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Stability of martensite with pulsed electric current in dual-phase steels

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ABSTRACT

Softening frequently occurs in dual-phase steels under isothermal tempering of martensite. Recently, non-isothermal tempering is implemented to decrease the softening process in dual-phase steels. Here, we have discovered using high power electropulsing treatment can significantly enhance the strengthening effects via the formation of ultrafine-grained ferrite with nano-cementite particles in tempered martensitic-ferritic steels. To the best our knowledge, electropulsing treatment is a proper candidate to retard even to recovery the softening problems in the tempering of martensite in comparison with other isothermal and non-isothermal tempering methods.

1. Introduction

Dual-phase, ferritic-martensitic steels with favourable combinations of high strength and good ductility have attracted significant attention recently in the automotive industries [1–5]. Although, dual-phase steels have outstanding mechanical properties compared with conventional steels, it has been reported that isothermal tempering of martensite (involving slow heating rate, long holding time and slow cooling rate) such as welding frequently leads to softening of the heated-affected zone (HAZ) i.e. a reduction in hardness for dual-phase steels [6–9].

In classical theory, the tempering of martensite occurs in four (temperature-related) stages during the softening process, as shown in Fig. 1 [10]. It can be clearly seen that the hardness of martensitic steels, just as dual-phase steels, are significantly affected by temperature. When the temperature is heated up to 200 °C at stage 1, carbon atoms diffuse and segregate in some specific areas with a high-energy state, such as the grain boundaries. During stage 2, various carbides, such as ε-carbide, start to precipitate in the range, 200–400 °C. On further heating, cementite particles start to precipitate and spheroidize at grain boundaries at temperatures of 400–600 °C during stage 3. When the temperature exceeds 600 °C, most of the martensite laths have recrystallized and the cementite particles have coarsened during stage 4. The total hardness of a dual-phase steel decreases continuously with increasing temperature during the four stages of softening process. However, this softening (induced by the tempering of martensite) frequently causes premature failure in the HAZ of dual-phase steels during welding due to concentration of high strain in the softened regions [11,12]. Thus, many investigators have studied using non-isothermal tempering to replace isothermal tempering [6,12,13]. Non-isothermal tempering, as carried out in e.g. Nd: YAG laser welding involves a high heating rate, a short holding time at the tempering temperature and a high cooling rate. It was found that the non-isothermal tempering effectively decreases the softening by delaying stage 4 of the softening process [6]. Although, non-isothermal tempering is expected to decrease the hardness reduction, there is still a possibility of failure in the HAZ of dual-phase steel induced by softening. Thus, a way of overcoming the softening during the tempering of martensite in welding, is still urgently required to aid the application of dual-phase steels in many industrial installations.

One possible way of solving the above-mentioned difficulties is to use electropulsing treatment (EPT), which is an instantaneous, high- energy- input method. Previous studies using EPT on polycrystalline metals and alloys have shown that grain refinement can be achieved through the combination of thermal and electric effects generated in EPT [14–26]. Thus, the mechanical properties (associated with the changing of grain size) can be subsequently modified by EPT.

Most publications on dual-phase steels have concentrated on the methods to decrease the reduction of hardness (softening) during tempering of martensite [6,8,27]. Consequently, the present work has been focused, principally, on designing a novel method to retard (or overcome) the softening during the tempering of martensite in dual-phase steels. The strengthening mechanism is

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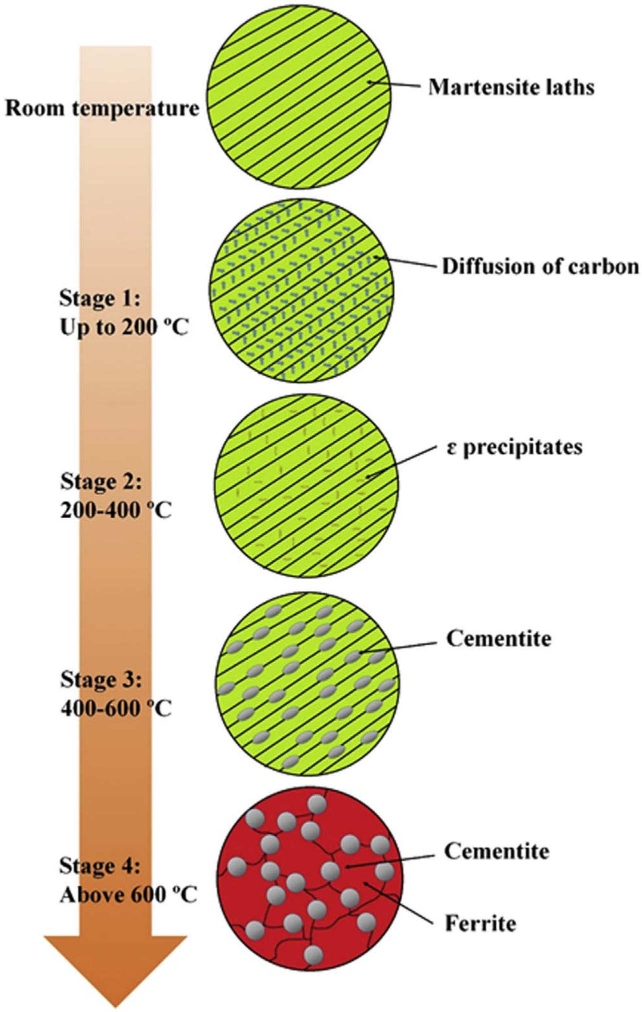

