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ARTICLE

Microstructure Evolution of SAF2205 Duplex Stainless Steel During Torsion Deformation at Elevated Temperature

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Abstract: Microstructure evolution of SAF2205 duplex stainless steel during torsion deformation was studied at elevated temperatures (600, 800 and 1000 °C). The results indicate that different degrees' recrystallization phenomena appear and the morphology of austenite is different for the deformed samples. The volume fraction of austenite decreases with the increase of deformation temperature. The fracture morphology of the deformed sample at 800 °C is quite different from that of deformed sample at room temperature. The ductile fracture occurs when the torsion is carried out at the room temperature. Also, the equiaxed and parabolic dimples are observed on fracture surface. However, the fracture morphology of the deformed sample at 800 °C is mainly covered by the intergranular fracture.

Key words: hot torsion; SAF2205 duplex stainless steel; microstructure evolution; fracture morphology

SAF2205 is a kind of stainless steel with ferrite and austenite microstructure, which has excellent toughness performance and good corrosion resistance to chloride corrosion concurrently[1-3]. Due to its excellent comprehensive properties, duplex stainless steels are used increasingly in marine, some petrochemical plants, oil refineries, the pulp and paper industries[4,5].

With the development of modern industry, the comprehensive properties of existing steels need to be improved. It is well known that the mechanical properties of steels are mainly determined by their chemical composition and microstructure[6]. And the phase distribution, morphology and grain size have a great influence on the strength, plasticity and toughness of the materials[6-9]. The strength and toughness of metal materials at room temperature will be improved with the grain refinement, so grain refinement is one of the most important and basic methods to control the microstructure and improve mechanical properties of metal materials. At present, the method of grain refinement has received extensive attention to prepare the new type high performance steels. And the method of grain refinement can be divided into alloy method, heat treatment and deformation heat treatment. Torsion deformation is a kind of plastic deformation mode which can refine the grain of the material, change the phase distribution and morphology. However, the accumulation of plastic deformation of the material is limited under the pure torsion deformation. Therefore, torsion deformation is usually combined with other techniques to achieve the severe plastic deformation (SPD), which is an emerging plastic deformation method well-investigated for producing ultrafine grained (UFG) metals[6,10]. Compared with the conventional materials with coarse grains, the SPDed material exhibits unique and excellent properties such as high strength and toughness[11]. For instance, high pressure torsion (HPT) combines torsion with the high pressure to make the deformation uniform, reduce the deformation resistance and increase the accumulated plastic strain[6,12]. The torsion extrusion (TE) technique uses a kind of twisted channel mould with diamond cross section in torsion process to get UFG metals[13-15]. Due to its enormous contribution to grain refinement, the torsion deformation has been paid extensive attention to.

In addition, metal materials exhibit a better thermal processing performance at higher temperature and higher strain rate[16,17]. When the temperature reaches a certain point,

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dynamic recovery and dynamic recrystallization of metal materials appear frequently[18-21]. Therefore, it is expected that high temperature can resolve the problem of the insufficient deformation at room temperature, change the phase distribution and morphology effectively. Furthermore, the effect of the friction between the specimen and the deformation tool, and the internal non-uniform temperature of the specimen caused by the heat transfer can be eliminated by the torsion deformation[17], which is of great significance to explore the grain refinement. The effect of deformation strengthening and heat treatment strengthening can be simultaneously played by the effective combination of deformation and heat treatment processes. This combined strengthening process is called thermomechanical treatment, which is very effective to obtain the billets with high strength and plasticity. In fact, some scholars have studied the deformation behavior and mechanisms of the metals by HPT. For example, some studies had been done on the microstructure evolution of aluminum alloy under hot torsion by Misiolek[22]. P. Jian had studied hot deformation behavior of ME21 magnesium alloy under hot torsion[20]. And some people had explored the deformation behavior of Al-Li alloy under high temperature torsion[23]. However, the microstructure evolution of every single phase during high temperature torsion for multiphase alloy has not get extensive attention. Therefore, this paper presents the results of microstructure evolution of ferrite and austenitic during hot torsion using the SAF2205 dual phase steel.

