

# Deformation behaviour of a twinning induced plasticity (TWIP) steel

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*The automotive industry is in a constant search for steels with improved mechanical properties to reduce the weight of structural components and thus, increase the efficiency of the vehicles. Unfortunately, most efforts to increase the strength result in a decrease of the ductility, which is detrimental to crash performance. However, there is a new family of advanced high strength steels which present outstanding strength and ductility properties. These steels are known as TWIP (Twinning Induced Plasticity) steels and their peculiarity is that they deform by twinning. Usually, high Mn contents, i.e. 20-25%Mn, are necessary to stabilize austenite at room temperature and control the stacking fault energy in values which promote twinning as the main deformation mechanism. In this study, the hot deformation characteristics of a TWIP steel were evaluated.*

*This aspect is important in order to control the hot working operations and consequently, the final microstructure and mechanical properties of the steel. With this purpose, hot compression tests were performed at temperatures ranging from 800 °C to 1200 °C and strain rates from 0.1 s<sup>-1</sup> to 0.001 s<sup>-1</sup>. Moreover, double hit compression tests were carried out at 900 °C with different interpass times in order to evaluate the static recrystallization kinetics at such temperature. Detailed metallographic examination was done by optical microscopy to assess the dynamic and static recrystallization characteristics of the steel in terms of recrystallized fraction and recrystallized grain size.*

## Keywords:

Hot deformation, twinning induced plasticity, high Mn steel, DRX, SRX

## INTRODUCTION

The automotive industry is in constant search of stronger ductile steels to cope their needs of weight reduction without impairment of crashworthiness. The development of steel grades such as CP, DP and TRIP steel, based on multiphase microstructures, involved a continuous increase of the strength. However, improvements in the strength invariably implied ductility penalties [1]. More recently, the development of TWIP (Twinning Induced Plasticity) steels has lead to tensile strengths which can reach 1000 MPa with optimum strength to ductility ratios (ductility can be as high as 100%) [2, 3].

These outstanding mechanical properties can be obtained when deformation takes place by twinning, as opposed to strain hardening due to dislocation motion or phase transformation [4,5]. Deformation mode is related to the SFE (Stacking Fault Energy) which mainly depends on the chemical composition and temperature. In the case of TWIP steels, i.e. twinning has to be the deformation mechanism, SFE can range from 12 to 35 mJ·mol<sup>-1</sup> [6],

and this can be obtained with high Mn contents. Regarding the composition, different alloying strategies can be followed in order to obtain a TWIP steel. Accordingly, both Fe-(25-30)Mn-3Al-3Si and Fe-22Mn-0.6C have showed twinning during deformation at room temperature [6].

The properties exhibited by these steels make them suitable to be used in car body applications, especially in the parts where both strength and ductility are required [7]. However, use of these new steel for the manufacture of body car components, may face processing problems, i.e. high rolling loads, heterogeneous microstructure, high sheet forming loads, springback, etc. [8]. In this paper, the hot formability of a TWIP steel will be discussed in terms of dynamic and static recrystallization (DRX and SRX)[9-10].

## MATERIAL AND EXPERIMENTAL METHOD

A TWIP steel containing 20%Mn, 1.5%Al, 1.5%Si, 0.40%C was analyzed in this study. The material was produced by ingot casting from an induction furnace. Ingots were subsequently homogenized to 1200 °C before being hot rolled. Thickness reduction was carried out in several rolling steps.

The hot rolled condition of the material was the initial condition for testing. However, different solution treatments were carried out to homogenize the microstructure. After the different solution treatments, the one carried out at 1200 °C for 1h was chosen. The general microstructure after the latter solution treatment can be seen in Figure 1.

