the end regions. The whole specimens were put in the high-frequency induction coil to assure the uniform specimen temperature.

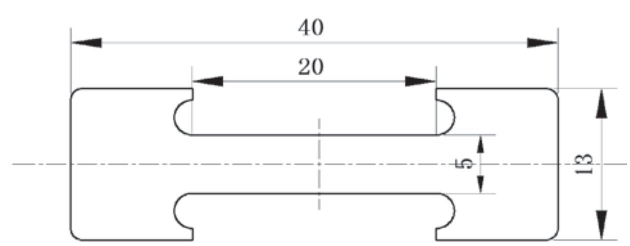

Fig. 1: Dimension of tensile specimens in mm

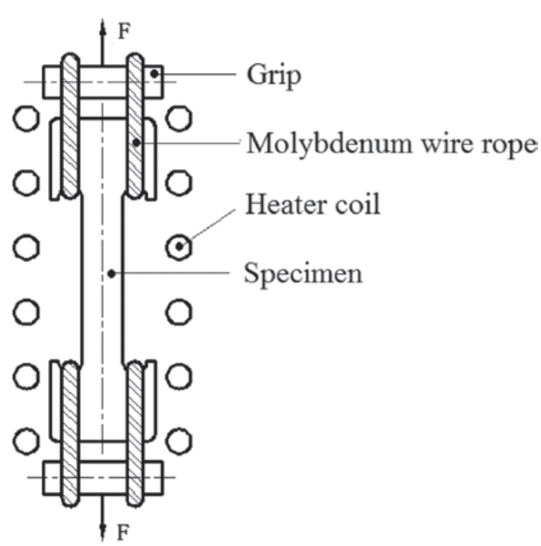

Fig. 2: Device for tension test

The test temperature range was from 950 °C to 1200 °C and the test temperature interval was 50 °C. Firstly, the tensile specimen was heated to 1250 °C in 125 s and was held for 120 s. Then it was cooled to test temperature at the rate of 10 °C/s and then the specimen was pulled until failure at the strain rate of 0.1/s. In order to analyze the surface morphology of the specimens in different deformation stages, at typical deformation temperature, tensile unload test was performed and the test rule is same as the tensile test. In this test, specimens were drawn to certain strains, and then were unloaded and preserved the surface morphology.

3 Results

3.1 Characteristics of tensile deformation

The engineering stress–engineering strain curves for the tested material were obtained from load-displacement curves recorded by instrument in uniaxial tensile tests. The characteristics of the curves of the two kinds of low nickel austenite stainless steel at various temperatures are very similar, with the typical curve shown in Figure 3. After plastic flow commenced, the engineering stress increased with the increase of engineering strain until reaching maximum engineering stress. After this, the engineering stress decreased with the increase of engineering strain until the engineering stress sharply decreased at some strain.

During tensile deformation of the plastic material, the deformation is stable if load gradually increases, otherwise the load instability appears. As shown in Figure 3, the engineering stress reached maximum at strain ε_n after the commencement of plastic flow, then engineering

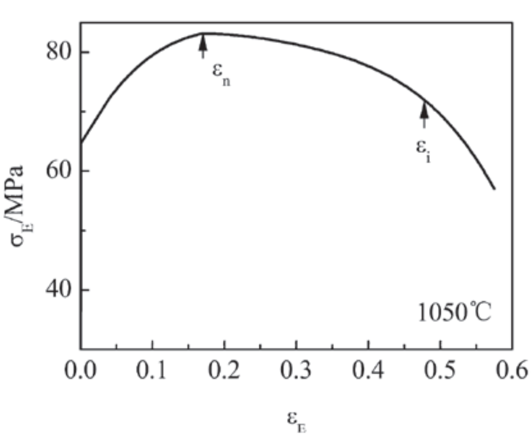

Fig. 3: A typical engineer stress-strain curve

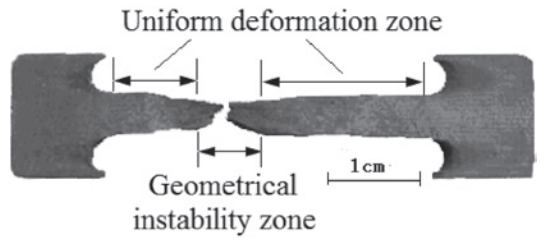

Fig. 4: Photo of tensile failure specimen

stress decreased. The phenomenon means that load instability occurs at maximum stress and load instability strain equals to ε_n. After the occurrence of load instability, the stress decreased slowly with the increase of strain until the strain equaled to ε_i, and then the stress sharply decreased.