1 Experiment

The SAF2205 dual phase steel was produced by Sandvik company. The material was supplied in the hot worked condition and it conformed to the standard (ASTM-A276). The nominal chemical composition is given in Table 1. The geometrical dimensions of torsion sample are shown in Fig.1a. And the torsion tests were conducted by the XC-10 wire torsion testing machine with the torsion speed 30 r/min at 600, 800 and 1000 °C. The samples were heated by high frequency induction heating (HD-40 kW), and the temperature was controlled by infrared temperature measurement (STB-42). When the temperature reached the experimental temperature, the torsion tests were conducted immediately. During high temperature torsion, the middle part of sample was wrapped by induction coil, as shown in Fig.1b. When the samples were twisted to fracture, the samples were quenched in water quickly[24].

For each of the deformed samples, the sampling location for microstructure observation (the length of 5 mm) was taken from the fracture end using the wire electrical discharge machining (WEDM), as shown in Fig.1c. The microstructure of each sample was characterized along the transversal section (T) and different longitudinal sections (L_1 and L_2), as shown in Fig.1d. And the chemical etchant used on the samples was a kind of solution of 5 g $FeCl_3$, 50 mL HCl and 100 mL H_2O. The corrosion time was about 15 s. After that, the optical microscope (OLYMPUS/PMG3) was used for the microstructure observation. The fracture surface morphology of samples was observed by a scanning electron microscope (SEM, MIRA3 TESCAN).

2 Results and Discussion

2.1 Microstructure evolution analysis

The metallographs of deformed samples at 600 and 800 °C are shown in Fig.2b, and 2c. And Fig.2a shows the microstructure of undeformed sample. It can be seen from Fig.2a that large number of equiaxed grains are distributed on T direction. The austenite is distributed uniformly on the ferrite matrix[24,25] and its average grain size is about 5 μm. The volume fraction of austenite is approximately equal to ferrite, which occupies about 50%. The direction indicated by the black arrow in L_1 and L_2 is the axial direction of the specimen, as shown in Fig.1d. From the observation of L_1 and L_2, the band-shaped austenite microstructure structure is distributed in continuous ferrite matrix for undeformed sample, which may be related to its processing state. Similarly, the volume fractions of austenite and ferrite are about the same. After torsion deformation at 600 °C, the average grain size of the austenite increases to about 15 μm on T direction, as illustrated

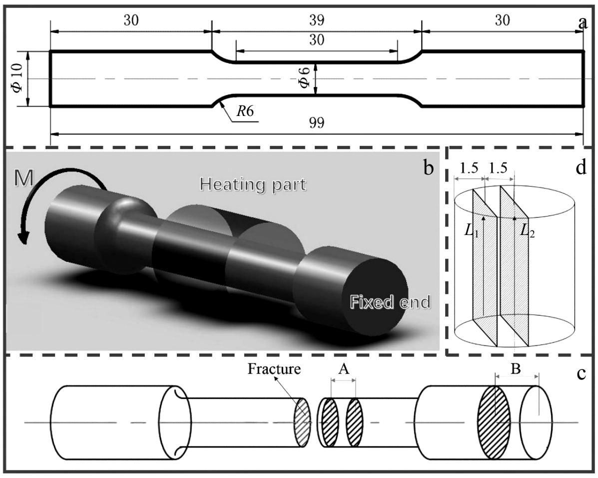

Fig.1 Geometrical dimensions of torsion sample (a), the schematic diagram of high frequency induction heating (b), the sampling location for deformed samples (c), and the positions for microstructure observation, L_1 and L_2 is the axial direction (d)

Table1 Nominal chemical composition of SAF2205 duplex stainless steel (wt%)

C	Mn	Si	S	P	Cr	Ni	Mo	N	Fe
≤0.03	≤2. 00	≤1.0	≤0.02	≤0. 03	21.0~23.0	4.50~6.50	2.50~3.50	0.08~0.20	Bal.