Fig. 1. Four stages in the softening process for the tempering of martenite in dual-phase steels.

responsible for the microstructure evolution under EPT observed in rapidly tempered specimens due to the thermal and electric effects. Therefore, in this study, the cold-rolled, dual-phase steels have been treated with EPT. The tensile mechanical behaviour and the Vickers hardness were measured along with the microstructure evolution, which was monitored using SEM and TEM. These methods provide direct evidence of grain refinement and data for the kinetics and thermodynamics model. This indicates improvements in all mechanical properties of the dual-phase steel, which has not been reported previously for steels of this grade.

2. Materials and methods

The samples consisted of 1 mm thick, dual-phase (DP600) steel plate containing ferrite and martensite phases (chemical composition (wt%): 0.10C, 0.25Si, 1.70Mn, 0.02 P, 0.005 S, 0.040Al and balance Fe). The steel plate was cold rolled to the thickness of 0.5 mm through five passes and the total thickness reduction was 50%. The steel samples were cut into dog-bone shape specimens (gauge length and width were 24.0 and 5.0 mm, respectively) with their longest edge perpendicular to the rolling direction, as shown in Fig. 2. In order to determine the effect of EPT, two sample groups were randomly selected and then one was subjected to EPT and the other used as a control (ie, without EPT). EPT was performed by converting the direct current into a pulsed electric current and the waveform of pulsed current was monitored, in-situ, by a digital storage oscilloscope, as shown in Fig. 2. The pulsed electric current was applied by using, cathode and anode clips to clamp to the steel sample. The pulsed electric current was applied for a total duration of 110 μs and had a peak current density 5.67×10^9 A m^{-2} at ambient temperature. A thermocouple displayed in Fig. 2 was connected with sample specimen and the peak temperature was recorded immediately after EPT.

High-resolution scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were to characterize the microstructure of treated samples and identify the phases present. The sample specimens were ground, polished and etched in 2 wt% Nital for 5 s for SEM analysis. The grain size and volume fraction of each phase were determined using, optical microscopy with $\times$ 100 magnification. This was used to randomly record the microstructure of samples at least 10 times and were then calculated by Image J. For TEM analysis, the specimens were mechanically polished to a thickness of 30 μm, punched to prepare disk specimens with a diameter of 3 mm by a copper disk cutter, and then jet polished to prepare thin foil specimens using a mixture solution of perchloric acid (10%) and acetic acid (90%) with 20 V at 15 °C.

The mechanical properties of the samples, before and after EPT, were measured at room temperature using a Zwick/Roell tensile test machine, with a strain rate 10^{-3} s^{-1}. The Software test Xpert II was used to fit and derive the yield stress (0.2% proof stress) and the elongation. A micro compact, hardness test machine (Zwick 3103 IRHD) with 10 kg load was used to measure the hardness value of samples. The electrical resistance of the samples (with and without EPT) was measured using a micro-ohmmeter (DO5000 series) at room temperature.

3. Results

3.1. Effects of EPT on microstructure evolutions

The optical microstructure of the cold-rolled steel specimen and its XRD spectrum are shown in Fig. 2c and d, respectively. It clearly shows the presence of only two phases. The martensite phase (black regions) is randomly distributed along the grain boundary of the ferrite matrix (grey regions). The volume fraction of ferrite and martensite were calculated to be 63.4% and 36.6%, respectively from Image J. It was found that, after applying EPT, the martensite laths were significantly altered without changing the portion of the two regions, as shown in SEM micrographs (Fig. 3).

Direct evidence of refinement can be clearly observed in martensitic regions (from micro-scale laths to nano-scale particles) in Fig. 3. TEM observations and selected area diffraction patterns (SADP) have been conducted in order to observe the microstructure of the samples (with and without EPT) and to detail and identify the nature of the nano-particles. The bright field images of the morphologies of the martensite laths and the corresponding SADP, for the sample without EPT (Fig. 3e and g, respectively). After EPT, a high density of nano-particles with average size 48 ± 8 nm were found around the grain boundary of the ferrite (indicated by arrows in Fig. 3f) and SADP confirmed that these nano-particles were cementite (Fig. 3h). These nano-sized cementite particles have an orientation relationship ($[012]_\alpha//[101]_\theta$) with the ferrite matrix [6]. In addition, the original martensite laths (Fig. 3e) were partially decomposed into ultra-fine-grained ferrite with a size about 78 ± 13 nm (Fig. 3f) after applying EPT.

3.2. Effects of EPT on mechanical properties

Standard stress-strain curves of samples (without and with EPT) were measured and are plotted in Fig. 4. It was found that EPT