DAMAGE FORMATION OF A 2304 DUPLEX STAINLESS STEEL UNDER HOT WORKING CONDITIONS

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ABSTRACT

The duplex stainless steels are materials, which present a better combination of mechanical properties and stress corrosion resistance than ferritic and/or austenitic stainless steels. However, in the processing of these materials, hot working is a critical step that leads in many cases to the generation of cracks and/or to an unacceptable surface finish.

In the present work, it has been observed that severe localisation of plastic flow into superficial shear bands is the responsible for transversal cracking during hot rolling of duplex stainless steels. Torsion is a deformation mode involving pure shear and it has been found to be very useful in tackling the problem of damage formation in these materials under hot working. The effects of the strain, temperature and the strain rate on the damage formation in duplex stainless steels have been analysed in order to improve the hot workability of this material. Microstructural observations reveal that cracks mainly concentrate at the ferrite/austenite interface. A relationship between the damage fraction and the deformation conditions has been determined.

INTRODUCTION

The hot rolling process of plastically deforming metal is the most widely used metalworking process because it leads itself to high production and close control of the final product. However, the hot industrial rolling of duplex stainless steels present, very often, severe crack formation and finishing problems due to the appearance of superficial defects, known as “slivers” [1].

In forming processes, which require large deformations, localisation of plastic flow into shear bands can become an important deformation mechanism. Shear bands are regions where plastic deformation in a material is highly concentrated. The formation of these shear bands is extremely important in fabrication processes of materials because they often are precursors to fracture and limit ductility and toughness. They can form in forging and rolling operations with effects on the final properties [2].

The poor hot ductility of a 2304 duplex stainless steel, under hot working conditions, has been related directly to the difference on strength of both phases ferrite and austenite and the nature of the δ/γ interface, among others [3]. The superficial finishing quality of these materials after hot rolling also depends on the dynamic and static microstructural changes which take place during the deformation. These factors are of critical importance on the hot rolling of these biphasic materials. The softening of the hard austenite during hot deformation of duplex stainless steels is an important requirement to guarantee a good hot ductility of such materials. In previous works, it has been seen that dynamic recrystallisation of austenite has not taken place at temperatures ranging from 1000 to 1200ºC and at a strain rate of 1 s^{-1} to a strain of 1.6 [3, 4] and austenite static recrystallisation is hindered with respect to a fully austenitic stainless steel specially at low temperatures (T=1000ºC) [5]. The lack of softening processes and the high strain rates in the industrial rolling allow non-uniform straining and shear bands may develop [1]. In the present work, it has been observed that severe localisation of plastic flow into superficial shear bands is responsible for transversal cracking in duplex stainless steels. Torsion tests have been found to be a useful tool in tackling the problem of ductility encountered in hot industrial rolling.

EXPERIMENTAL

A duplex stainless steel with a composition shown in Table I and supplied by CSM (Rome) in the as-cast and as-wrought conditions (77% reduction) with austenite volume fractions close to 65% and 50% respectively has been used in the present work. Solid torsion specimens were machined out from the as-cast and wrought materials and the corresponding tests were carried out, as described elsewhere [6].

To estimate the initial shear strain at which surface cracks appear at 1000ºC, torsion tests have been carried out at strain rates of 1.1 and 5.4 s^{-1}. The strain on the specimen surface, for the different tests, was 1.6, 0.9 and 0.5 for the first strain rate and 1 for the second. These samples were also immediately water quenched, cross-sectioned, polished and etched by conventional methods. The damage has been determined, in each sample, at different radii, and therefore at different interior conditions (strain rate, strain and stress), by quantitative metalography.

TABLE I

CHEMICAL COMPOSITION, WT-%.

Cr	Ni	Mo	Mn	C	N
23	4.8	0.22	1.3	0.025	0.095

RESULTS AND DISCUSSION

The duplex stainless steels present, very often, a poor hot workability which leads to the formation of defects during its industrial hot rolling. This damage formation can be detected at the exit of the roughing mill as superficial cracks perpendicular to the rolling direction, as can be seen in Figure 1, or at later stages.