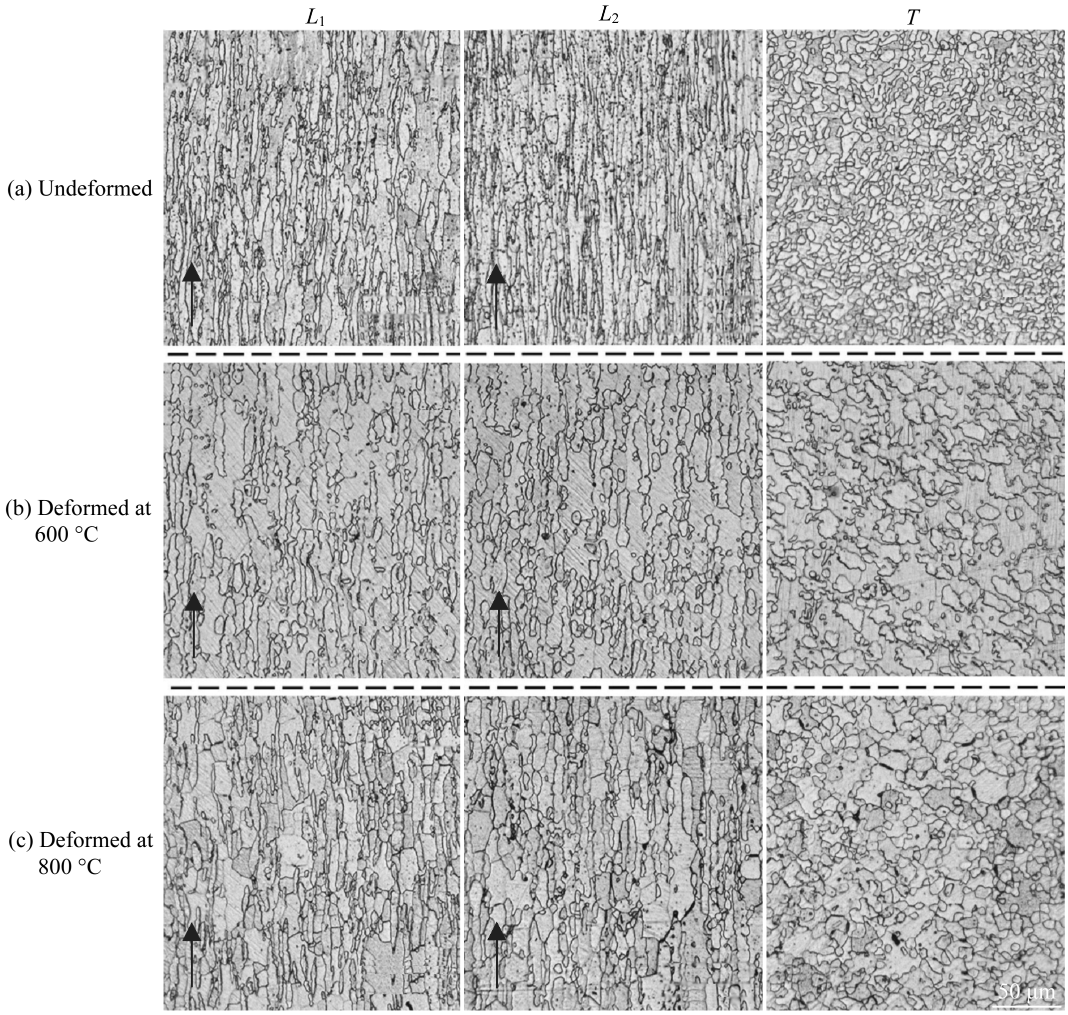

Fig.2 Microstructures of undeformed sample (a), deformed sample at 600 °C (b) and deformed sample at 800 °C (c) (T-radial direction, L_1 and L_2-the axial direction)

in Fig.2b. Also, the average grain size of ferrite is more than 25 μm. Lots of equiaxed fine grains appear around the large grains. It is supposed that the dynamic recrystallization occurs in the austenite phase under this condition[26]. Meanwhile, the proportion of austenite phase decreases slightly on T direction in Fig.2b compared with that in Fig.2a. The banded austenite microstructure structure is replaced by short rod-shaped microstructure structure on the L_1 and L_2, as shown in Fig.2b. The degree of grain elongation is weakened owing to introduction of torsion shear stress. Similarly, some fine grains appear around some large grains and the proportion of ferrite increases. In general, the ratio of the austenite to ferrite has not changed apparently compared with the undeformed sample. And the phenomenon of grain growth indicates that the softening mechanism caused by dynamic recrystallization appears.