After solution treatment, the mechanical properties of the material were determined through tensile testing. Moreover, compression samples were machined for hot compression testing and double hit compression testing. Flow curves were obtained at temperatures ranging from 800 to 1100 °C every 100 °C and

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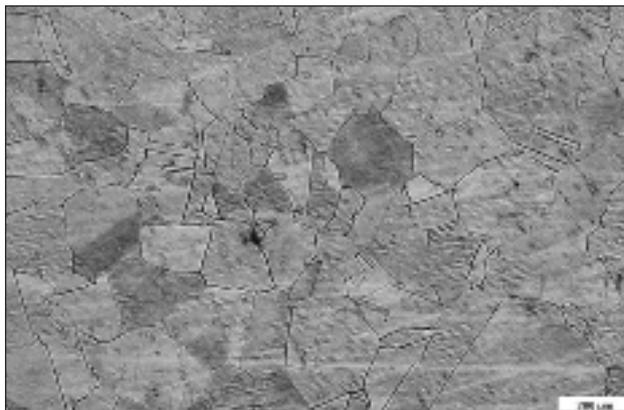
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**FIG. 1** *Microstructure after solution treatment at 1200 °C for 1h.*

*Microstruttura dopo trattamento in solubilizzazione a 1200 °C per 1h.*

constant strain rates of  $10^{-3} \text{ s}^{-1}$ ,  $10^{-2} \text{ s}^{-1}$  and  $10^{-1} \text{ s}^{-1}$ . All samples were heated up to 1100 °C for 10 minutes and then cooled down to the testing temperature where they were kept at the testing temperature for 5 minutes prior to deformation. After deformation, samples were quenched in order to carry out metallography examination to reveal the dynamically recrystallized microstructure. Double hit compression tests were carried out at 900 °C, deformation at the first pass was 0.2 and at the second pass 0.4, strain rate of  $10^{-2} \text{ s}^{-1}$  and interpass times ranged from 0.5 to

200 s. Some samples were quenched after different interpass times to evaluate the evolution of static recrystallization. Such microstructural characterization was done by optical microscopy. In order to reveal the austenitic structure, samples were etched in 4% Nital at 80 °C.

## RESULTS AND DISCUSSION

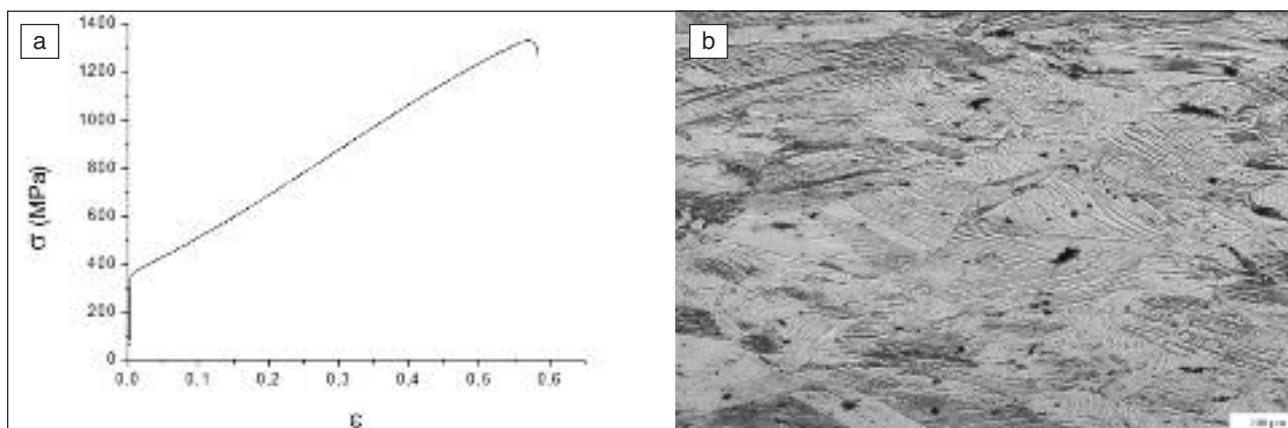
### Mechanical properties at room temperature

Figure 2a represents the tensile behaviour of the steel and the microstructure of the steel after deformation. As expected for TWIP steels, tensile strength is very high, i.e. in excess of 1300 MPa with and homogeneous deformation in excess of 55%. Figure 2b shows that deformation was related to extensive twinning in the microstructure. Even though other mechanisms, such as martensitic transformation, cannot be disregarded, it seems reasonable to consider that the steel is indeed a TWIP steel. In fact, this is important because the steel has a composition which combines different alloying strategies for TWIP steel, and twinning is still active when Al and Si are reduced to 1.5% if this reduction is compensated with 0.4%C.