Figure 2 shows the microstructure of the steel, on the rolling plane, just under the external surface. A complex microstructure can be observed, like some regions denoted by A, where an intense localisation of the deformation is clearly apparent.

On deforming metal between rolls, the material is subjected to high compressive stresses and to surface shear stresses as a result of the friction between the rolls and the metal [7]. As a consequence of such shear stresses, localisation of plastic flow into shear bands constitutes an important surface deformation mechanism. This can explain the observed behaviour of the duplex stainless steel close to the surface and the occurrence there of shear bands formation. In rolled materials, shear bands have been reported to occur at ≈35º to the rolling plane [8]. The shear bands have been observed in the present steel to concentrate at the surface and not to penetrate deeply into the interior of the slab, as can be seen in Figure 3. This result agrees with the predictions of the FEM rolling models [1] in the sense that the outer layer of the material under the rolls undergoes the maximum shear. In the case of a duplex stainless steel it is to be taken into account, additionally, that the presence of two phases with significantly different mechanical properties [9,10] has an important effect on the heterogeneous distribution of the deformation [3].

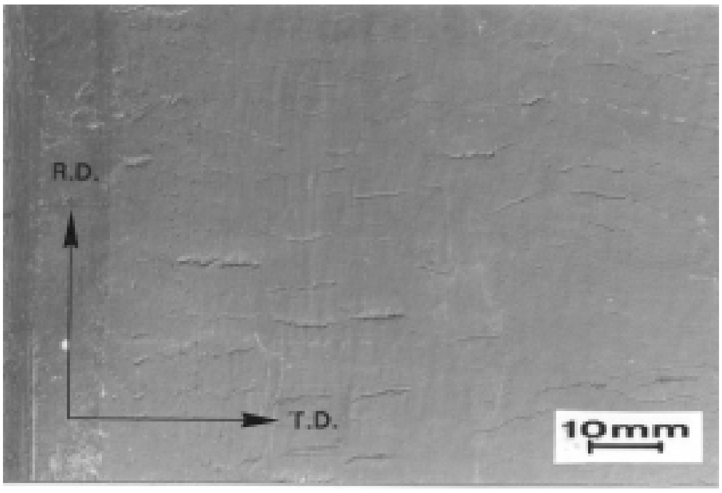

Figure 1: Aspect of the surface defects at the exit of the roughing mill on the rolling plane.

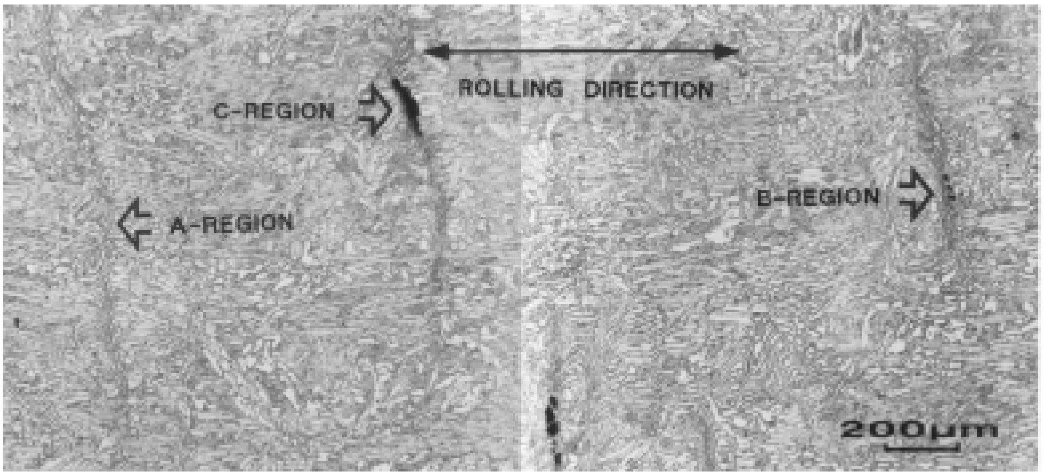

Figure 2: Microstructure of the steel on the rolling plane.

