

Effect of thermomechanical processing on the microstructure of Si-Mn TRIP steel

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High strength and ductility of the transformation-induced plasticity (TRIP) steels are attributed to strain-induced martensitic transformation of the retained austenite in the multiphase microstructure (ferrite and bainite). Thermomechanical processing (TMP) was performed on Si-Mn bulk TRIP steel using a computer controlled torsion machine with different rolling schedules, by varying the deformation in the austenitic recrystallization region and non-recrystallization region, as well as the isothermal hold temperature for ferrite transformation. It was found that the choice of applied strain and temperature of deformation prior to transformation had a strong impact on transformation kinetics, final multiphase (ferrite, bainite and retained austenite) structure characteristics and mechanical properties of TRIP steel. The volume fraction of retained austenite was measured by both X-ray diffraction and image analysis method. The retained austenite volume fraction varied with strain in the non-recrystallization region. The increase of percentage reduction in the non-recrystallization region results in a greater amount of elongated austenite grains and deformation bands in the interior of the grains consequently very fine ferrite structures were formed. Furthermore, the dynamically recrystallized austenite structure tends to retain more austenite at room temperature.

KEYWORDS:

TRIP steel, torsion test, retained austenite, thermomechanical processing

INTRODUCTION

One of the important tasks for the 21st century is the maintaining of sound ecology. The reduction of the burden on the environment is an inevitable task assigned to industry. Recently, Japan internationally announced that it would reduce the generation of CO₂ by 6% during the 5 years from 2008 to 2012 in comparison with the level in 1990. To satisfy this declaration, the automotive industry generating around 17 % of total CO₂ is now aiming at an improvement of fuel efficiency by 22.8 % in 2010 compared with the level in 1995. Fuel savings between 0.3 l/km and 0.5 l/km can be achieved by a weight reduction of 100 kg, depending on the particular drive train technology. The CO₂ reduction of up to 10 g CO₂/ km is significant. A direct contribution of the steel industry to the reduction of fuel consumption is the supply of steels enabling the lightening of automotive weight. The sustainable requirements of automotive industry are directed to the development of multiphase steels, and particularly to the development of TRIP steels. Employing the TRIP (transformation-induced plasticity) phenomenon to produce steels with higher strength ranging from 800 to 1000 MPa and elongation of up to 30% has been the subject of many recent investigations [1-3]. Transformation-induced plasticity steels have been introduced as a fundamentally different type of higher strength steels [1,4]. As well known, during the crashing of the automobile body or the forming of structural part, the deformation of sheet steel is not at a static or quasi-static manner. TRIP-aided steel is mainly used in such impact-absorbing structural parts of car body. The microstructure of these steels, with typical composition of Fe-

0.2C-1.7Mn-1.5Si (in wt.%), consists of polygonal ferrite, bainite and significant amount of retained austenite [5]. Silicon addition over 1% results in a significant increase in the volume fraction of retained austenite due to the change in second phase from bainite + pearlite to ferrite + bainite, on the other hand the increase in manganese content from 1 to 2% shifts the $\gamma \rightarrow \alpha$ transformation region to the right side and decreases the cooling rate necessary to produce the same amount of ferrite. Therefore, if 2% manganese steel was rapidly cooled at a rate over 10°C/sec, the austenite directly transforms to bainite or martensite without ferrite formation during the continuous cooling. The volume fraction of retained austenite increases with lowering the finishing temperature and it is slightly affected by the amount of slow-cooling time after hot-deformation. It has been shown that the optimum combination of tensile strength and ductility is obtained in steels having 1.5% manganese and 2% silicon [6]. Higher level of ductility is achieved by the transformation of metastable retained austenite to martensite during forming of the component at room temperature. The amount and stability of the retained austenite controls mechanical properties of TRIP steels [7]. It was observed that an increase in the volume fraction of retained austenite resulted in increased coefficient of strengthening and subsequently in higher formability of steel. Based on this, most of the past research has concentrated on the relationship between the volume fraction of retained austenite and mechanical properties [8-10]. Favourable strength and ductility properties can be reached by producing a multiphase structure through controlled transformation of austenite obtained by thermomechanical (TM) processing [11]. Traditionally, the main objective in conventional TM processing of steels has been to refine the ferrite structure through deformation and recrystallization effects in austenite [12].

