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LETTER

Accelerated bainitic transformation during cyclic austempering

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Austempering is an important thermal processing operation, where strong and tough bainitic steel is produced in a single heat treatment [1, 2]. During the austempering process, the steel is first austenitized and then cooled rapidly just above the martensite start temperature until bainite nucleates and grows, usually until the transformation stops and then it is cooled to room temperature. Due to the sluggish solid-state transformation kinetics, industrial austempering necessitates isothermal holds of 2–24 h, depending on the size and composition of steel. In contrast to conventional isothermal processing, cyclic thermal processing has been shown to accelerate the kinetics of several phase transformations [3–5], with a significant beneficial impact on productivity and energy consumption of these energy intensive operations. This was attributed to the non-isothermal effects resulting from cyclic treatment. The non-isothermal effect on phase transformations has also been utilized to enhance the productivity of a modern batch annealing operation [6]. In the present work, the effect of cyclic processing on austempering kinetics has been compared with conventional isothermal processing for 1080 steel. Furthermore, the effect of cyclic frequency on the austempering kinetics has been studied.

Austempering kinetics experiments were performed on 6 mm diameter cylindrical samples of a 1080 steel using a Gleeble^{TM} 3500 thermo-mechanical simulator (DSI Poestenkill, NY). A diametrical dilatometer was mounted on the specimen to measure the diameter change during the thermal processing. The austempering experiments were performed in two cycles, where the first cycle provides the same initial microstructure prior to each experiment. After completing the first cycle, the cylindrical specimens were heated to the austenitizing temperature (850 °C), held for 5 min and then cooled to different austempering temperatures, where the bainite transformation was monitored for the desired period of time, followed by cooling to room temperature. The cooling rate was sufficiently fast to avoid any transformation occurring before reaching the austempering temperature (Fig. 1). The isothermal experiments were carried out at austempering temperatures of 260 and 300 °C, whereas the cyclic experiments were carried out between 260 °C and 300 °C at two different heating/cooling rates of 1 and 5 °C/min. The percentage of bainitic transformation as a function of time was computed from the dilation curve [2] in conjunction with the microstructural examination by optical microscopy and SEM.

The normalized dilatation curves for isothermal austempering at 260, 300 °C, and cyclic austempering between 260 °C and 300 °C for 1 °C/min and 5 °C/min are shown in Fig. 2. In this figure, only the portion of the curve corresponding to austempering is shown and the dilatation curve has been offset to start at zero. The plateau of the dilatation curve with respect to the time represents the end of the transformation to bainite. It must be noted that the end of the bainite transformation does not necessarily correspond to 100% volume fraction of bainite [1]. Previously, using the same type of Gleeble experiments, it was shown that the end of the transformation corresponds closely to the austenite carbon content corresponding to a T_0 equal to the austempering temperature [2, 7]. Furthermore the transformation dilatation at the end of the

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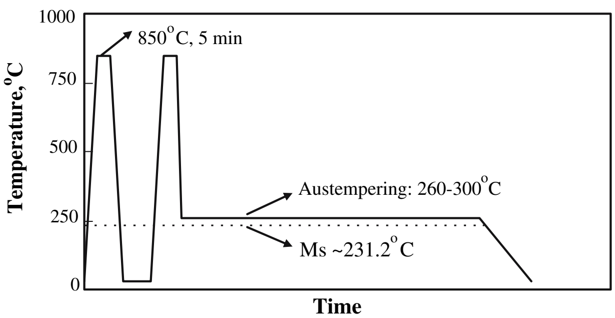

Fig. 1 Austempering experiment temperature-time profiles for 1080 steel

transformation was less the higher the austempering temperature as expected with less bainite fraction [8]. In this work the total transformation dilatation calculated at 260 and 300 °C from Fig. 2 are 0.0069 and 0.0065, respectively. The dilatation at 260 °C is greater at 300°C corresponding to a higher fraction transformed, as expected at lower austempering temperatures. The percentage bainite at the end of the bainitic transformation was estimated from optical and SEM microscopy. The dilatation versus time profiles for long times (250–300 min) were used to determine the actual time for complete transformation for both the isothermal and cyclic processes. It can also be observed from this figure that the cyclic austempering kinetics is faster than the isothermal austempering. As shown in Fig. 3, the isothermal austempering time for the complete bainite transformation requires 160 and 140 min at 260 and 300 °C, respectively. In contrast, for cyclic austempering at 1 and 5°C/min the transformation is completed in much shorter times of about 80 ± 20 and 32 ± 4 min, respectively. The error limit is due to the estimation of the completion time from the plateau of the dilatation curve, at both 260 and 300 °C and allowing for the difference in dilatation caused by thermal expansion/contraction this can be estimated to within the time for half a thermal cycle. This conclusion is also evident from the SEM microstructures shown in Fig. 4, where islands of retained austenite are visible in the isothermally transformed samples, whereas the cyclically austempered samples reveal completely transformed bainitic sheaths after 32 min. It must be noted that the morphology of the isothermally austempered sample at 260 °C is slightly different at 300 °C, whereas the cyclic austempering sample exhibits mixed morphology. The exact nature of the accelerated transformation kinetics will be the subject of further work.

