CAPÍTULO 8

MICROSTRUCTURE AND PLASTIC FLOW OF DUPLEX STAINLESS STEEL IN HOT TORSION TEST

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Jean Robert Pereira Rodrigues

Antônio Santos Araujo Júnior

José Roberto Pereira Rodrigues

Wellinton de Assunção

Fernando Lima de Oliveira

Moisés dos Santos Rocha

Sebastião Raimundo de Jesus Belém Leitão Filho

Fabio Alejandro Carvajal Florez

ABSTRACT: duplex stainless steels are used in many industrial applications due to their combination of mechanical properties and resistance to corrosion. The hot deformation of these two-phase materials is still a critical issue due to the different mechanical responses of austenite and ferrite, which often lead to the appearance of imperfections. In this paper, the duplex stainless-steel DIN W. Nr. 1.4462 has been subjected to hot torsion tests with deformation rates of 0.3 s^{-1}, 0.5 s^{-1}, and 1 s^{-1} at temperatures of 1000 °C and 1150 °C. The microstructural changes produced as a consequence of the different test conditions were analyzed by optical microscopy. The characteristics of the plastic flow curves have been interpreted in terms of the localized flow parameters as a mechanism for accommodating deformation during the hot torsion. As a result, two types of microstructures have been obtained in which austenite particles appear by percolating the ferrite matrix in the case of cold rolled steel and disperse in the case of heat-treated steel at 1250 °C for 1 h. Each of these types of microstructure presented characteristic plastic flow curves and microstructural behavior in which it was evidenced the occurrence of the phenomenon of localized plastic flow in both cases, only for the deformation rates below 1 s^{-1}.

KEYWORDS: Industrial applications; Steel; Microstructure; Deformation rates.

INTRODUCTION

The development of new materials, in order to meet the demands of the accelerated pace of technological advances that are present today, has become a necessity in the centers of technological research. This trend forces professionals in this area to seek solutions that respond to the needs that arise from different sectors of the industry, which has sought to improve its production process at all levels (Momeni et al. 2014).

Studies in metal processing have been seeking optimization in production methods through scientific and technological development to understand more deeply the microstructural behavior of these materials during their processing, in order to better control their properties. The investigation of these aspects often becomes impractical to be carried out in the industry itself due to the dimensions of the equipment and materials involved in the process. The solution is to use laboratories where it can be executed experiments that simulate the stages of industrial processing and thus allow the control of the parameters involved (Soares et al., 2017).

Traction, compression and torsion tests have been used with some frequency in the simulation of industrial operations such as lamination, forging and extrusion. The hot torsion test has been one of the most used by scientists, because of the advantages of using a test body with geometry that undergoes little variation with torsion, allowing large levels of deformation. This type of test also makes it possible to monitor microstructural evolution throughout the deformation process by means of interrupted tests, in addition to the ability to simulate industrial processes with multi-pass tests, allowing variation in deformation rates and temperature during the test (Traphöner et al., 2018).

Often, the execution of these tests faces difficulties related to the chemical composition of the material as well as its microstructural characteristics, as in biphasic steel. In these kinds of steel, the combination of two phases with different properties makes the relationship between the mechanisms involved in hot processing more complex (Li and Gao, 2020).

A specific case of two-phase steel is the duplex stainless steel, which has features an excellent combination of mechanical strength and corrosion resistance. However, they need special care during hot mechanical processing, due to the existence of an area of low ductility during the execution, which may compromise the final and expected properties (Patra et al., 2016).

Faced with these demands, this study aims to study the correlation between the microstructure and the plastic runoff of the duplex DIN W stainless steel. Nr. 1.4462, when subjected to hot work by means of torsion tests, with the application of metallurgical parameters for the verification of the occurrence or non-occurrence of the flow phenomenon located in the ferritic matrix.

MATERIAL AND METHODS

The workpiece material used in the experiments was DIN W. Nr. 1.4462 duplex stainless steel in the form of cylindrical bars (diameter 110 mm and length 230 mm). Table 1 shows the chemical composition of this steel.