Contemporary technologies are focused particularly on hot-strip mill production of TRIP steels. The key objective of this work is

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the control of microstructure development in C-Si-Mn bulk steel employing hot torsion simulation. The strain and temperature parameters during roughing and finishing process were used to clarify different prior-austenite conditions on the transformation kinetics of TRIP steel. Wide range of the thermal and deformation parameters was involved in designing of TMP schedules in order to attain optimum structural characteristics of complex structure.

EXPERIMENTAL PROCEDURES

Vacuum-melted medium carbon low-alloyed C-Si-Mn TRIP-aided steel in the form of bars of 25mm in diameter was used for the present study. The chemical composition of the steel is shown in Table 1. Torsion samples were machined to 10 mm in diameter with a gauge length of 15mm to investigate T_{nr} , A_1 and A_3 temperatures, which are non static recrystallization temperature and the starting and finishing temperatures of the austenite-to-ferrite transformation, respectively. To obtain TRIP structure transformation holding time is very important as well as transformation temperature. Therefore, heat treatments were carried out in order to find the best transformation temperature and holding time. Three different temperatures were selected as 720°C, 760°C and 800°C in between calculated Ar_1 and Ar_3 temperatures. After austenitizing at 1000°C for 5min, samples were held for 1, 3 and 5 min at each temperature and quenched immediately in water.

Four different thermomechanical cycles were designed to obtain optimum TRIP behaviour. The TMP cycles are shown in Fig.1. A

computer controlled torsion machine was used to simulate the hot rolling behaviour of the thermomechanical cycles. Specimens used for TM cycles were 10 mm in diameter with a gauge length of 15mm. Samples were heated in air by a high frequency induction coil to reach the austenizing temperature selected as 1000°C. After a 5 minutes holding time at 1000°C, TMP1, TMP3 and TMP4 samples were subjected to two equal deformation steps, a $\epsilon_1 = 0.8$ with a 30s holding time in between these two deformations in the recrystallization region. Whereas TMP2 was subjected only to one deformation step at $\epsilon_1 = 1$ in the recrystallization region, held 30s at this temperature and cooled to 780°C at a rate of 4°C/s. TMP1, TMP3 and TMP4, with the same cooling rate, were cooled to 750°C, 760°C and 800°C, respectively. The second deformation of the TMP cycles was applied at these temperatures in the non-recrystallization region. Intercritical annealing for austenite decomposition to ferrite (in the $\alpha+\gamma$ two-phase region) was carried out at 750°C for 5 min for all TMP samples. The coiling process was simulated at 420°C/600s for TMP2 and 420°C/300s for the others TMP. The samples were then air cooled to room temperature as described below and shown in Fig. 1.

The samples after reaching 1000°C:

- TMP1 (1) holding at 1000°C/300s → (2) first deformation $\epsilon_1 = 0.8$ → (3) holding at 1000°C/30s → (4) second deformation $\epsilon_2 = 0.8$ ($T = 1000^\circ\text{C}$) → (5) air cooling to 750°C (6) first transformation $\gamma \rightarrow \alpha$ at $T = 750^\circ\text{C}/300\text{s}$ (7) water cooling → (8) second transformation at 420°C/300 s → (9) air cooling.

C	Mn	Si	P	S	Cr	Ni	Cu	Nb	Al	Fe
0.18	1.47	1.8	0.015	0.007	0.06	0.04	0.06	0.005	0.28	Bal.

TAB. 1 Chemical composition of the experimental TRIP steel grade. (in wt.%).

La composizione chimica in peso dell'acciaio TRIP.