When the torsion test is carried out at 800 °C, the microstructure on T, L_1 and L_2 direction is similar to that at 600 °C, as shown in Fig.2c. In Fig.2c, the grain size of austenite becomes large and the number of fine produced austenite grains increases on T direction in contrast to Fig.2b. Besides, the morphology of the austenite grains approaches to equiaxed shape and their proportion decreases. Therefore, parts of austenite microstructure may transform to ferrite microstructure. In fact, the transformation temperature of austenite to ferrite is about 890 °C[27], but the introduction of distortion energy caused by torsion may decrease the phase transition temperature[28,29]. Meanwhile, the grain with large size may be attributed to the recrystallization at higher temperature. Similarly, it is observed from Fig.2c that the austenite and ferrite grains on L_1 and L_2 direction are elongated again.

When the torsion test is carried out at 1000 °C, the coarsening phenomenon of ferrite microstructure is observed from Fig.3a. And the microstructure shows the characteristics of Widmanstatten structure on T direction, as is shown in

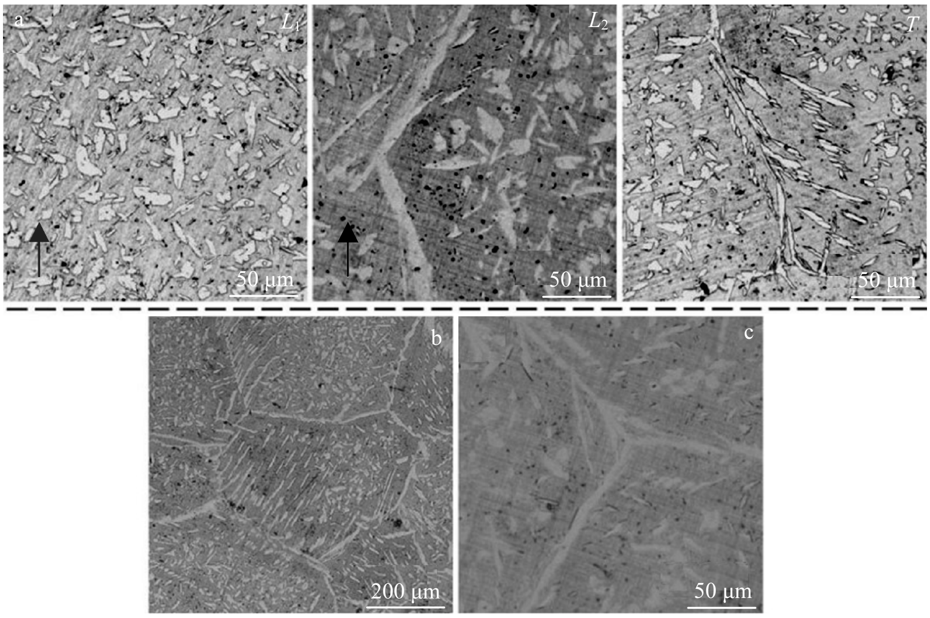

Fig.3 Microstructure of deformed sample at 1000 °C (a), global microstructure in L_2 (b), and its local amplification (c)

Fig.3a and Fig.3b [24]. The long strip shaped, banded, rod-shaped and equiaxed austenite microstructure structure coexist on *T*, L_1 and L_2 direction, as shown in Fig.3a. The volume fraction of the continuous ferrite increases dramatically compared with that in Fig.2a and Fig.2b. The occurrence of recrystallization makes the austenite grain grow up unusually, as shown in Fig.3b. However, quantities of more fine grains are distributed in the coarse austenite grains, which are attributed to the grain refinement caused by dynamic recrystallization[30]. Similarly, the mechanisms of refinement and coarsening compete, so the austenite microstructure with different grain sizes coexists.