C	Si	Mn	Cr	Mo	Ni	P	S	N	Fe
0,037	0,48	1,80	22,2	3,03	5,58	0,22	0,002	0,12	base

Table 1 - Chemical composition of DIN W. Nr. 1.4462 duplex stainless steel (%weight)

After the tests, the samples were prepared for microstructural observation, in which they were taken from the test bodies in order to obtain the best use of the usable area. Considering that the tension, deformation and deformation rate vary along the radius of the cross-section of the test body, it is usually used only a thin layer, close to the surface, for microstructural analysis. Therefore, observations were made on the external surface of the samples, Fig. 1.

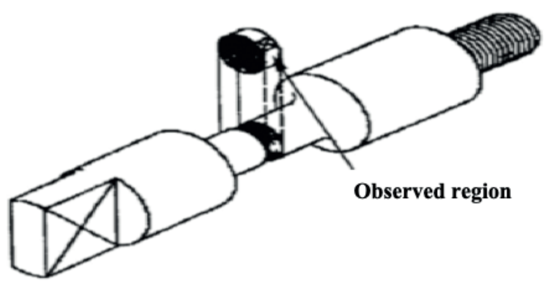

Figure 1 - Indication of the cut in the useful part of the sample and region and to be observed

The steps of preparation of the samples for metallographic observation and analysis were carried out from the cutting of the usable part of the test body. The material removed was embedded in bakelite and sanded using sandpaper 180, 240, 320, 400, 600, 1200, and 2000. The samples were polished with chromium oxide in a polisher until a mirrored surface was obtained. The microstructure was revealed by chemical attack with a reagent called Behara II, whose chemical composition contains 40 ml of distilled water, 20 ml of hydrochloric acid, 2.4 g of ammonia bifluoride and 0.6 g of potassium bisulphite.

The production of the microstructures was carried out with the aim of scanning the entire surface of each sample, obeying an alignment criterion, where the lower lateral edge of the visible part of the embedded samples was arranged parallel to the lower lateral edge of the microscope tray, allowing the monitoring of the microstructural evolution relative to the deformations performed in the test bodies. This methodology made it possible to select the images that best represent the microstructural behavior, where it was possible to filter the images that presented some type of flaw relative to the phases of sanding, polishing, and chemical attack.

The hot torsion tests were carried out on a horizontal hot torsion test machine connected to a computerized data acquisition system, as shown in Fig. 2. A radiation furnace of maximum power of 6 kW was used, in which the test bodies were involved by a quartz tube, within which the argon gas circulates, to protect against oxidation. Through this tube, water is injected at the end of each test to “freeze” the microstructures.

Figure 2. Hot torsion test machine

The equivalent stress-deformation ratio is used to provide material responses to mechanical stress. Measures of the rotation angle carried out by the rotation transducer shall be used to calculate the deformation and deformation rate. The rotation angle of the machine is calculated by Eq. 1.

$$\theta = \frac{2\pi}{90} \cdot l \qquad (1)$$

Being *l* the reading registered.

For equivalent deformation by Eq.2.

$$\varepsilon = \frac{R \cdot \theta}{\sqrt{3} \cdot L} \qquad (2)$$

where,

θ is the rotation angle;

R e L are the radius and the useful length of the specimen;

where *L* is the useful length of the test body. The deformation rate shall be calculated by dividing the deformation by the total test time. The equivalent voltage is calculated by Eq. 3.

$$\sigma = \frac{\sqrt{3} \cdot M}{2 \cdot \pi \cdot R^3}(3 + m + n) \qquad (3)$$

Where:

M is the applied torque;

R e L are the radius and the useful length of the specimen;

The coefficients m and n represent the material's sensitivity to changes in strain rate and strain, respectively;

In which *M* is the twisting moment, *R* is the test body radius and *m* and *n* are the material's coefficients of sensitivity to the deformation rate and to the hardening, respectively, where *n* is the coefficient that is related to the inclination of the *ln m x ln θ* curve. The coefficient of sensitivity to the deformation rate is determined by the inclinations of the curve *log m x log ε* (Traphöner et. al., 2018; Soares et. al., 2017; Jonas et. al., 2013).

Initially, five isothermal and continuous torsion tests were carried out until fracture. These tests were carried out in heating as shown in Fig.3 with hot and cold rolled steel. In both cases, the tests were carried out at a temperature of 1150 °C with a one-minute soaking time, following a sequence of deformation rates of 0.3 s^{-1}, 0.5 s^{-1} and 1.0, s^{-1}. The purpose of these tests was to reveal a percolated microstructure and to show plastic flow curves with characteristics that would allow the calculation of flow indication parameters located in the samples tested.