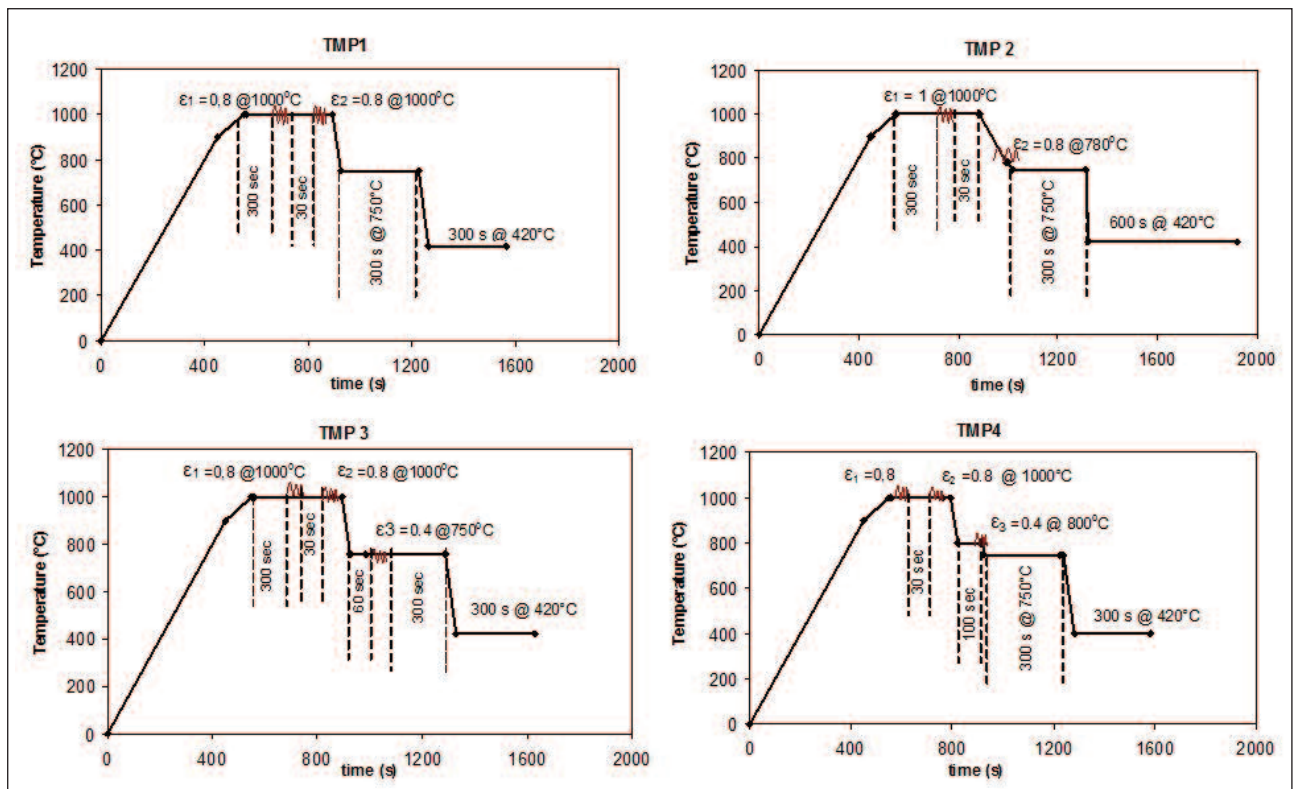


FIG. 1 Schemes of the four TMP schedules.

Gli schemi dei 4 cicli di laminazione.

- TMP2 (1) holding at 1000°C/300s → (2) first deformation $\epsilon_1 = 1$ → (3) holding at 1000°C/30s → (5) air cooling to 780°C → (6) second deformation $\epsilon_2 = 0.4$ (T = 780°C) (7) first transformation $\gamma \rightarrow \alpha$ at T = 750°C/300s (8) water cooling → (9) second transformation at 420°C/600 s → (10) air cooling.
- TMP3 (1) holding at 1000°C/300s → (2) first deformation $\epsilon_1 = 0.8$ → (3) holding at 1000°C/30s → (4) second deformation $\epsilon_2 = 0.8$ (T = 1000°C) → (5) air cooling to 750°C (6) holding at 750°C/60s (7) third deformation $\epsilon_3 = 0.4$ (T = 750°C) (8) first transformation $\gamma \rightarrow \alpha$ at T = 750°C/300s (9) water cooling → (10) second transformation at 420°C/300 s → (11) air cooling.
- TMP4 (1) holding at 1000°C/200s → (2) first deformation $\epsilon_1 = 0.8$ → (3) holding at 1000°C/30s → (4) second deformation $\epsilon_2 = 0.8$ (T = 1000°C) → (5) air cooling to 800°C (6) third deformation $\epsilon_3 = 0.4$ (T = 800°C) (7) first transformation $\gamma \rightarrow \alpha$ at T = 750°C/300s (8) water cooling → (9) second transformation at 420°C/300 s → (10) air cooling.

The volume fraction of retained austenite in treated samples was determined by X-ray diffraction (XRD) using Mo K α radiation. Integrated intensity of (110), (200), (211) peaks of ferrite and (111), (200), (220) peaks of austenite were used for this purpose and the volume fraction of retained austenite was calculated according to the ASTM E975-03. The microstructure investigations were made on the surface part of torsion samples, the samples were polished to the surface quality of 1 micron by using the diamond paste. The specimens were then etched with the Lepera colour-tint etching technique and were analysed by light optical microscopy.