In the present work, it has been shown that cyclic austempering can result in up to about an 80% reduction in

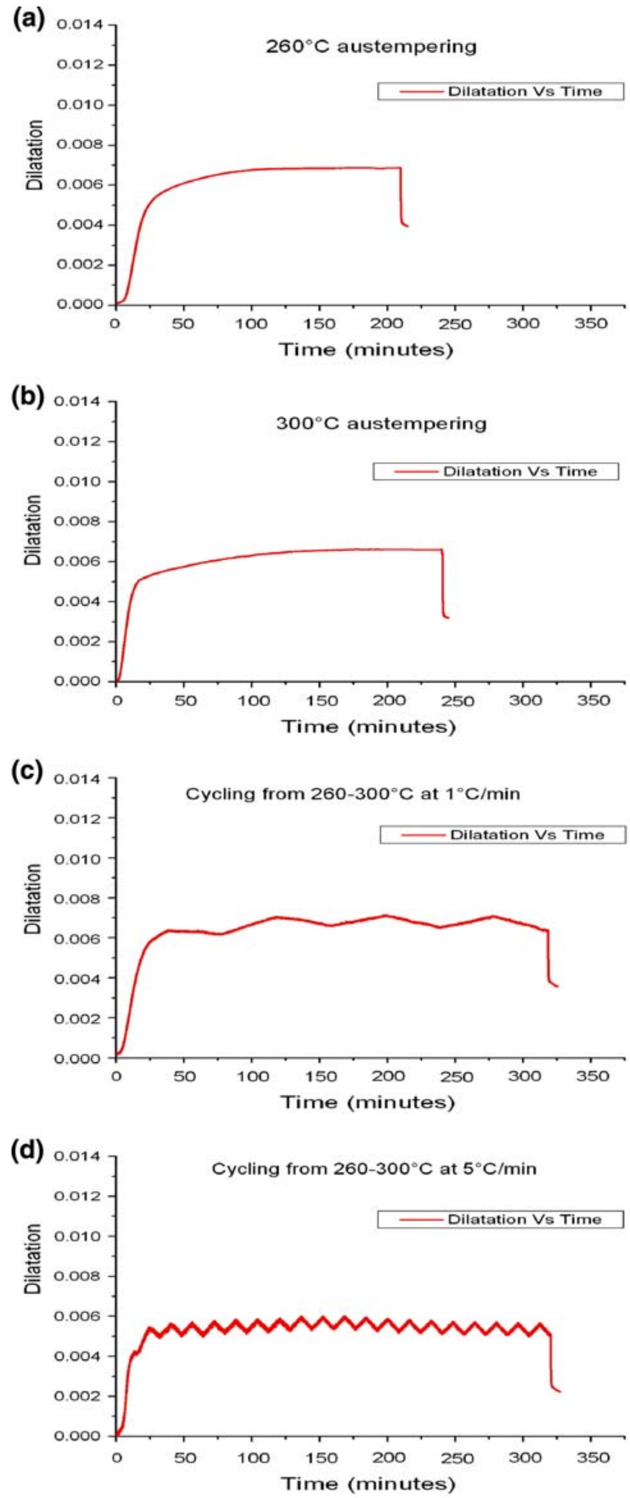

Fig. 2 Dilation as a function of time; (**a**) isothermal austempering at 260 °C for 240 min (**b**) austempered at 300 °C for 240 min (**c**) cyclic austempering between 260 °C and 300 °C at 1 °C/min for 330 min (**d**) cyclic austempering between 260 °C and 300 °C at 5 °C/min for 330 min

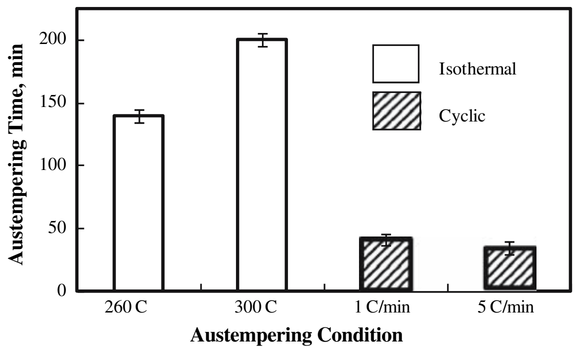

Fig. 3 The time to complete the bainitic transformation during isothermal and cyclic austempering