### Hot deformation behaviour

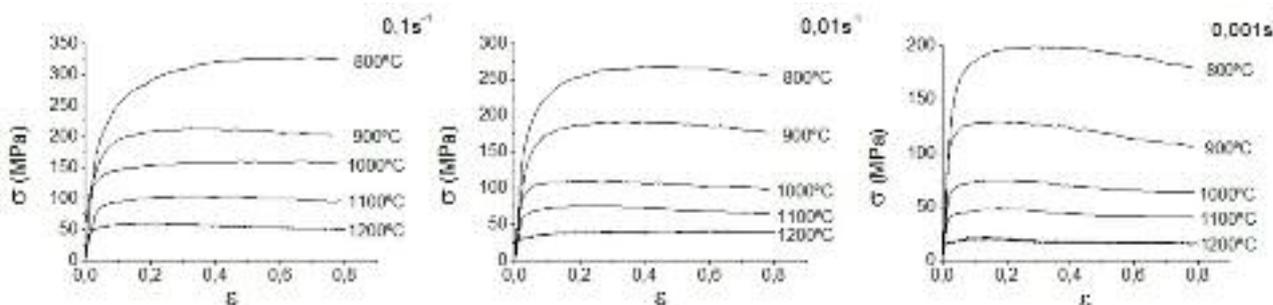
#### Flow curves

The true stress-true strain curves and the different temperatures and strain rates can be observed in Figure 3. This figure shows the typical dependence of the stress with the deformation parameters, i.e. the stress increases when the temperature is reduced or the strain rate is increased. Moreover, most of the curves present a single peak followed by a plateau which indi-



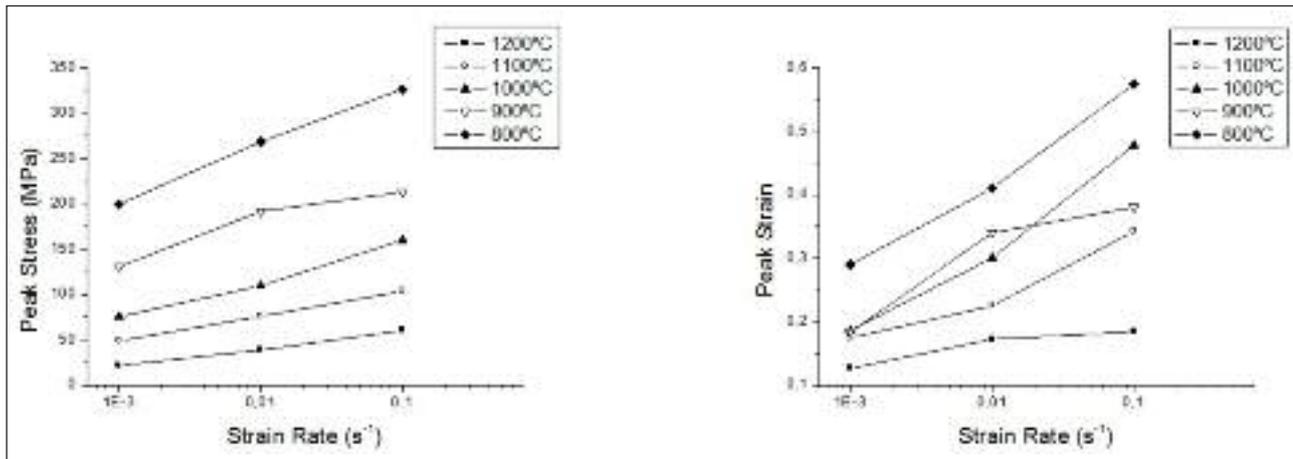
**FIG. 2** *a) True Stress - True Strain curve for the TWIP steel and b) microstructure after deformation.*

*a) Curva tensione - deformazione reale per l'acciaio TWIP e b) microstruttura dopo deformazione.*