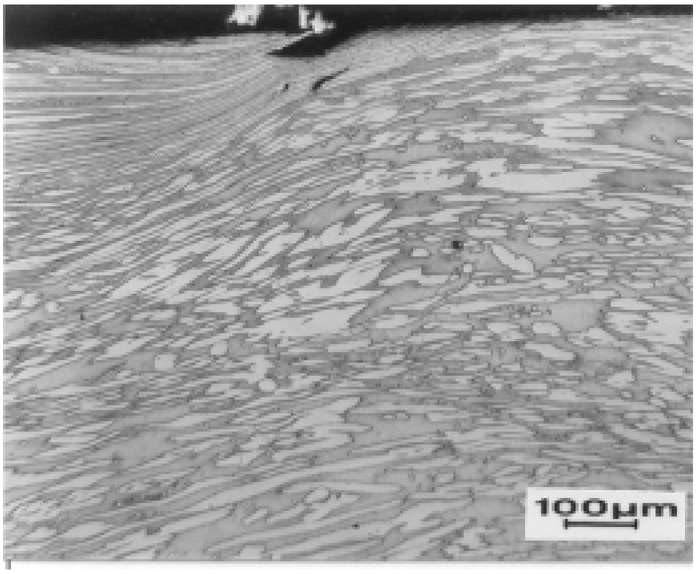

Figure 3: Microstructure of duplex stainless steel, in the longitudinal section, showing a shear band with crack formation.

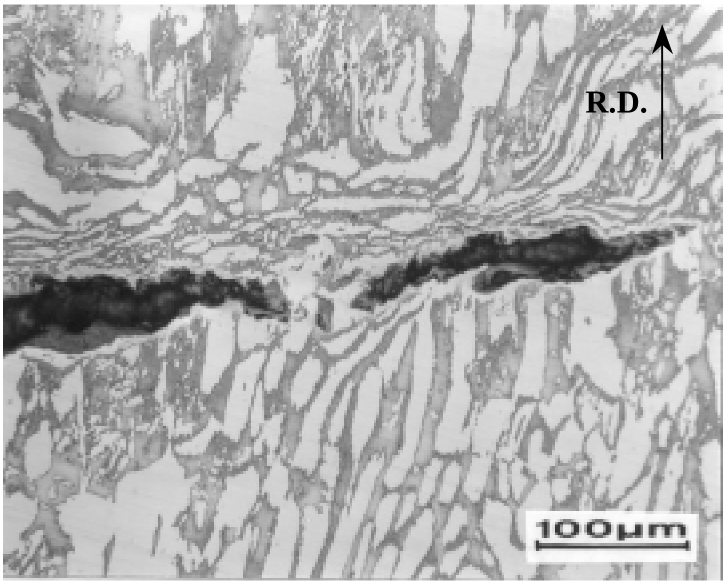

Figure 4: Microstructural details around a surface crack on the rolling plane.