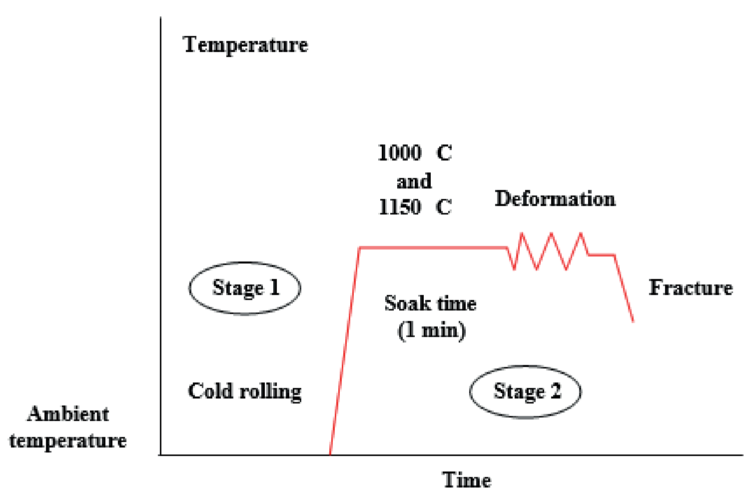

Figure 3. Schematic representation of cold rolled steel tests.

RESULTS AND DISCUSSION

Figure 4 shows the initial and final microstructures for the test carried out in heating at 1150 °C from the cold rolled material, the test body of which has been kept at this temperature for 1 min and then deformed by hot twisting at a rate of 0.3 s^{-1} until fracture.

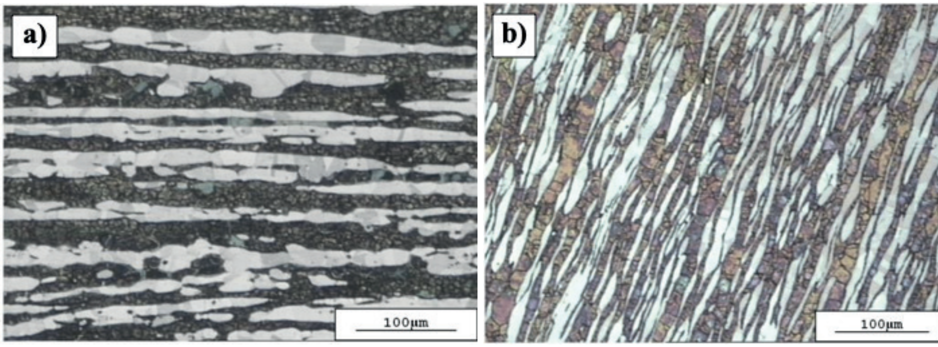

Figure 4. Relative microstructures for the test carried out at 1150 °C with a deformation rate of 0.3 s^{-1} and deformed until fracture using cold rolled steel, where (a) represents the initial microstructure before deformation and (b) represents the final microstructure deformed fracture $\varepsilon f=2.2$

It is possible to see in the initial microstructure that austenite appears in the form of plates aligned with the direction of lamination, while in the final microstructure the austenite plates align with the direction of deformation, becoming fragmented.

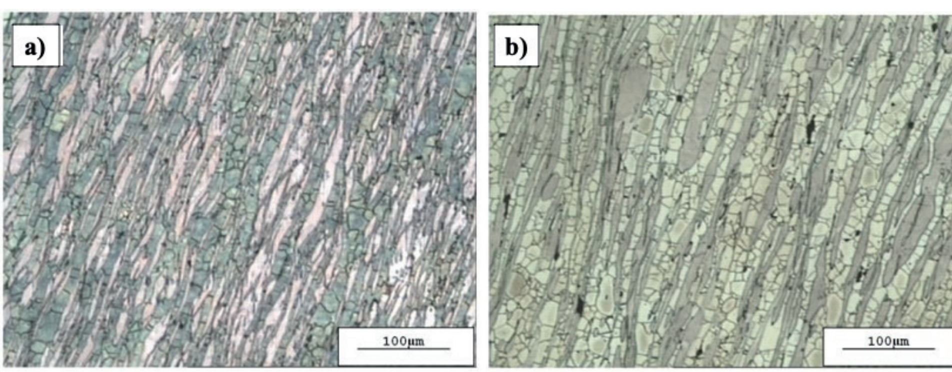

Figure 6. Microstructures for tests performed at 1150 ° C with deformation rates of (a) 0.5 s^{-1} and (b) 1 s^{-1} using cold rolled steel deformed $\varepsilon f = 3.0$ and $\varepsilon f = 2.5$, respectively