**FIG. 3** *True Stress - True Strain curves at temperatures ranging from 800 °C and 1200 °C at three different strain rates : 0.1 s<sup>-1</sup>, 0.01 s<sup>-1</sup> and 0.001 s<sup>-1</sup>.*

*Curve tensione - deformazione reale a temperature che vanno da 800 °C a 1200 °C con tre diverse velocità di deformazione: 0,1 s<sup>-1</sup>, 0,01 s<sup>-1</sup> e 0,001 s<sup>-1</sup>.*



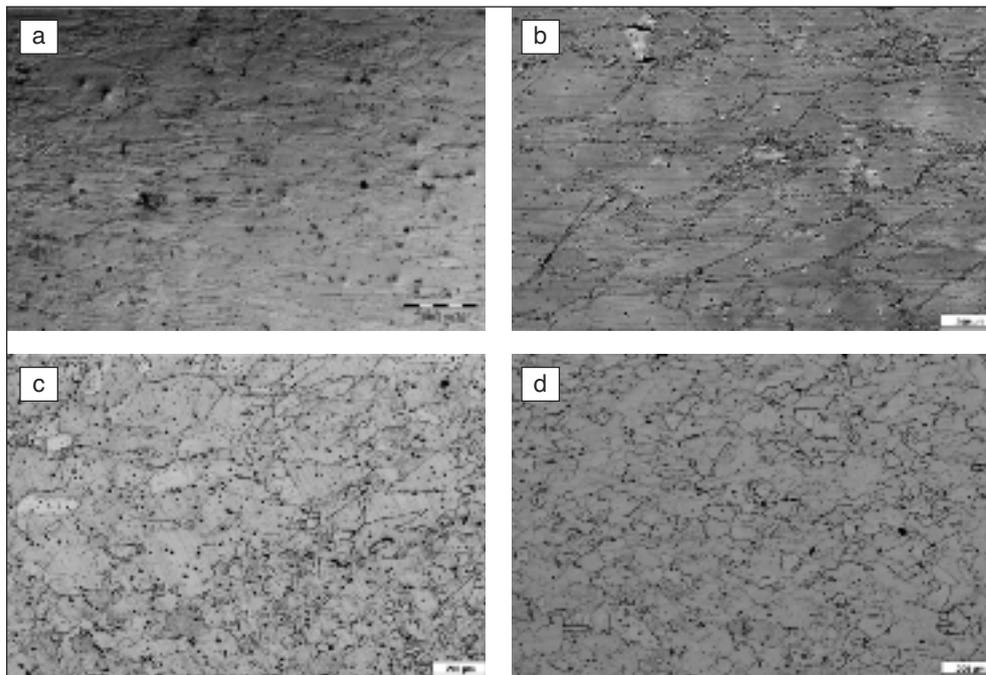
**FIG. 4** Variation of peak stress and peak strain with the strain rate at the different testing temperatures.

Variatione della massima tensione e massima deformazione in funzione della velocità di deformazione alle diverse temperature di prova.

**FIG. 5**

**Microstructure of the samples tested at a) 800 °C, 0.1 s<sup>-1</sup>, b) 900 °C, 0.001 s<sup>-1</sup>, c) 1000 °C 0.001 s<sup>-1</sup> and d) 1100 °C, 0.001 s<sup>-1</sup>.**

Microstruttura dei campioni in prova a a) 800 °C, 0,1 s<sup>-1</sup>, b) 900 °C, 0,001 s<sup>-1</sup>, c) 1000 °C 0,001 s<sup>-1</sup> e d) 1100 °C, 0,001 s<sup>-1</sup>.



icates that work hardening is competing with softening processes, i.e. (DRX).

The dependence of the peak stress,  $\sigma_p$ , and peak strain,  $\epsilon_p$ , on the strain rate at the different testing temperatures can also be observed in Figure 4. According to these graphs, the material is sensitive to the strain rate, i.e. both  $\sigma_p$  and  $\epsilon_p$  increase with increasing strain rate. Additionally, the effect of the temperature on these parameters is also evident. In fact, the material becomes more sensitive to strain rate as the temperature is increased since the slope of the curves become higher as the testing temperature is raised.