RESULTS AND DISCUSSION

The microstructure of the as-received steel is shown in Fig. 2, composed of ferrite (mainly Widmanstätten like) and pearlite structure. The torsion test gives the values of torque applied versus the number of turns made on the specimen, which are transformed respectively into equivalent stress and strain using Von Mises criterion [13]. Fig. 3 (a) shows the simulation of 20 rolling passes for the steel studied with an interpass time of 30 s. Stress raises as temperature decreases, there being a change in the slope with a growth in the stress, which means a greater tendency to strengthening. Later, stress drops and grows again at final passes. The meaning of these zones is better explained by observing Fig. 3(b), which shows the graphic representation of Mean Flow Stress (MFS) versus the inverse of the absolute temperature for an interpass time of 30 s. MFS is determined in each step by dividing the area below the stress-strain curve by the strain applied. In Fig.3 (b) it is possible to see four different zones. In the first zone (I), which corresponds to deformations at highest temperatures, MFS grows as temperature decreases. Austenite recrystallizes completely between passes and there is no accumulated stress. The increase in stress is only due to the decrease in temperature. In the second zone of the curve (II) there is a change in the slope, which indicates a greater tendency towards hardening. Here the stress accumulates in the austenite, whose recrystallization between passes is partially inhibited. The third phase (III), characterized by a drop in MFS as the temperature decreases, corresponds to the austenite → ferrite partial transformation. In the fourth and final region (IV), where the stress again rises as the temperature drops, the austenite → ferrite transformation finishes and the eutectoid transformation takes place.

The intersection of the straight regression lines of phases I and II defines the value of T_{nr} and the intersection of the regression

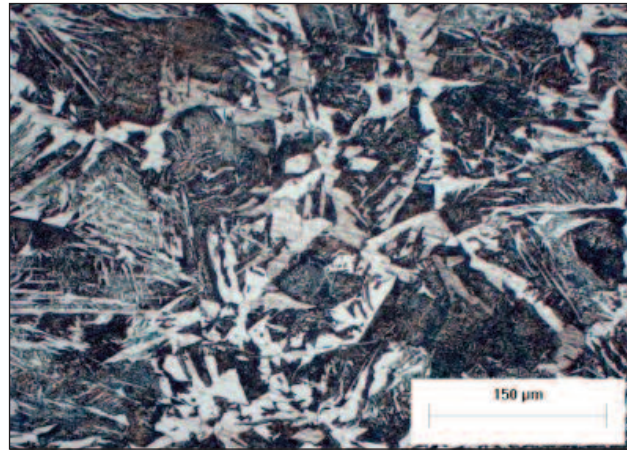


FIG. 2 **The microstructure of the as received samples.**
La microstruttura dell'acciaio allo stato tale - quale.

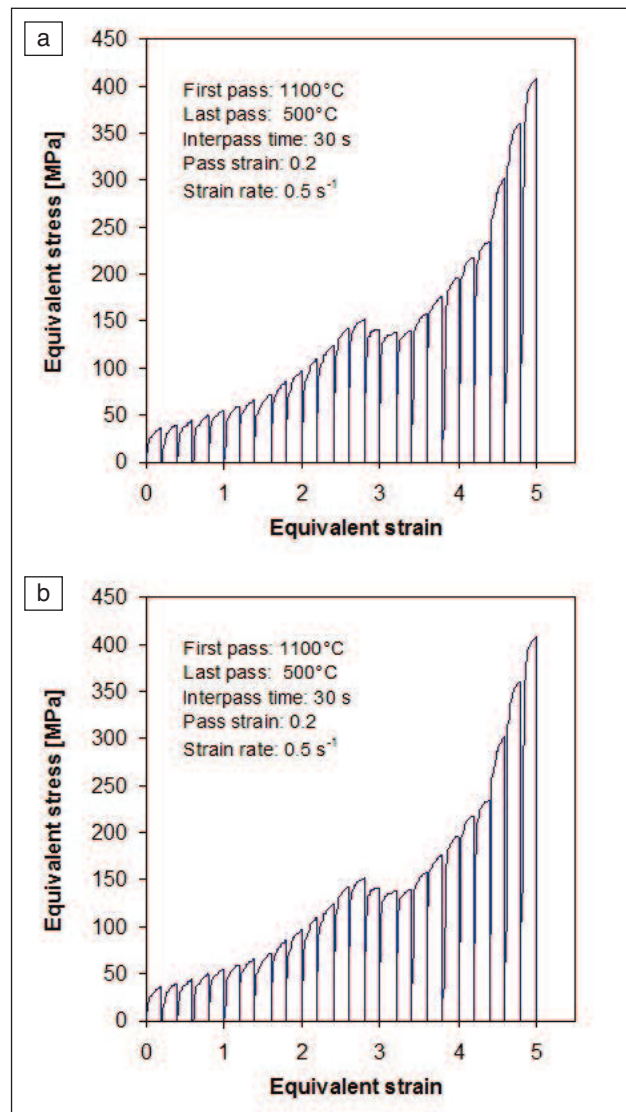


FIG. 3 **Stress-strain curves corresponding to 20 pass torsion sequence (a), dependence of MFS on inverse absolute temperature (b).**