For common metals and alloys, the geometrical instability strain can be obtained from engineering stress–engineering strain curves because that geometrical instability strain equals to load instability strain. However, at high temperature deformation, load instability and geometrical instability do not occur at the same time and load instability strain does not equal to geometrical instability strain. So the geometrical instability strain should be determined by measuring the geometrical shape of fractured specimens. The fractured specimen is divided into macroscopic uniform deformation zone and geometrical instability zone nearby fracture by measuring the geometrical shape in gauge length, as shown in Figure 4. Before the occurrence of geometrical instability, the deformation is macroscopically uniform. The uniform deformation length before geometrical instability is the sum of the macroscopic uniform deformation length and the instant length which geometrical instability zone appears instability. According to the constant volume principle, the instant length can be calculated by equation $l_i = (s_{0l} - sd_{lu})/s_d$, where s_d and l_u are the cross-section area and length in uniform deformation zone of fractured specimen respectively, and s_0 and l are the cross-section area and length of non-deformation specimen respectively. Comparing the geometrical instability strain which was obtained by measurement with ε_i, it was found that geometrical instability strain equals to ε_i. The result indicates that geometrical instability occurs when engineering stress rapidly decreases.

In order to investigate the surface morphology and geometrical shape during the tensile deformation, the appearance of specimen in various strains was preserved in tensile unloading test. Figure 5 shows the morphology of a specimen at the typical testing strain and temperature. The deformation of the specimen is uniform in gauge

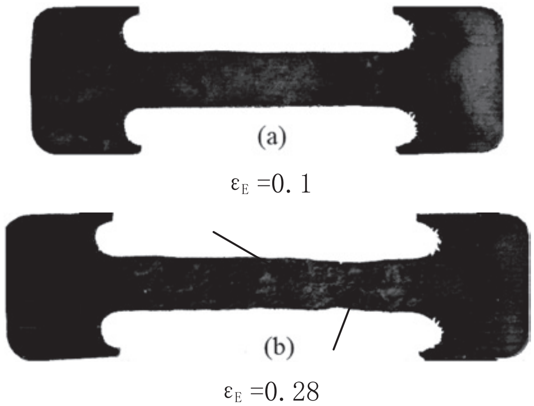

Fig. 5: Surface morphology of the specimen under various strains

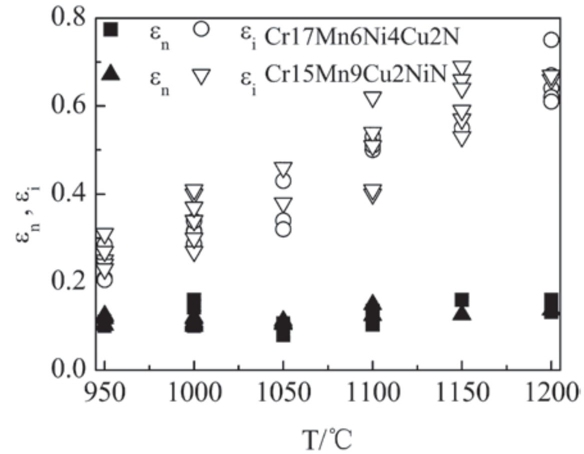

Fig. 6: Geometrical instability strains and necking strains

length before ε_n, as seen from Figure 5a. The deformation is macroscopically uniform between ε_n and ε_i, and there are a lot of dents, as indicated by arrows in Figure 5b. From this surface morphology, it is evident that geometrical instability and load instability did not occur at the same time, and the deformation of specimen is uniform before load instability and the deformation is macroscopically uniform between load instability and geometrical instability.

The results of experiment above show that the load instability and geometrical instability did not appear at the same time, and the load instability appeared when stress got maximum at the strain of ε_n, and geometrical instability occurred at the strain of ε_i during high temperature tensile. The deformation of specimen is uniform before load instability, and the deformation is macroscopically uniform between load instability and geometrical instability in the gauge length. It also should be noted that the non-uniform deformation region in the stage of macroscopically uniform deformation was constantly removed, and then there were a lot of dents in the surface of specimen. The uniform deformation elongation before geometrical instability is the combined consequence of the uniform deformation elongation before load instability and the deformation between load instability and geometrical instability.