Figure 6 shows the set of plastic flow curves obtained in experiments with cold rolled steel. It is observed that the tension increases with the deformation imposed until it reaches a maximum point, then decreases until rupture, denoting a typical behavior of metallic materials, in which the curves have a hardening region, followed by softening after a peak of tension. There is also a long hardening region up to the peak and an extensive region of softening after the peak. The difference between peak voltage and initial flow voltage is not so marked.

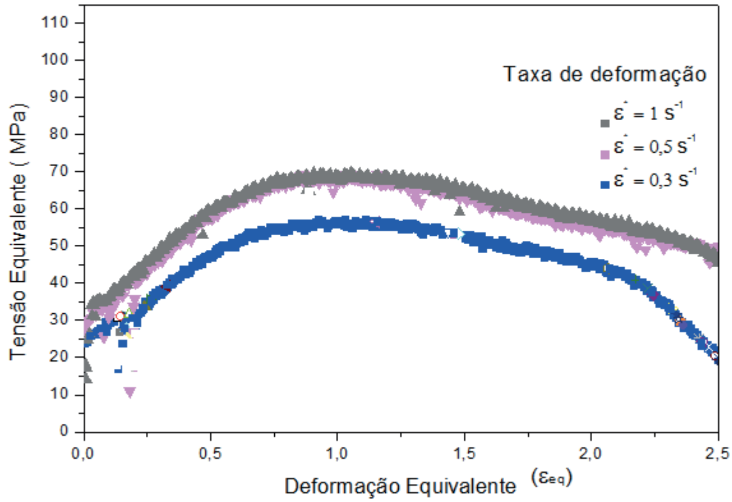

Figure 6. Plastic flow curves from tests performed at 1150 ° C with deformation rates of 0.3 s^{-1}, 0.5 s^{-1} and 1 s^{-1} using cold rolled steel.

Tests performed at 1000 °C with a deformation rate of 1 s^{-1} using cold rolled steel were intended to complement studies on the occurrence of plastic instability or localized flow in tests performed at 1150 ° C. Figures 7 to 8 show, respectively, the plastic flow curves and the microstructural evolution referring to these tests, where test bodies made from cold rolled steel were used. In this case, the temperature of 1000 °C and a deformation rate equal to 1 s^{-1} were used, generating higher peak voltages than those of the tests made with the same steel at 1150 °C also with a rate of 1 s^{-1}.

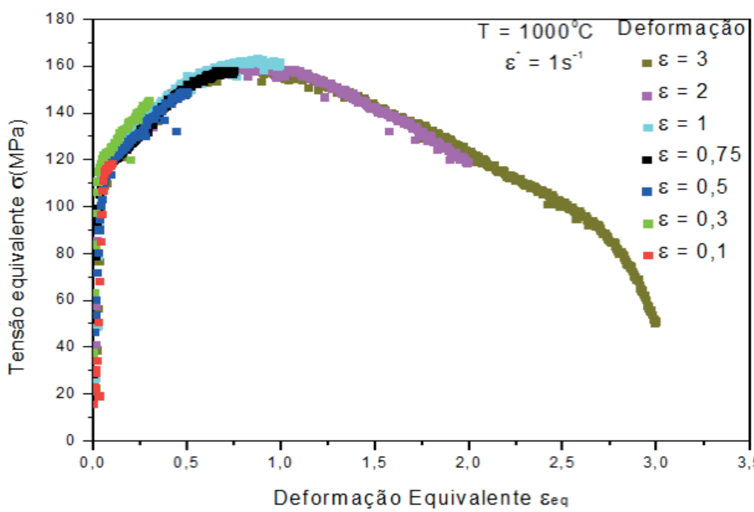

Figure 7. Curves and microstructures for tests conducted at 1000 °C with a deformation rate of 1 s^{-1} using cold rolled steel