The deformation at the peak,  $\epsilon_p$ , can be seen as a parameter which indicates the energy required, in terms of deformation, to activate DRX, although it has been shown that the real critical deformation,  $\epsilon_c$ , is in fact around 0.8 times  $\epsilon_p$ . For this steel,  $\epsilon_p$  values are higher than for other C-Mn steels, as a consequence of the effect of the alloying additions on retarding the onset of DRX. However, which is an important characteristic of high Mn steels is that they present a broad peak, indicating a slow pro-

gress of dynamic recrystallization [11-13]. At the lowest testing temperature, i.e. 800 °C, and 0.1 s<sup>-1</sup> the maximum stress reached is around 325 MPa and the curve shows continuous hardening; no softening mechanisms seems to be taking place. Some of the abovementioned characteristic of the flow behaviour of the steel can be analyzed with regard to the microstructure of the samples. Figure 5 shows the microstructure of the samples after different deformation conditions. Figure 5a shows the microstructure of the sample tested at 800 °C and 0.1s<sup>-1</sup> corresponding to a flow curve (Figure 3a) which shows no evidence of softening. The microstructure corroborates this interpretation since only elongated grains can be observed, and there is no sign of DRX. On the other hand, for curves showing a peak, which would be related to DRX, this mechanism can be identified in the microstructures. For example, Figure 5b for the sample tested at 900 °C at 0.001 s<sup>-1</sup>, it is clear that DRX has started at grain boundaries, although it has not taken place throughout the whole microstructure. DRX is slow and this leads to a broad peak in the stress-strain curve (Figure 3c). On the other hand,

the deformation conditions which promote a peak behaviour followed by a plateau, can be related to full DRX of the microstructure as can be seen in Figures 5c and 5d for the samples tested at  $0.001 \text{ s}^{-1}$  at  $1000 \text{ }^\circ\text{C}$  and  $1100 \text{ }^\circ\text{C}$ , respectively. Even though these microstructures show a refinement of the grain size as compared to the original microstructure in Figure 1, grain size distribution appears more homogeneous for the sample tested at the highest temperature which could be indicating either that recrystallization has not been fully achieved or that there has been some grain growth.

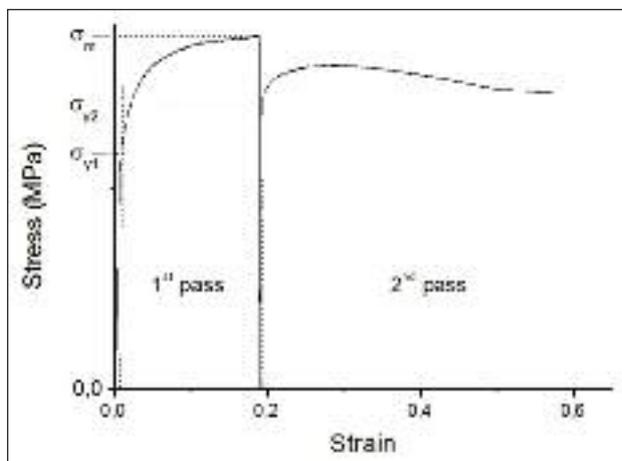
### Double hit compression tests

Double hit compression tests were carried out at  $900 \text{ }^\circ\text{C}$  and  $0.01 \text{ s}^{-1}$ . During the first pass, a 0.2 deformation was applied to the samples and after different interpass times, samples were reloaded and 0.4 deformation was applied in a second pass. According to Figure 3b, a 0.2 deformation is not enough to start DRX at  $900 \text{ }^\circ\text{C}$  and  $0.01 \text{ s}^{-1}$ , although under these conditions recrystallization could take place, as a consequence of the energy stored during deformation, after a certain time, i.e. the objective of the test is the determination of static recrystallization (SRX) kinetics under the abovementioned conditions.

