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Nano-twinned steel exhibits high mechanical properties obtained through ultra-rapid heat treatment

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ABSTRACT

Ultra-rapid heat treatment was performed on cold rolled high manganese TWIP steel. This process obtains very high mechanical strength and good ductility through the recovery of dislocations, whereas the twins introduced during the cold rolling remain thin and stable. The maximal temperature to retain high yield strength is shown to be around 615 °C, where the first recrystallized grains appear. This heat treatment is found to provide reproducible properties across a wide temperature range and could thus open new perspectives for this type of steel. Finally, a physically based model is used to predict the yield strength resulting from ultra-rapid heat treatments.

1. Introduction

Discovered by Sir Robert Hadfield in 1880 [1], high manganese twinning-induced plasticity steels are currently attracting a lot of attention; their unique combination of high tensile strength (up to 2 GPa) and large ductility (up to 50%) [2–8] through twin formation and dislocation glide may improve the safety of products in the automotive sector. However, the use of these TWIP steels in sectors such as the automotive industry is restricted by its low yield strength. Different solutions have been proposed to improve this property, including precipitation strengthening (adding of Ti, V or Nb) [9] or smaller grain size [8,10]. The first solution leads to a decreased strain hardening, while the sub-micronic grain size required to attain sufficient yield strength for automotive applications (600–700 MPa) is quite difficult to obtain on an industrial scale [10]. Some trials have been carried out, but solely concern the effect of severe plastic deformation on small samples [11]. The third means to increase the yield strength is pre-straining by rolling [8]. However, this process greatly reduces the initial strain-hardening coefficient, resulting in anisotropic behavior. The most promising method is therefore to achieve the recovery and partial recrystallization of pre-strained sheets, providing a high strain hardening and an increased yield strength. As the twins exhibit a relatively high thermal stability up to the recrystallization temperature, heat treatments were carried out to recover the dislocations whilst preserving as many twins as possible. This treatment consists of heating the steel to temperatures between 350 °C and 600 °C for periods ranging from 3 min to 1 h [8]. The authors conclude that these partial recrystallization treatments have a high potential, since a yield strength of 1750–1350 MPa associated to a total elongation of 5–15% were obtained from a 50% cold rolled Fe-22Mn-0.6 C TWIP steel sheet. The drastic variation of the mechanical properties with a small variation of temperature is a major drawback of this process, which is hardly reproducible at the industrial scale. A recent study on Fe-31Mn-3Al-3Si [10] shows that an annealing heat treatment at 650 °C for 300 s after severe cold rolling produces a submicron grain size and leaves a reasonable twin density in the structure. This results in very high mechanical properties, with a yield strength of approximately 700 MPa and an ultimate tensile strength of 840 MPa at 48.5% elongation. However, this kind of microstructure requires a large initial strain, i.e. a Von Mises strain value of approximately 2.9.

More recently, ultra-rapid heat treatments have been studied as a possible solution. Evidence has been provided that unlike conventional processes, this treatment can decrease the grain size of ferrite after annealing in low carbon steels [12] or in initial dual phase microstructure [13]. The heating rate in these treatments is usually between 100 °C/s and 1000 °C/s. This kind of heat treatment has been proved to be industrially feasible [14], and is indeed representative of the thermal cycle experienced during welding, i.e. the assembling process used for these steels in the automotive industry. In this paper, the same concept will be used for recovery of TWIP steels. Rapid heat treatment will be

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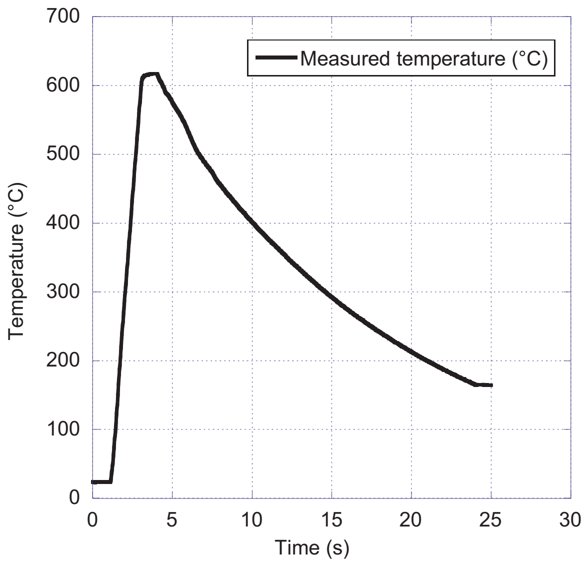

Fig. 1. Temperature measured on the sample for heat treatment at 615 °C (single column figure).

performed on conventional cold rolled high-Mn TWIP steel to obtain a nano-twinned microstructure with an ongoing recovery that provides a good balance between strength and ductility.

2. Method

A Fe-22Mn-0.6 C steel sheet was cold rolled to 50%, with a final thickness of 1.5 mm. Ultra-rapid heat treatment consisting of a rapid heating at 500 °C/s to the desired temperature (from 520 °C to 700 °C) was then performed on samples 30 mm wide and 120 mm long in a Gleeble 3500, followed by air quenching at about 100 °C/s. A holding time of 1 s was used. The typical heat treatment used is shown in Fig. 1.