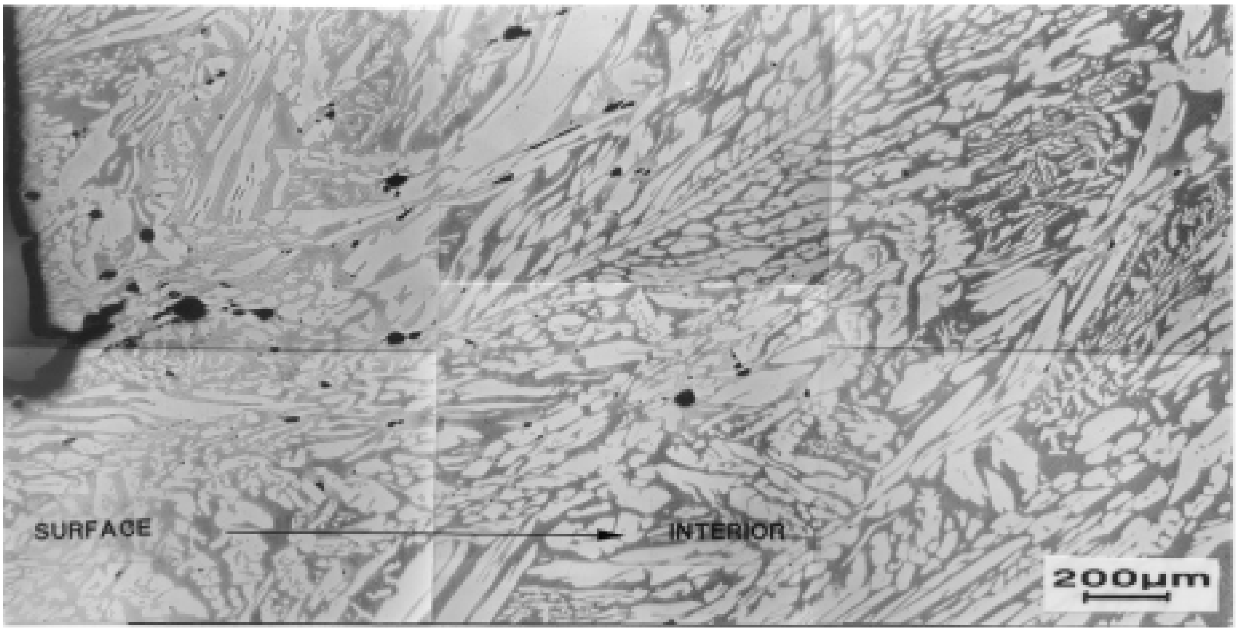

Figure 5: Optical micrograph of the as-cast duplex stainless steel deformed by hot torsion at 1000ºC, showing cracks running parallel to the δ/γ.

It is clearly apparent in Figure 2 that, in certain cases, this heterogeneous deformation leads to the formation of voids (see B-region) whose coalescence can produce crack formation (C-region). In Figure 4, microstructural details around a surface crack on the rolling plane can be seen. It is not possible to determine if the crack forms along the δ/γ interface or across the γ-phase, and it is also observed some elongated units disposed perpendicular to the rolling direction. This is a quite common feature to all the shear bands associated or not to cracks, in the present steel. At the other side of the same crack, in Figure 3, the austenite grains are elongated in the rolling direction.

Besides, the sliding, concentrated on regions where a high angle boundary is present (in the as cast material, the initial ferrite grain boundaries and regions where two different austenite packets meet together) and/or the shearing have been reported to be a source for the formation of cracks running parallel to the ferrite-austenite interface [6, 12]. This seems to be applicable, also in the present case.

Shearing, therefore, seems to be the responsible, as can be seen in Figure 2 and 3, at least of the first stage of surface cracking during hot rolling of the present duplex stainless steels. Torsion is a deformation mode involving pure shear and it has been found to be very useful in tackling the problem of damage formation in duplex stainless steels under hot working [13].

The ductility of the as-cast duplex stainless steel decreases, as the deformation temperature approaches to 1000°C, see Table II. Additionally, damage is formed well before the final fracture of material takes place. The torsion samples show a large number of cracks on the surface and these cracks continue through the section of the specimen, running parallel to the δ/γ interface, as can be seen in Figure 5.

TABLE II

SUPERFICIAL QUALITY ON FUNCTION OF DEFORMATION CONDITIONS.

Material	**Temperature (°C)**	**$\dot{\varepsilon}$ (s^{-1})**	**Strain**	**Presence of damage**
As-cast	1200	1	≈1.6	Practically free of superficial damage
	1100	1	≈1.6	Superficial damage
	1000	1	Low ($\varepsilon < 0.6$)	Superficial damage
		1	High ($\varepsilon > 0.6$)	Superficial and internal damage

TABLE III

DAMAGE AS A FUNCTION OF THE DEFORMATION CONDITIONS FOR THE AS-CAST DUPLEX STAINLESS STEEL.