The stress-strain curves for each interpass time is similar to the curve shown in Figure 6 corresponding to the test with an interpass time of 20 s. In this figure,  $\sigma_{y1}$  is the yield strength of the first pass,  $\sigma_{y2}$  is the yield strength of the second pass, and  $\sigma_m$  is the maximum strength reached during the first pass. Taking into account these parameters, the statically recrystallized fraction ( $\chi$ ) for each interpass time can be calculated using equation (1) [14]:

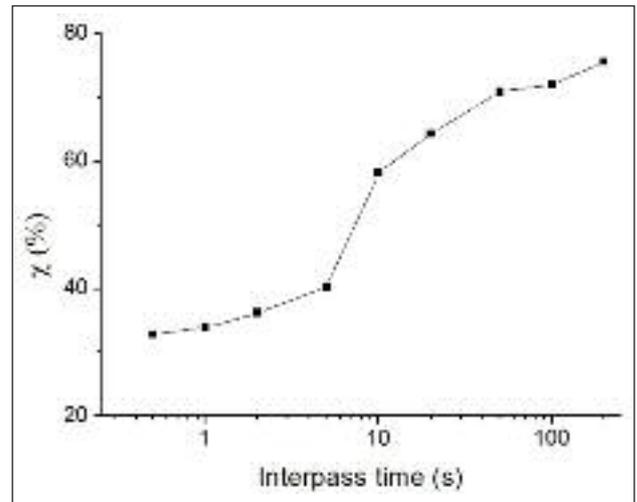
$$\chi = \frac{\sigma_m - \sigma_{y2}}{\sigma_m - \sigma_{y1}} \times 100 \quad (1)$$

Figure 7 represents the recrystallization kinetics at  $900 \text{ }^\circ\text{C}$  when the steel has undergone a 0.2 deformation. This curve follows the Avrami behaviour of nucleation and growth processes, such as recrystallization. According to these results, even for very short interpass times there is some recrystallized fraction. This may be due to the fact that strain rate is very slow and the beginning of the deformation at the second pass could be activating recrystallization dynamically. On the other hand, after 200 s the microstructure does not seem to have fully recrystallized.



**FIG. 6** Sketch of a true stress - true strain curve showing the way used to calculate the recrystallized fraction.

Diagramma di una curva tensione - deformazione reale che mostrano la modalità di doppia compressione usata per arrivare a determinare la frazione ricristallizzata.



**FIG. 7** Recrystallized fraction vs interpass time at  $900 \text{ }^\circ\text{C}$  after 0.2 deformation at  $0.01 \text{ s}^{-1}$ .

Frazione ricristallizzata in funzione del tempo di interpass a  $900 \text{ }^\circ\text{C}$  dopo deformazione dello 0,2 in  $0,01 \text{ s}^{-1}$ .

Figure 8 represents the microstructure of the steel after 0.2 deformation at  $900 \text{ }^\circ\text{C}$  and  $0.01 \text{ s}^{-1}$  after interpass times of 50 s and 100 s. According to the double hit test, these conditions correspond to 70% and 72% recrystallized fractions. In the figure it is evident that new grains have formed at grain boundaries and the microstructure has not fully recrystallized.

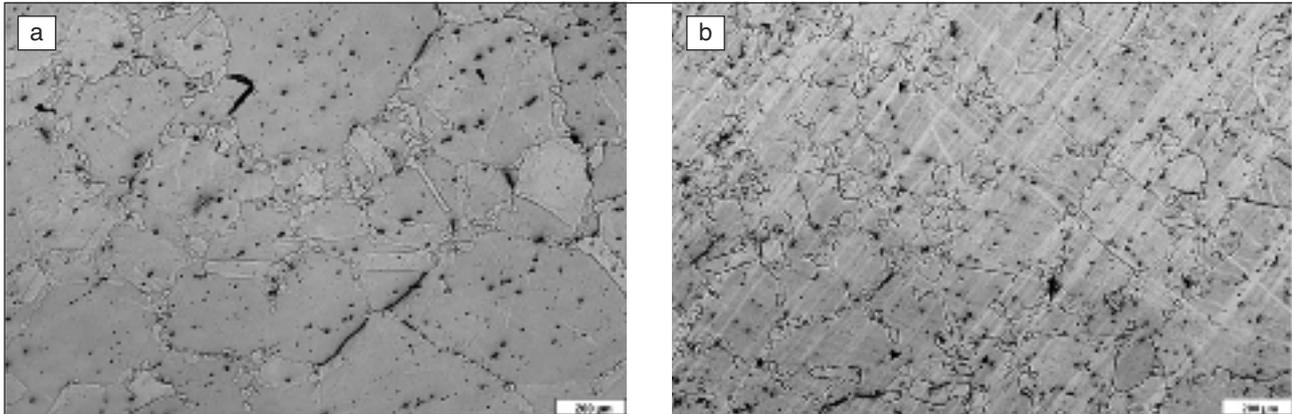
A complete evaluation of static recrystallization kinetics should contemplate other series of double hit tests at different temperatures and deformation levels. However, these results show that static recrystallization kinetics is relatively slow.