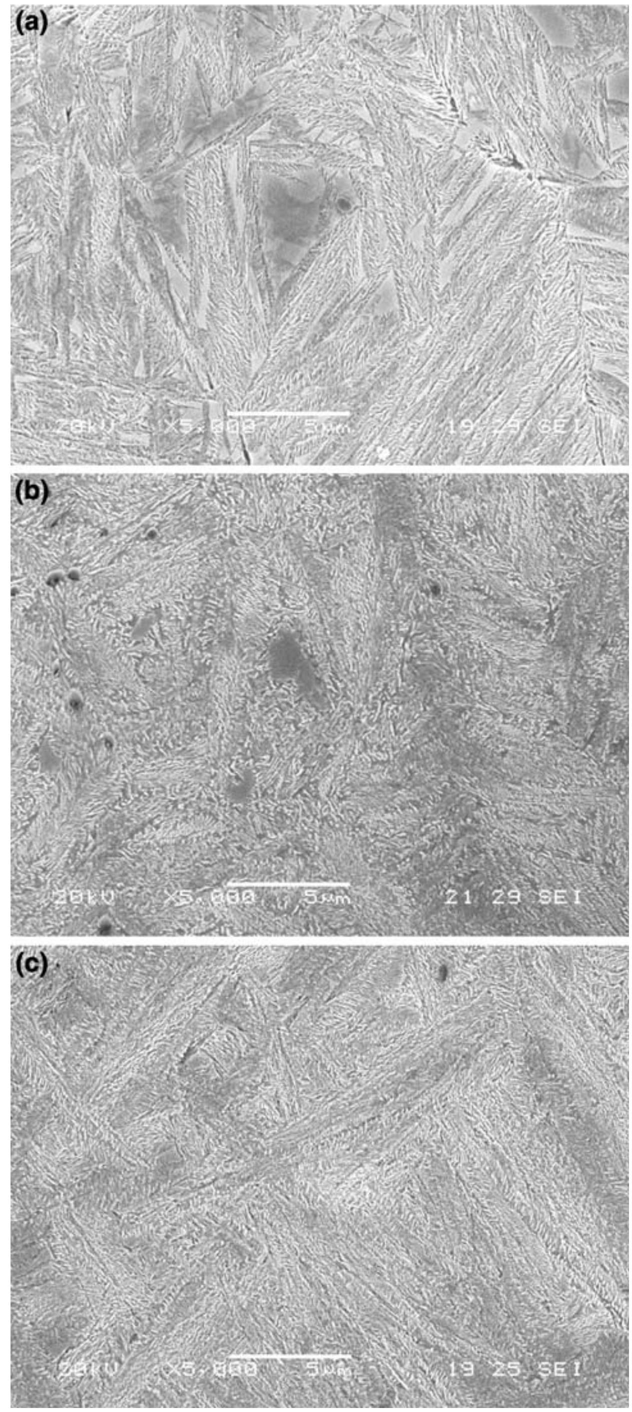

Fig. 4 SEM Microstructure after (**a**) isothermal austempering at 260 °C for 32 min (**b**) isothermal austempering at 300 °C for 32 min (**c**) cyclic austempering between 260 °C and 300 °C at 5 °C/min for 32 min

time for complete bainitic transformation as compared to conventional isothermal austempering. This has direct implications for the productivity of industrial austempering operations. Furthermore, increase in cyclic frequency from 1 °C/min to 5 °C/min resulted in about a 50% reduction in transformation time. As has been explained earlier, [3] these results cannot be explained on the basis of the prevalent quasi-isothermal approach as that does not capture non-isothermal effects, such as heating rate and temperature reversal effects imposed during cyclic annealing. Although these results are in-line with the cyclic recrystallization and grain growth kinetics in cold rolled steel samples, the magnitude of accelerated kinetics (80% increase for austempering) observed in the present work is much higher than the earlier [3] observations of around 20% enhancement during recrystallization and grain growth kinetics. This is likely due to additional effects for bainite transformation, such as enhanced nucleation and relief of transformation stresses. Further work is also underway to model and validate the cyclic austempering behavior, as well as to optimize the cyclic frequency and amplitude for maximizing the austempering kinetics and examining its feasibility for industrial implementation.

In summary, we have shown that the bainitic transformation kinetics during austempering is significantly accelerated (up to 80% reduction in time) during cyclic processing as compared to the conventional isothermal processing. These results could have a significant impact on industrial austempering productivity. Further work is underway to optimize the cyclic austempering profile, the mechanism of accelerated transformation and its feasibility for industrial implementation.

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