2.2 Fracture analysis

The morphological features of fracture surfaces are observed by SEM. Fig.4a shows the fracture morphology of the deformed sample at room temperature. It is clear to see that the equiaxial and parabolic ductile dimples cover the whole fracture surface. It is inferred that microscopic voids

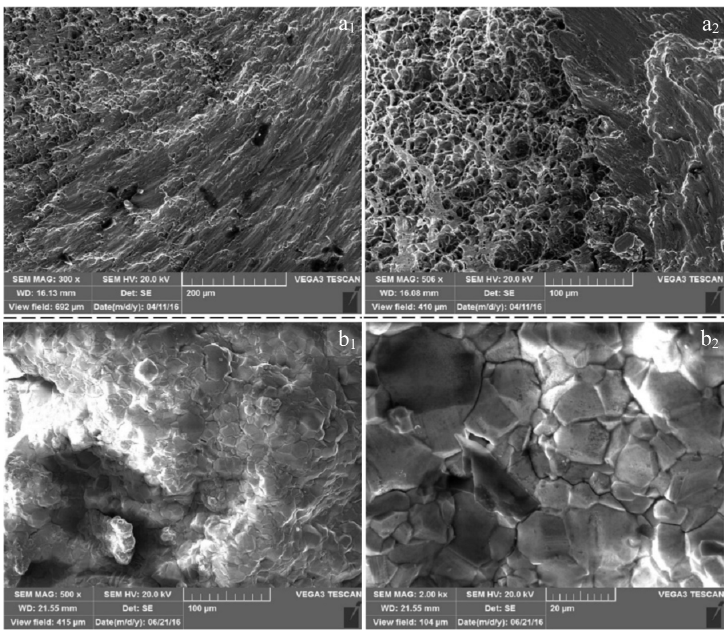

Fig.4 Fracture morphologies of the deformed sample at room temperature (a_1, a_2) and 800 °C (b_1, b_2)

are formed at the separation part between inclusion (or second phase particles) and matrix interface. And the micro voids are connected with each other until fracture, which leads to the formation of the fracture morphology[31-33]. It can be seen from Fig.4a that the fracture mode belongs to ductile fracture. The torsion track can be seen easily from Fig.4a_1. Parabolic and equiaxed dimples are observed on fracture surface, as shown in Fig.4a_2. The dimples with different types and sizes are attributed to torsion gradient stress distribution[31].

Fig.4b shows the fracture morphology of the fractured sample at 800 °C. The fracture morphology in rock candy and the grain in polygon shape are shown in Fig.4b_1 and Fig.4b_2, which indicates that intergranular fracture occurs [34]. It is inferred that lots of energy is accumulated at the grain boundaries due to the effect of thermal stress under high temperature conditions. And then the brittle sediments precipitate along the grain boundaries. Accordingly, intergranular fracture tends to occur in the material. It indicates that the plasticity of the material is reduced partly under hot deformation condition. The grain size of the rock candy is diverse in Fig.4b_2. It can be explained from the previous analysis of microstructure. When the temperature reaches 800 °C, obvious recrystallization phenomenon appears, so the grain size is not uniform and some of the grains become large, which intensifies the formation of intergranular fracture. Besides, a small amount of tear ridges and tongue pattern can be found in Fig.4b_1, which shows the feature of transcrystalline fracture. And it can be seen from Fig.4b_1 that traces of torsion appear around a large hole and the grain boundaries become curved. In general, the fracture mode is not a single type but the mixture of intergranular and transcrystalline fracture, and the former mode dominates.

3 Conclusions

1) The grain shape of SAF2205 duplex stainless steel changes obviously and the grains grow up in different degrees due to the appearance of dynamic recrystallization at different temperatures during torsion.

2) The volume fraction of austenite microstructure decreases gradually with the increase of torsion temperature for the austenite transforms to ferrite.

3) The fracture morphology at room temperature is a typical ductile fracture, and equiaxed and parabolic dimples are observed on fracture surface. The fracture morphology is mainly characterized by intergranular fracture when torsion test is carried out at 800 °C.

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SAF2205 双相不锈钢在高温扭转变形条件下的组织演化

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摘　要：研究了 SAF2205 双相不锈钢在高温（600，800 和 1000 ℃）扭转变形条件下的微观组织演化。微观组织演化的结果表明，不同程度的再结晶现象出现，对应变形试样中的奥氏体的形貌不同。奥氏体的体积分数随着变形温度的增加而减少。800 ℃扭转条件下的试样断口形貌和室温下试样断口形貌有很大差异，实验结果表明，当扭转在室温条件下进行时，断口形貌呈现韧性断裂特征，等轴状和抛物线状的韧窝分布在断面上。然而，在 800 ℃条件下扭转的试样的断口形貌主要呈现出沿晶断裂特征。

关键词：热扭；SAF2205 双相不锈钢；微观组织演化；断口形貌

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