3.2 Load instability and geometrical instability at testing temperature

The strains of load instability and geometrical instability can be obtained from the engineering stress–engineering strain curves of the two testing steel at various deformation temperatures. The strains of load instability and geometrical instability are shown in Figure 6. The load instability strains are about 0.1 and there is not marked variation as temperature and the geometrical instability strains increased. The geometrical instability strain consisted of load instability strain and the strain between load instability and geometrical instability. The result shows that the increase of strain between load instability and geometrical instability leads to the increase of geometrical instability strain, and it is the main part of geometrical instability strain.

4 Discussions

In literature [19, 20], high temperature compression test on Cr15Mn9Cu2NiN and Cr17Mn6Ni4Cu2N austenitic stainless steel were carried out in the temperature range of 950–1200 °C, in the strain rate regime of 0.01 to 2.5/s. The work hardening exponent *n* and strain rate sensitivity coefficient *m* of two steel were determined by the true stress–true strain curves which were obtained from the compression tests. Figure 7 shows the experimental values of *n* and *m* for the two steels as a function of the temperature. The values of *n* on the two steel do not change obviously with temperatures (about 0.10). The values of *m* for the two steel both increase with the deformation temperatures.

In high temperature deformation, the geometrical instability appears in the end of a period of macroscopic uniform deformation which occurs after load instability. Below the relation between instability strains which contain load instability and geometrical and material performance is determined.

Figure 8 shows that the experimental values of *n* and the load instability true strain with temperature for the two testing stainless steel. The load instability true strain

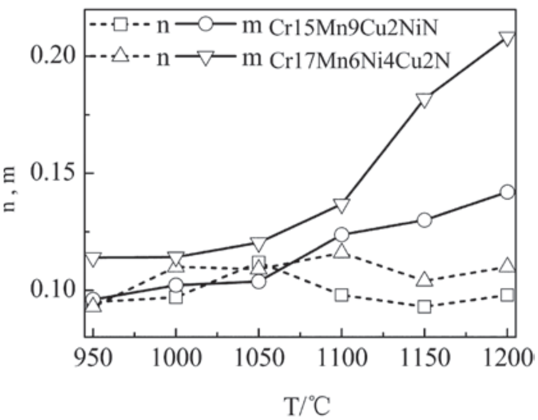

Fig. 7: Effect of temperature on *m* and *n* value

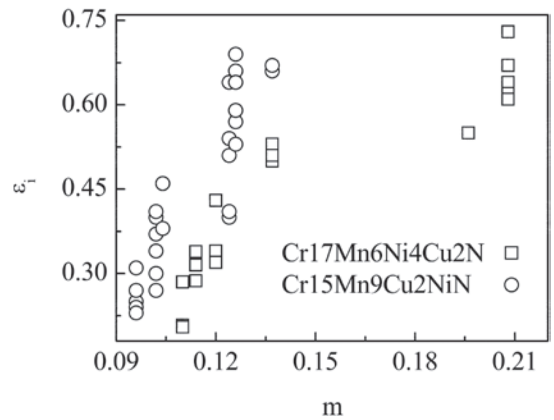

Fig. 9: *m* value and geometric instability strains

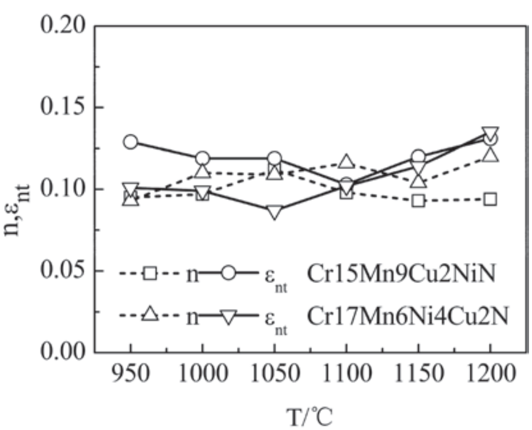

Fig. 8: The *n* value and necking true strains

is obtained by the formula $\varepsilon_T = \ln(1 + \varepsilon_E)$. The load instability true stains and the value of *n* are not obvious variance and the number values are about 0.1. The uniform deformation length of plastic material is controlled by the strengthening property in uniaxial tensile test [21, 22]. At room temperature, the deformation is uniform in tensile test and the relation of true stress–true strain can be represented by the formula $\sigma = k\varepsilon^n$. According to Considere's criterion, load instability true strain equals to the value of *n*. Similarly, at high temperature, the load instability true strain equals to the value of *n* too, and the uniform deformation length before load instability is dependent on the value of *n*.

