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Microstructural control of the austenite stability in low-alloyed TRIP steels

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Key words: TRIP steels, Magnetization measurements, Synchrotron X-Ray Diffraction, Austenite stability

Abstract. We have performed in-situ magnetization and high-energy X-ray diffraction measurements on two aluminum-based TRIP steels from room temperature down to 100 K in order to evaluate amount and stability of the retained austenite for different heat treatment conditions. We have found that the bainitic holding temperature affects the initial fraction of retained austenite at room temperature but does not to influence significantly the rate of transformation upon cooling.

Introduction

Low-alloyed transformation-induced plasticity (TRIP) steels have attracted significant interest for automotive applications due to their high strength and formability [1]. A relatively complex two-stage heat treatment leads to the presence of a significant amount of austenite (<20%) in a metastable condition at room temperature [2]. The transformation of this metastable austenite into martensite can be induced by changes in temperature and/or an applied stress [3, 4]. This transformation seems to constitute the key process to obtain a high work hardening rate and a large uniform elongation in these materials [2, 4]. We have recently derived a new equation that links the martensitic transformation temperature not only to the carbon content of the austenite grains but also to the grain size [5]. These two microstructural parameters are controlled by the heat treatment and the chemical composition of the material. The aim of this work is to maximize the amount of metastable austenite present in the room-temperature TRIP microstructure in order to improve the strength/ductility combination in these materials. To achieve this goal, we have varied the heat treatment parameters systematically in two aluminum-based TRIP steel grades. We have subsequently studied the thermal stability of the retained austenite by using two in-situ bulk techniques: magnetization measurements using a SQUID magnetometer [6] and high-energy X-ray diffraction at a synchrotron source [5, 7].

Experimental

Two TRIP steels grades with a different aluminum content were used: 0.188C-1.502Mn-0.254Si-0.015P-0.443Al (Al_{0.4}) and 0.218C-1.539Mn-0.267Si-0.018P-1.750Al (Al_{1.8}) in wt.%. Cylindrical samples with a length of 10 mm and a diameter of 5 mm were machined from the hot-rolled steel material and heat treated under vacuum using a Bähr 850a dilatometer. The samples were first annealed during 30 minutes at an intercritical temperature of 1098 K for Al_{0.4} and 1143 K for Al_{1.8},

corresponding to approx. equal fractions of austenite and ferrite. The second stage was to quench the samples to a lower temperature where part of the intercritical austenite transformed into bainite. In order to assess the influence of the bainitic holding temperature (T_{bh}) on the resultant TRIP microstructure at room temperature, we have prepared samples at three different temperatures: 623, 648 and 673 K. At each temperature, the holding time was varied systematically from 30 s to 10 min. Finally, the material was quenched to room temperature. The austenite grains with sufficient stability did not transform into martensite during the final quenching step and remained in the room-temperature microstructure in a metastable condition. This specific heat treatment yielded a multiphase microstructure composed of ferrite, bainite and retained austenite. Fig. 1 shows the resultant microstructure of $Al_{0.4}$ and $Al_{1.8}$ at room temperature for two bainitic holding temperatures: 623 and 673 K, and a holding time of 2 min.

The thermal stability of retained austenite was studied by magnetization measurements using a SQUID magnetometer while cooling the material down to 100 K and heating back to room temperature in the presence of magnetic field of 5 T. The difference in saturation magnetization of the TRIP steel containing the metastable austenite and the as-received ferritic steel is directly related to the volume fraction of the non-magnetic austenite [6]. The magnetization results are compared with those of our earlier in-situ high-energy ($E = 80$ keV) X-ray diffraction measurements performed in transmission geometry at the beam line ID11 of the European Synchrotron Radiation Facility (Grenoble, France) [5, 7]. In this experiment, the sample was cooled from room temperature to 100 K in steps of 20 K using a nitrogen gas cryostream cooler. For each temperature step, the diffracted intensity from the different phases present in the microstructure was recorded on a two-dimensional detector placed behind the sample.

Results and discussion

Austenite fraction at room temperature

Fig. 2 shows the austenite fraction present at room temperature as a function of the bainitic holding temperature and time for the two studied TRIP compositions. Fig. 2b shows that for the $Al_{1.8}$ sample and $T_{bh} = 673$ K, the austenite fraction increases with the holding time up to 2 min and then decreases slowly at longer times. By decreasing the bainitic temperature from 673 to 623 K, the austenite fraction is reduced and the maximum in the austenite fraction is shifted towards longer times. By comparing Fig. 2a and b, the austenite fraction at room temperature turns out to be lower for the $Al_{0.4}$ sample than for the $Al_{1.8}$ sample at the same T_{bh} . The shape of the curve is similar for both compositions, but in the case of $Al_{0.4}$ the maximum in austenite fraction appears at a shorter holding time of 1 min at 673 K and 2 min at 648 K and 623 K. The retained austenite fraction decreases faster at longer holding times in the $Al_{0.4}$ sample.

Fig. 1. Room-temperature microstructure of the two studied TRIP steel grades as revealed by optical microscopy. The micrographs correspond to a bainitic holding temperature of $T_{bh} = 623$ and 673 K and a holding time of 2 min. Austenite and martensite appear in white, while bainite and ferrite grains are shown in brown.