Le curve tensione-deformazione del ciclo composto da 20 passate (a), la tensione media di flusso in funzione dell'inverso della temperatura assoluta (b).

lines of phases II and III determines the value of Ar_3 . The value of Ar_1 is placed at a point close to the minimum of the parabola corresponding to phases III and IV. In this way, the values found for the three critical temperatures when interpass time was 30 s were: $T_{nr} \approx 935$ °C, $Ar_3 \approx 796$ °C, $Ar_1 \approx 723$ °C.

Figure 4 shows the change in microstructure of the samples as a function of holding times and temperatures after holding at 1000°C for 5 minutes. Each sample was analysed by image analysis method for the distributions of phases which are composed of martensite and ferrite. Depending on the temperature and holding time, different amounts of ferrite and martensite were observed. Since the samples were immediately quenched after holding time, the transformed ferrite remained as itself and the austenite phase was transformed into martensite. The austenite quantity is assumed to be equal to the transformed martensite quantity at room temperature. The fractions in percentage of austenite and ferrite are reported in Table 2. The highest volume fraction of ferrite was obtained at 750°C after 5 minutes holding.

One reason why intercritical deformation could suppress bainite

formation is that intercritical deformation causes enrichment of carbon in austenite by formation of more ferrite and then enhances the stability of the remained austenite against bainite formation [14]. By employing TMP schedules, a complex structure of polygonal ferrite, bainite and retained austenite was observed. To characterize morphology and distribution of the structure, tint etching technique (LePera's reagent) gave the possibility to distinguish bainite, ferrite and retained austenite. Ferrite appears as blue green, bainite is brown, and retained austenite is white. Fig. 5a shows coarse structure, whilst in Fig. 5b deformation bands produced by large reduction in non-recrystallization temperature region of austenite acted as nucleation sites for ferrite formation and finally refine the ferrite grains. These bands in austenite produced by intercritical deformation would transform to ferrite, which straightly crossed the austenite grains and divided austenite grains into several parts. Furthermore, a larger deformation (TMP2) could lead to more deformation bands within austenite grains and more ferrite fragments compared to TMP4 (Fig. 5b and Fig. 8a). The results related to austenite decomposition to ferrite showed that