As-cast material torsion tested at 1000°C				
	Strain	**$\dot{\varepsilon}$ (s^{-1})**	**σ (MPa)**	**Damage**
Superficial damage	1.44	1.06	95	0.0529
	0.88	1.06	111	0.0173
	0.49	1.06	126	0.0058
	0.98	5.4	132	0.022
Interior damage	1.26	0.91	92	0.024
	1.09	0.80	90	0.014
	0.93	0.68	87	0.006
	0.81	0.98	109	0.0019
	0.81	4.5	140	0.0043
	0.76	4.2	141	0.0068
	0.7	3.87	142	0.00067

With the aim to study the initial shear strain for which cracks appear, several torsion tests have been carried out at 1000°C and 1 and 5.4 s^{-1} and different strains. As cracks concentrate at the δ/γ interface, (see Figure 5) the fraction of damage, D, has been determined according to the following equation:

$$D=\frac{L_{\delta/\gamma}^{craks}}{L_{\delta/\gamma}^{total}} \qquad (1)$$

Where $L_{\delta/\gamma}^{cracks}$ is the length of the cracks at the interface and $L_{\delta/\gamma}^{total}$ is the total length of the δ/γ interface. In each sample the superficial damage and the damage observed at different interior radii have been measured.

Such measures are shown in Table III, and Figure 6 shows the obtained results in the different torsion samples as a function of the strain. It can be seen that superficial damage is higher than internal one. In the later case, the amount of damage decreases from the external surface to the centre of the sample. It can also be seen that damage appears at very low deformations. The values into brackets, in the figure, indicate the strain rate and the stress level corresponding to the place where the damage determinations have been carried out. It seems there is no systematic dependence of the damage amount neither on the strain rate nor on the stress level, at least in the range analysed in the present work. The main difference seems to arise from the location into the sample, as mentioned. The experimental results can be fitted to two potential equations, one for superficial damage and the other for internal one.

Superficial damage $\quad D_{sup} = 0.0241\ \varepsilon^{2.05}$ (2)
Internal damage $\quad D_{int} = 0.0089\ \varepsilon^{4.86}$ (3)

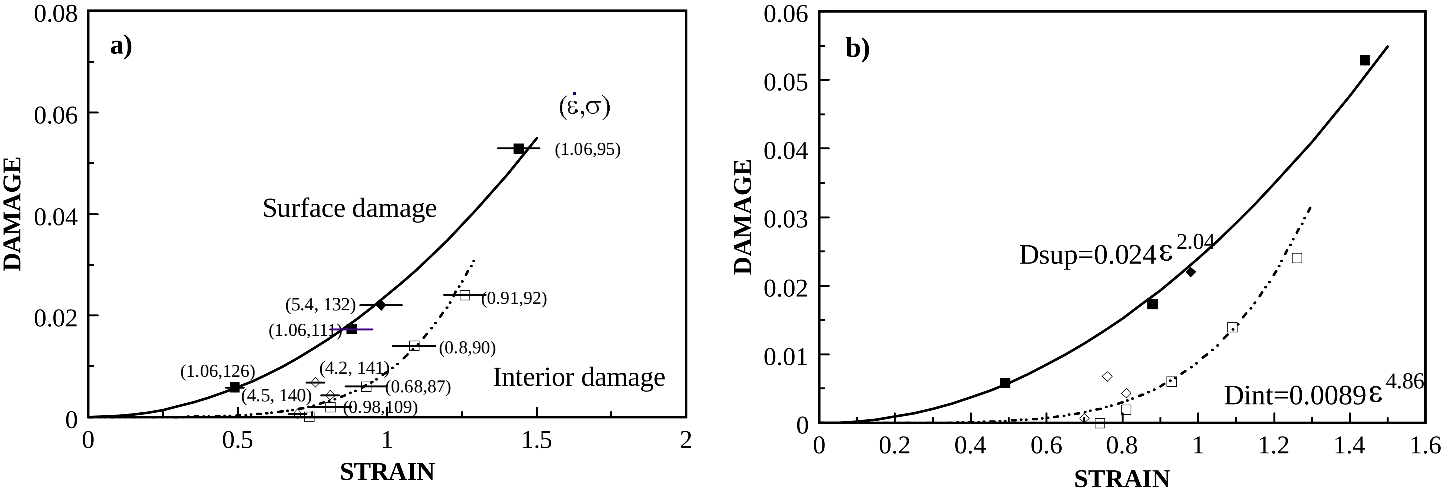

Figure 6: a) Curve of damage as a function of the strain and b) results fitted to potential equations.