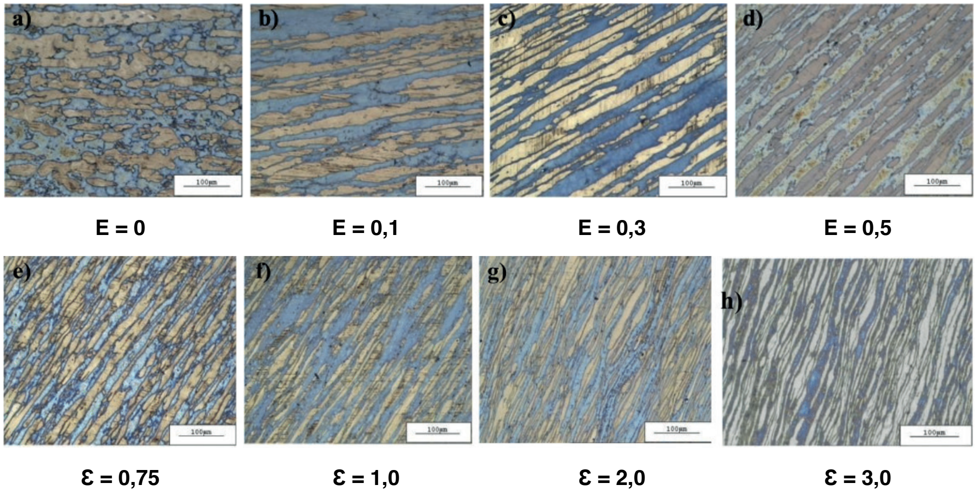

Figure 8 - Cold rolled duplex stainless steel microstructures with different deformations; test temperature 1000 °C and deformation rate 1 s^{-1}

The ferritic phase is more ductile than the austenitic phase when subjected to the hot deformation under similar conditions. It is also known that the starting stresses of plastic flow from ferrite and duplex steel are close, indicating that in the case of duplex, the deformation is concentrated in the ferritic matrix at the beginning of the test, leading to the occurrence of flow located there, which is softer than in the austenitic phase (Kingklang and Uthaisangsuk, 2017). Such a phenomenon can be observed by analyzing the microstructures shown in Figures 2 and 3, where distortions with a winding aspect can be noticed, indicating the occurrence of flow located in this stage of deformation.

CONCLUSIONS

The experiments carried out in this study led to the following conclusions:

- Tests using different initial microstructures have shown that the behavior of the plastic flow curves is influenced by the initial disposition of austenite particles in the ferritic matrix and metallurgical parameters.
- It has been observed and quantified that for the microstructure with austenite roughly dispersed and percolated from duplex stainless-steel DIN W. Nr. 1.4462, heat-treated at 1350 °C and tested at 1150 °C occurred the flow phenomenon located at the rates of 0.3 s^{-1}, 0.5 s^{-1}, 1 s^{-1}, 3 s^{-1}, and 5 s^{-1}.
- It has been observed and quantified that for the microstructure with austenite roughly dispersed and percolated from duplex stainless steel DIN W. Nr. 1.4462, heat-treated at 1250 °C, tested at 1150 °C and deformed with deformation rate below 1 s^{-1}, the phenomenon of the localized flow occurred.

- It has been observed and quantified that for the microstructure with austenite roughly dispersed and percolated from duplex stainless steel DIN W. Nr. 1.4462, heat-treated at 1250 °C, tested at 1150 °C and deformed with deformation rate below 1 s^{-1}, the phenomenon of the localized flow occurred.
- It has been observed and quantified that for the microstructure with percolated austenite from duplex stainless steel DIN W. Nr. 1.4463, heat-treated at 1350 °C and tested at 1000 °C it didn't occur the phenomenon of localized flow at the rates of 0.3 s^{-1}, 0.5 s^{-1}, 1 s^{-1}, 3 s^{-1}, and 5 s^{-1}.
- The tension drop after the peak, observed in the plastic flow curves, is related to the occurrence of flow located in the ferritic matrix associated with the fragmentation of the austenite particles during processing, as well as the phenomena of dynamic recovery and recrystallization, typical of duplex stainless steels.
- There has been the emergence of cavities in triple and parallel junctions of the interfaces of the austenitic and ferritic phases as a consequence of the accumulation of deformation in them.

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AUTHORAL RESPONSIBILITY

The authors are solely responsible for the content of this article.

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