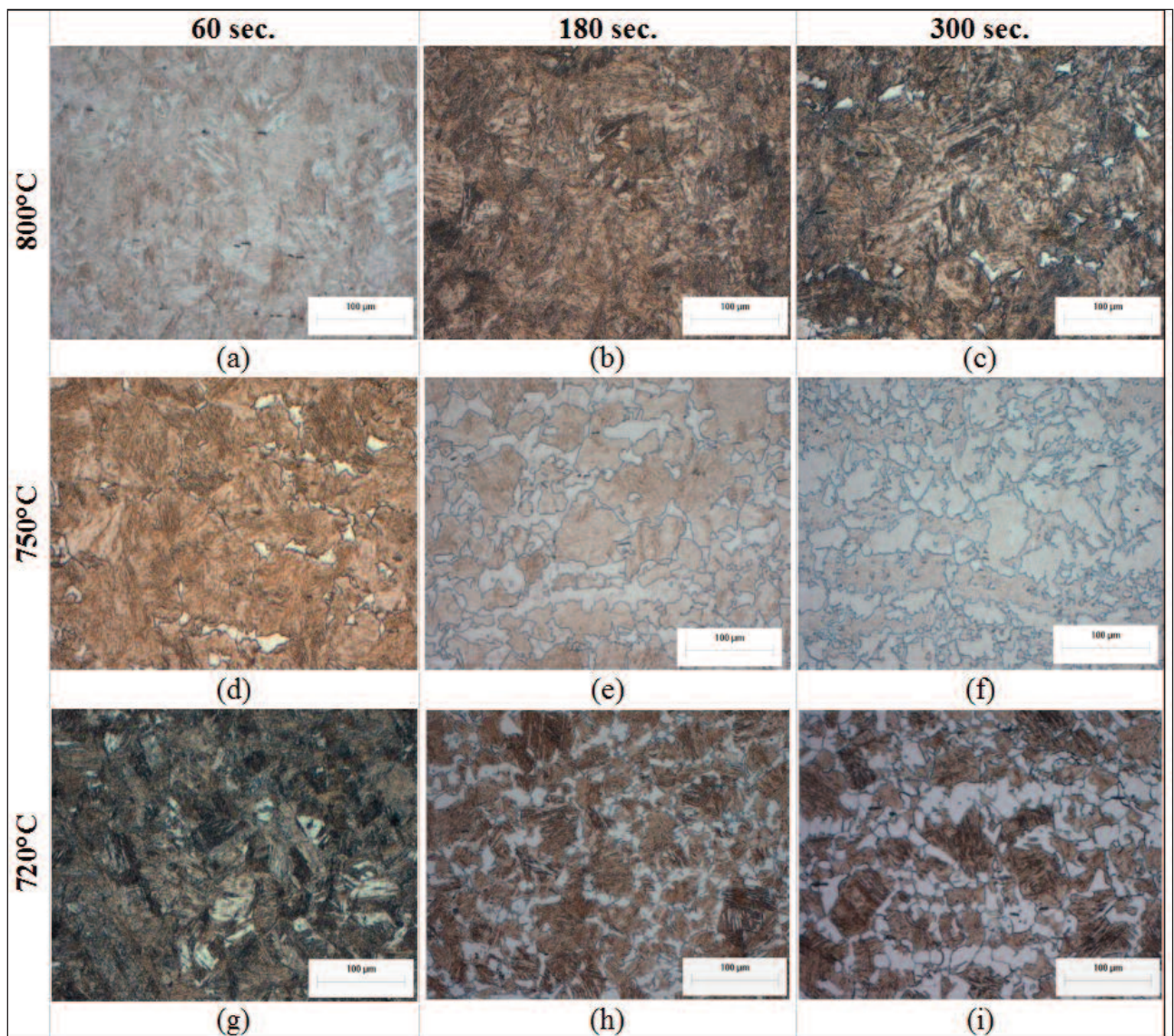


Fig. 4 Microstructures of heat treated samples after holding at 1000°C for 5 minutes, (a) 800°C 1min, (b) 800°C 3min, (c) 800°C 5min, (d) 750°C 1min, (e) 750°C 3min, (f) 750°C 5min, (g) 720°C 1min, (h) 720°C 3min, (i) 720°C 5min.

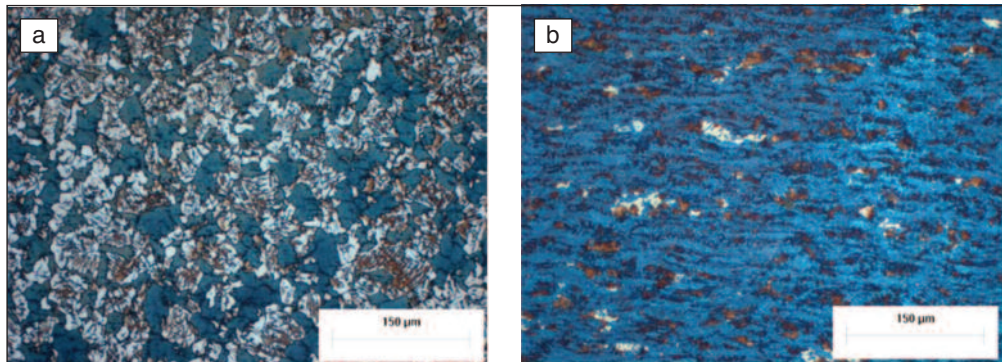
La microstruttura dei campioni trattati termicamente a 1000°C per 5 minuti dopo, (a) 800°C 1min, (b) 800°C 3min, (c) 800°C 5min, (d) 750°C 1min, (e) 750°C 3min, (f) 750°C 5min, (g) 720°C 1min, (h) 720°C 3min, (i) 720°C 5min.

TAB. 2
Volume fraction of ferrite and austenite at different holding time and temperature, calculated from the metallographic measurements, and Vickers microhardness.