Figure 9 shows the geometrical instability strain for the two steels as a function of the strain rate sensitivity coefficient *m*. The geometrical instability strains increase with temperature increasing, and the strains between load instability and geometrical instability also increase with temperature because the load instability strains have no variation with temperature. Because the strain rate sensitivity enhances at high temperature, the geometrical instability does not immediately occur but appears in non-uniform deformation after load instability. The strain rate sensitivity enhances and makes material strengthen, as soon as the non-uniform deformation appears in local region of specimens. The non-uniform deformation is moved from local region and the specimen keeps the macroscopic uniform state. This makes the geometrical instability not appear immediately and increases the uniform elongation of specimens after load instability.

The above analysis manifests that the load instability strain is dependent on the work hardening exponent *n*, and the strain between load instability to geometrical instability is dependent on the strain rate sensitivity coefficient *m*. The strain between load instability to geometrical instability increases with the value of *m* increasing, and the strain is the main part of geometrical instability strain.

5 Conclusions

The phenomenon that load instability and geometrical instability do not appear at the same time has been revealed by the uniaxial tensile test of plastic metal at high temperature. The load instability appears at maximum engineering stress and the geometrical instability occurs at the end of a period of macroscopically uniform deformation which occurs after load instability. The deformation of specimen is uniform before load instability, and the deformation is macroscopically uniform between load instability and geometrical instability in the gauge length. The uniform deformation length before geometrical instability consisted of the uniform deformation length of the two stages.

With the increase of deformation temperature, there is no evident variation for the load instability true strain and work hardening exponent n (about 0.1), and the geometrical instability strain and strain rate sensitivity coefficient m increases. It is indicated that load instability strain depends on work hardening exponent n and the strain between load instability to geometrical instability depends on strain rate sensitivity coefficient m. The strain increases with the increase of m and is the main part of geometrical instability strain.

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References

[1] F. Thovnik, F. VodoPivec and L. Kosec, Materiali in Tehnologije, 40(4) (2006) 129.
[2] M. H. Parsa, M. N. Ahmadabadi and H. Shirazi, Journal of Materials Processing Technology, 199(1–3) (2008) 304.
[3] J. N. Tarboton, L. M. Matthews, A. Sutcliffe, et al., Mate. Sci. Forum, 318–320 (1999) 777–784.
[4] R. Krieg, Nuclear Engineering and Design, 235 (2005) 199–212.
[5] Wlodzimierz Bochniak, Materials Science and Engineering A, 190 (1995) 81–86.
[6] H. Yao and D. G. Wang, Acta Mechanica Solida Sinica, 1(8) (1980) 77–84.
[7] Y. G. Kim and CH. Y. Lim, Metallurgical Transactions A, 19A (1988) 1625–1626.
[8] A. K. Ghosh, Metallurgical Transactions A, 8A (1977) 1221–1232.
[9] E. W. Hart, Asta Metallurgica, 16 (1967) 13–17.
[10] M. Brünig, Computer and Structure, 69(1) (1998) 117–128.
[11] L. Xue, Engineering Fracture Mechanics, 77 (2010) 1275–1297.
[12] S. Y. Yang and W. Tong, Experimental Mechanical, 49 (2009) 317–330.
[13] J. Jeschke, D. Ostermann and R. Krieg, Nuclear Engineering and Design, 241 (2011) 2045–2052.
[14] L. Y. Zeng, Y. Q. Zhao, D. K. Li and Q. Li, Jouranal of Aeronautical Materials, 26(5) (2006) 6–9.
[15] M. A. Burke and W. D. Nix, Acta Met., 23 (1975) 793–798.
[16] Y. Q. Song, Z. L. Suo, Z. P. Guan and Y. Liu, Acta Metallurgica Sinica, 42(4) (2006) 337–340.
[17] J. J. Joans and B. Baudelet, Acta Metallurgica, 25 (1977) 43–50.
[18] L. Zhu, R. Ma and G. Q. Hou, Journal of Plasticity Engineering, 17(4) (2010) 110–115.
[19] X. P. Zhang, Master's thesis, Lanzhou University of Technology, (2009) 19–22.
[20] Y. Y. Zhang, Master's thesis, University of Science and Technology Beijing, (2009) 45–47.
[21] A. K. Ghosh, J. Eng. Mater. Technol., 99(3) (1977) 264–274.
[22] R. Mahmudi, J. Mater. Process Tech., 37(1–4) (1993) 203–216.