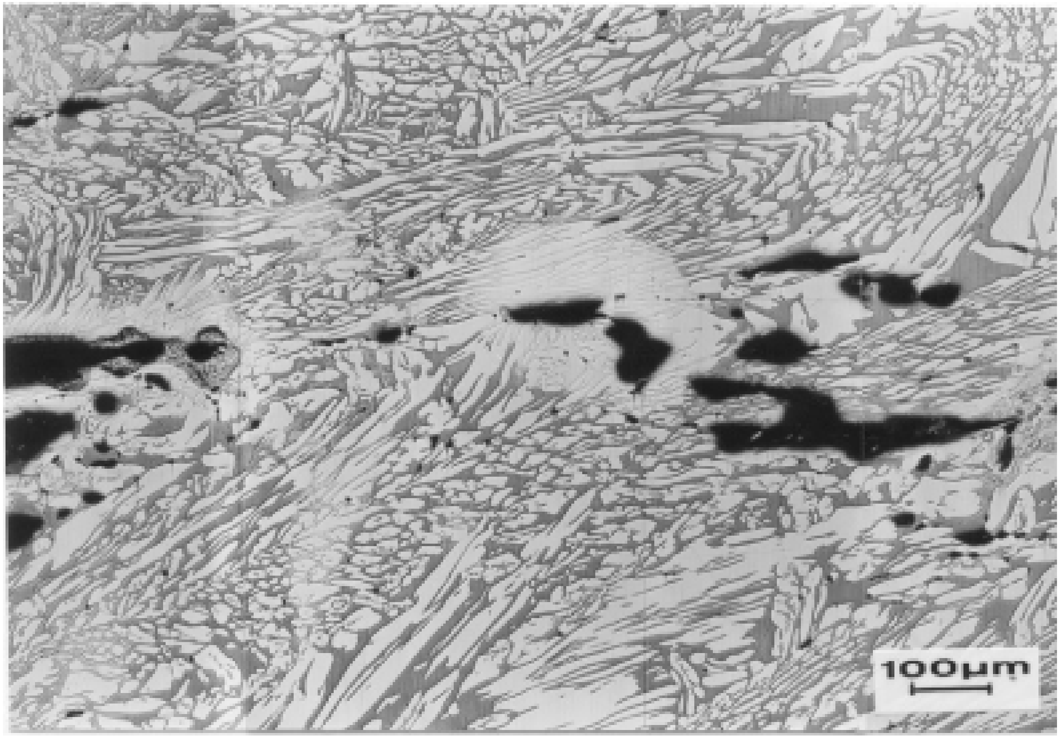

Figure 7: Optical micrograph of the as-cast duplex stainless steel deformed by hot torsion at 1000ºC, $1s^{-1}$ to ε=1.6.

It is to be mentioned that these expressions have been obtained using mean damage values. But, in reality, most of the times, damage has been found to concentrate on certain areas of the torsion sample. These areas can have very high local damage fraction as shown in Figure 7. Consequently, it would be expected that from relatively low macroscopic deformations local areas exhibiting a high damage concentration can be produced around 1000ºC. Additionally, the change on the conditions of contiguity at the sample surface seem to enhance the crack formation. Surface cracks are the most deleterious because further rolling will not be able to close them due to oxidation

CONCLUSIONS

The surface shear stress as a result of the friction between the rolls and the superficial material is responsible for deformation localisation in shear bands. This inhomogeneous deformation leads to superficial defects in industrial hot rolling of duplex stainless steels.

A critical temperature range has been determined by torsion tests around 1000ºC, leading to the formation of damage located at the δ/γ interface boundary, from very low strains. For this temperature, expressions have been deduced relating superficial and internal damage to the applied strain and applicable to different deformation conditions.

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