Holding time (sec.)	Temperature (oC) (After 1000oC, 5min)						
	720°C		HV ₅₀₀	750 °C		800°C	
% Ferrite	% Austenite	% Ferrite		Hardness (HV ₅₀₀)	% Ferrite	Hardness (HV ₅₀₀)	
60	8	92	355±9	3,5	386±11	0	394±15
180	17	83	320±8	24	325±6	0	396±10
300	38	62	307±5	50	247±7	3	392±13

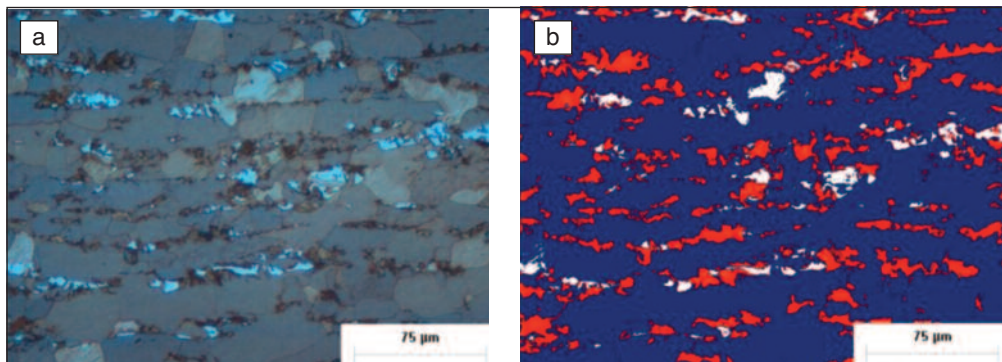
La frazione volumetrica della ferrite e dell'austenite alle diverse temperature e tempi di permanenza e le relative microdurezza Vickers.

FIG. 5
Micrograph of multiphase structure of ferrite (blue), Bainite (brown) and retained austenite (white) resulting from samples deformed following TMP1 (a) and TMP2 (b).



Le micrografie dei campioni deformati secondo lo schema TMP1 (a) e TMP2 (b), vengono evidenziate: in blu la ferrite, in marrone la bainite ed in bianco l'austenite residua.

FIG. 6
Micrograph of multiphase structure of ferrite (blue), Bainite (brown) and retained austenite (white) resulting from sample deformed following TMP3 (a) and the relative image analysis (b).



La micrografia del campione deformato con il ciclo TMP3 (a) e la sua relativa immagine usata per l'analisi dell'immagine.

TAB. 3
Volume fractions of structural phases.
La frazione Volumetrica delle fasi.

TM schedule	TMP1	TMP2	TMP3	TMP4
Retained austenite (%)	28.5	7.4	7.6	11.5
Ferrite (%)	49	70	55	54

transformation kinetics of austenite can be affected significantly by austenite grain size and its morphology prior to transformation. The effect of austenite conditioning on ferrite transformation differs from one transformation to another, given different volume fractions of ferrite. Indeed, large prior-austenite grains retain higher fractions of austenite (Fig. 5a). Since each phase has different color, it was possible to determine the volume fraction of the phases with the image analyser. Figure 6b shows the image analyses of sample TMP3. The presence of retained austenite was also proved by X-Ray dif-

FIG. 7
Equivalent stress-strain curves of TMP4, by applying two deformations ϵ_1 , ϵ_2 at 1000°C and ϵ_3 at 800°C.

Le curve di flusso tensione-deformazione del ciclo TMP4, applicando 2 deformazioni ϵ_1 , ϵ_2 a 1000°C e ϵ_3 a 800°C.

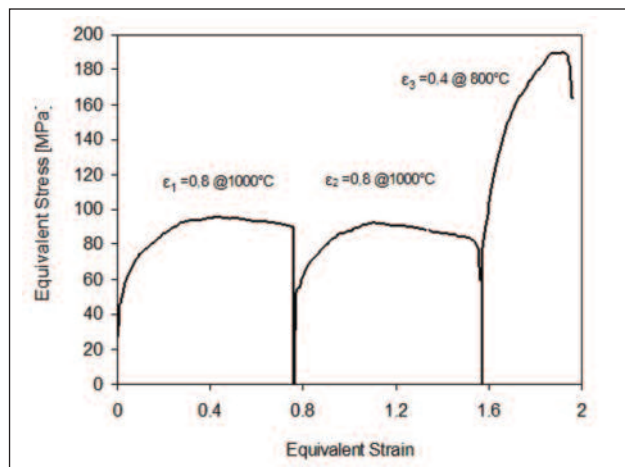
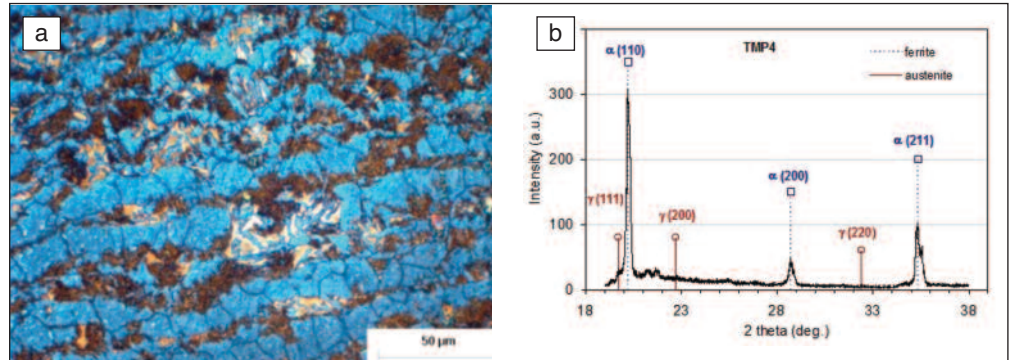