Tensile samples were then machined in the shape shown in Fig. 2.

This shape was chosen to ensure that the region used for mechanical testing would be homogeneous in terms of temperature. This sample design excludes the possibility of gradient-related problems. Measurement of the temperature showed the gradient to be within the measurement error range (± 2 °C). Tensile tests were performed on an INSTRON 30 kN machine equipped with an optical extensometer. A displacement speed of 2 mm/min was applied until sample fracture. Specimens were prepared for SEM observation as follows: after grinding with P4000 abrasive paper, smooth polishing was carried out using silica colloidal suspension (OPS). Microstructures were analyzed using a JEOL 7001 F FEGSEM and a backscattered electron detector.

3. Results

Fig. 3 presents the results of the tensile tests for different temperatures.

The influence of the heat treatment is clearly visible. As the temperature increases, yield strength decreases and elongation at break increases. For temperatures below 630 °C, yield strength remains remarkably high (up to 1.35 GPa at 615 °C). A sudden decrease to 1050 MPa is then observed at 630 °C. For the sake of comparison, Fig. 4 gives the true stress/true strain curves for the fully recrystallized state

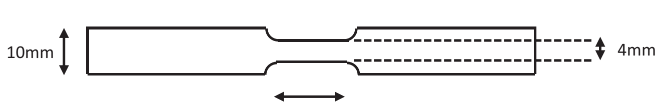

Fig. 2. Scheme of the tensile samples (single column figure).

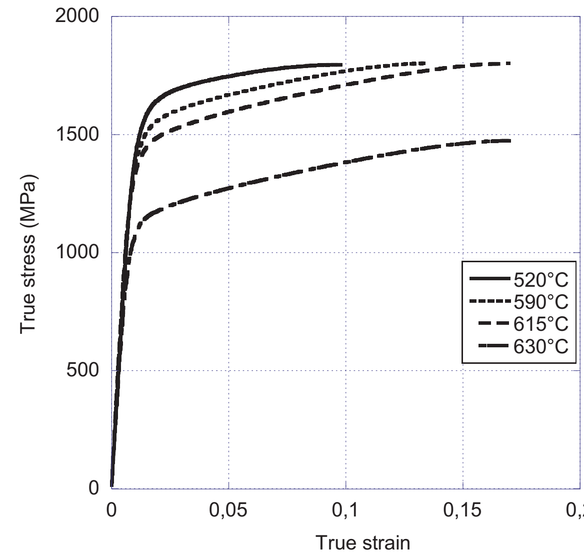

Fig. 3. True stress/true strain curves for different temperatures of recovery treatment (single column figure).

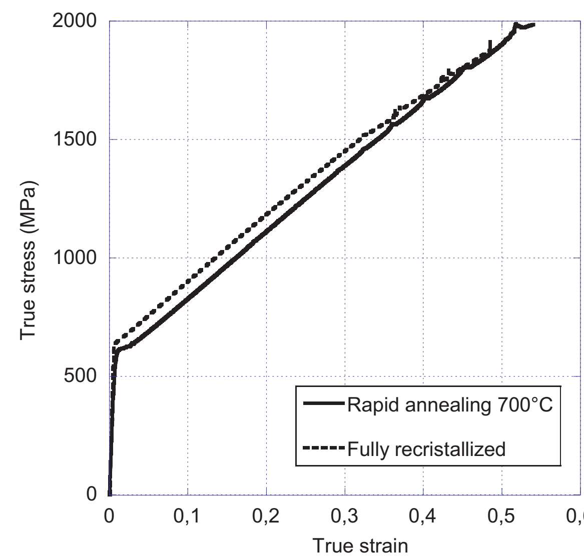

Fig. 4. True stress/true strain curves after ultra-rapid heat treatment at 700 °C and for the fully recrystallized state (one column figure).

(obtained after a heat treatment of 3 min at 800 °C in a conventional furnace) and an ultra-rapid heat treatment carried out at 700 °C.

It is clear that ultra-rapid heat treatment at 700 °C provides a strength close to the fully recrystallized state. In these cases, the yield strength is quite low (about 600 MPa) but the ductility is large (about 50%) and quite unusual for a metallic material. These curves reveal that ultra-rapid heat treatments at temperatures below 700 °C provide very high mechanical strength in comparison with the fully recrystallized state with a decent ductility. The level of strength attained for low temperature heat treatment is among the highest found in the most common forms of carbon steel. It is also worth noting that strain hardening values are comparable between the different temperatures. This point will be discussed in the following sections.

Fig. 5a) and b) show the evolution of the mechanical properties (yield strength YS, ultimate tensile strength UTS, uniform strain and total strain) as a function of the temperature.

A smooth decrease of the yield strength occurs from 520 °C to 615 °C. A drastic decrease is then observed at 630 °C. However, the ultimate tensile strength remains almost constant up to 630 °C. This