### CONCLUSION

A steel containing 20%Mn, 1.5%Al, 1-5%Si and 0.4%C has been produced and its mechanical properties and hot deformation behaviour have been characterized. At room temperatures the steel presents a tensile strength in excess of 1200 MPa and elongations higher than 55%. These outstanding mechanical properties are related to the activation of twinning as a deformation mechanism. Therefore, the abovementioned composition with lower alloying contents when compared to other TWIP steels, is in fact exhibiting the desired behaviour in terms of mechanical properties. On the other hand, flow curves have been obtained at different temperatures and strain rates. It has been found that at  $800 \text{ }^\circ\text{C}$  and  $900 \text{ }^\circ\text{C}$ , it is difficult to activate DRX and this leads to high stresses. Moreover, at  $900 \text{ }^\circ\text{C}$ , strains higher than 20% are needed in order to obtain a fully recrystallized microstructure by SRX. These results should be taking into account when designing a rolling schedule in order to avoid excessive rolling loads and control the evolution of the microstructure.

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**FIG. 8** *Microstructure of the samples deformed at 0.2 strain at 900 °C and 0.01 s<sup>-1</sup> after a) 50 s and b) 100 s.*  
*Microstruttura dei campioni deformati con deformazione dello 0,2 in 900 °C e 0,01 s<sup>-1</sup> dopo a) 50 s e b) 100 s.*

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## Abstract

### Comportamento a deformazione di un acciaio TWIP (Twinning Induced Plasticity)

Parole chiave: acciaio, deformazioni plastiche

L'industria automobilistica è alla costante ricerca di acciai con caratteristiche meccaniche che permettano di ridurre il peso dei componenti strutturali e, quindi, di aumentare l'efficienza dei veicoli. Purtroppo, la maggior parte degli sforzi/tentativi per incrementare la resistenza comportano una diminuzione della duttilità, il che è peggiorativo nel comportamento alla collisione. Tuttavia, esiste una nuova famiglia di acciai avanzati ad alta resistenza che presentano eccezionali caratteristiche di resistenza e duttilità. Questi acciai sono conosciuti come TWIP (Twinning Induced Plasticity), e la loro peculiarità consiste nel fatto che si deformano per il germinazione. Di solito, è necessario un alto tenore di Mn, nell'ordine del 20-25% di Mn, per stabilizzare l'austenite a temperatura ambiente e controllare l'energia dei difetti d'impilamento (Stacking Fault Energy), entro valori che inducano la germinazione come principale meccanismo di deformazione. In questo studio sono state valutate le caratteristiche di deformazione a caldo di un acciaio TWIP. Questo aspetto è importante al fine di controllare le operazioni di lavorazione a caldo e, di conseguenza, la microstruttura finale e le caratteristiche meccaniche dell'acciaio. A tale scopo, sono state effettuate prove di compressione a caldo a temperature che vanno da 800 °C a 1200 °C con tassi di deformazione da 0,1 s<sup>-1</sup> a 0.001 s<sup>-1</sup>. Inoltre sono state condotte, prove di compressione a 900 °C in due diverse passate, distanziate fra loro con tempi diversi, al fine di valutare la cinetica di ricristallizzazione statica a tale temperatura. E' stata effettuata una dettagliato analisi metallografica mediante microscopia ottica per accertare le caratteristiche della ricristallizzazione dinamica e statica dell'acciaio in termini di frazione ricristallizzata e di dimensione del grano ricristallizzato.