FIG. 8
Micrograph of multiphase structure from the sample deformed following TMP4 (a) and the relative X-Ray diffraction pattern (b).

La micrografia del campione deformato con il ciclo TMP4 (a) e il relativo X-Ray diffraction pattern (b).



fraction analysis as well. The volume fractions of ferrite and retained austenite for each specimen are in Table 3, the balance is the bainite fractions.

Figure 7 shows the stress-strain curves of the TMP4 sample, the flow stress in the second deformation is lower than the first step indicating the occurrence of recrystallization.

The resulting structure for TMP4 schedule is documented in Fig. 8. The obtained morphological and distribution characteristics of retained austenite as well as ferrite and bainite unanimously proved it as more favourable than the other three procedures. The volume fraction of retained austenite in the specimens processed according to TMP4 was considerably higher than TMP2 and TMP3, but largely lower than TMP1.

CONCLUSIONS

Thermomechanical processing (TMP) was performed on Si-Mn bulk TRIP steel, by using a computer controlled torsion machine with different rolling schedules by varying, the deformation in the austenitic recrystallization region and non-recrystallization region and the cooling temperature. The investigation resulted in the following conclusions:

- The values found by interrupted torsion cycle for the three critical temperatures were $T_{nr} \approx 935$ °C, $A_{r3} \approx 796$ °C, $A_{r1} \approx 723$ °C
- The ferrite volume fraction was maximised (50%) at the transformation temperature of 750 °C after holding time of 300 sec.
- Introduction of high strain (0.8) in the intercritical interval in TMP2 resulted in a fine structure of ferrite and bainite with volume fraction of retained austenite around 7%.
- A high volume fraction of retained austenite was obtained when deforming two successive deformation steps above T_{nr} (TMP1), but the best result was reached when the third straining was applied below T_{nr} (800 °C) and held at 750 °C for 300 s before bainite transformation (TMP4), giving 11% of retained austenite.

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Abstract

Effetto dei parametri termomeccanici sulla microstruttura di un acciaio TRIP al Si-Mn

Parole chiave:
acciaio, processi termomeccanici

L'elevata resistenza meccanica e duttilità degli acciai TRIP (Transformation-Induced Plasticity) sono dovute fondamentalmente grazie alla trasformazione dell'austenite residua in martensite durante la deformazione, nella struttura multi-fasica (ferritico bainitica). L'effetto dei parametri di processo, durante i trattamenti termomeccanici (TMP) su un acciaio TRIP al Si-Mn, è stato studiato mediante la macchina di torsione, simulando diversi schemi di laminazione. Questi schemi comprendevano la variazione della deformazione nell'intervallo di completa ricristallizzazione dinamica dell'austenite, alle temperature di non ricristallizzazione dell'austenite e la temperatura di raffreddamento per la trasformazione bainitica. È stato analizzato l'effetto della morfologia dell'austenite ricristallizzata o deformata a pancake insieme alla temperatura di finitura sotto T_{nr} (temperatura di non ricristallizzazione statica dell'austenite) sulla presenza di austenite residua a temperatura ambiente. La frazione in volume dell'austenite residua è stata determinata sia mediante diffrattometria a raggi-X sia con tecniche di analisi dell'immagine. La microstruttura è composta da ferrite poligonale, bainite ed austenite residua. La percentuale di austenite residua variava in funzione della deformazione nella zona di non ricristallizzazione dinamica. Inoltre, partendo da una struttura austenitica completamente ricristallizzata tende ad aumentare il tenore di austenite residua a fine processo.