The microstructure of TRIP steels depends on the bainitic holding time. For short holding times, the austenite fraction at room temperature is relatively low due to a limited carbon enrichment during the bainitic transformation. Consequently, part of the austenite transforms into martensite during the quenching to room temperature. By increasing the holding time, the austenite fraction increases to reach a maximum value, which indicates the minimum degree of bainitic transformation necessary to hinder the partial transformation of the remaining austenite into martensite above room temperature. The position of this maximum depends on the bainitic holding temperature due to the influence of temperature on carbon diffusion. For longer times, a significant amount of bainite plates have grown into the austenite grains leading to a reduction in the austenite fraction with time. A second parameter that affects the austenite fraction at room temperature is the aluminum content. Aluminum increases the driving force of the bainitic transformation and retards the cementite formation during the bainitic holding step [5]. As shown in Fig. 2, the austenite fraction decreases with the aluminum content due to a reduced degree of bainite formation. Consequently, a lower carbon enrichment in austenite is expected. For longer holding times, the austenite fraction seems to tend to zero. This may indicate the possible formation of carbides in the TRIP sample with only 0.4 wt.% Al at long holding times. A higher bainitic holding temperature leads to faster bainite transformation kinetics, and therefore induces a faster austenite stabilization with a maximum point at 673 K for 1 min instead of 2 min for the Al_{0.4} sample.

Fig. 2. Variation of the austenite fraction at room temperature with the bainitic holding temperature and time for (a) $Al_{0.4}$ and (b) $Al_{1.8}$.

Austenite stability below room temperature

The heat treatment leading to the highest fraction of retained austenite at room temperature ($T_{bh} = 673\text{ K}$ for 2 min in $Al_{1.8}$) was selected as base material to study the thermal stability of the retained austenite at lower temperatures. For comparison, the bainitic holding temperature was varied from 673 to 623 K for a fixed holding time of 2 min for both chemical compositions. Fig. 3a and b shows the austenite fraction as a function of the temperature during cooling down to 100 K. In all cases, the austenite fraction decreases during the cooling process, what indicates that part of the metastable austenite has transformed into martensite. The transformation starts at 250-275 K irrespective of the bainitic holding temperature and the chemical composition, and stops in the temperature range of 120-150 K. As expected, the austenite fraction does not change any further upon heating the material back to room temperature. An austenite fraction of 1.4% transforms thermally into martensite in the $Al_{0.4}$ sample for all bainitic holding temperatures, while the transformed austenite fraction is around 2.3% in the $Al_{1.8}$ sample. The bainitic temperature turns out to have a weak influence on the austenite stability when varied from 623 to 673 K, only on the initial austenite fraction before cooling. Moreover, a fraction of the initial metastable austenite grains still remain untransformed at the lowest temperature of 100 K in all samples. The average austenite carbon content ($\langle x_c' \rangle$) and grain volume ($\langle V_\gamma \rangle$) have been compared before and after cooling down to 100 K using high-energy X-ray diffraction [5], see Table 1. These data indicate that only small grains with a high carbon content remain untransformed at 100 K.

Fig. 3. Evolution of the austenite fraction as a function of the temperature for (a) Al_{0.4} and (b) Al_{1.8}. The relative volume fraction as a function of the temperature is shown in (c) and (d) for both chemical compositions and for a bainitic holding time of 2 min. The green dots correspond to the data obtained by in-situ X-ray diffraction (taken from ref. [7]). The dashed line indicates the temperature region where the austenite transforms into thermal martensite.

Finally, in Fig. 3c and d the comparison between the results of the magnetization measurements and those of the in-situ X-ray diffraction experiment is displayed. A very satisfactory agreement is obtained between both techniques. All the curves have the same slope, what means that the transformation behaviour is similar for all process routes for a selected chemical composition. The martensitic transformation occurs in a narrower temperature range between 150 K and 250 K for Al_{0.4} sample. A higher aluminum content is found to induce a more gradual transformation of the austenite during cooling down to 100 K.

Table 1. Average grain volume ($\langle V_\gamma \rangle$) and carbon content ($\langle x_c^\gamma \rangle$) of austenite before and after cooling down to 100 K for both compositions, taken from ref. [5]. The width of the distribution (standard deviation) is indicated in parenthesis.

Material	$\langle V_\gamma \rangle (\mu m^3)$		$\langle x_c^\gamma \rangle (wt. \%)$	
	Before	After	Before	After
Al _{0.4}	11.8 (6.5)	7.8 (2.9)	0.92 (0.10)	1.01 (0.16)
Al _{1.8}	20.9 (12.2)	11.5 (7.2)	0.81 (0.14)	1.02 (0.11)

Conclusions

The thermal stability of retained austenite in two aluminum-based TRIP steels was studied by a combination of two in-situ bulk experimental techniques: magnetization measurements and high-energy X-ray diffraction. The main conclusions of the present study are:

1. The austenite fraction at room temperature increases with the bainitic holding time up to a maximum value, and then decreases slowly for longer times. If the bainitic holding temperature is lowered, this maximum is shifted towards longer holding times. A decrease in the aluminum content causes a reduction in the austenite fraction and the maximum occurs at shorter holding times.
2. The thermal stability of the retained austenite does not vary significantly with the bainitic holding temperature in the range of 623-673 K for each of the two studied TRIP steels. An increase in the aluminum content leads to a more gradual transformation of the metastable austenite.
3. A certain amount of austenite remains untransformed at 100 K in all the studied samples. These remaining austenite grains are too stable due to a high carbon content and a small grain size that gives a very low value for their martensite transformation temperature.
4. In-situ magnetization and high-energy X-ray diffraction measurements show similar results with respect to the transformation behavior of the metastable austenite below room temperature. Both techniques are successful in monitoring in-situ the martensite transformation of a small amount of retained austenite.

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