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Development of ultrafine ferritic sheaves/plates in SAE 52100 steel for enhancement of strength by controlled thermomechanical processing

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ABSTRACT

The present study attempts to tailor the size, morphology and distribution of the ferrite needles/sheaves by thermomechanical processing and develop an ultrafine ferrite + martensite duplex microstructure for enhancement of strength and toughness in SAE 52100 steel. The thermo-mechanical routine included 5% hot deformation before, during or after austenitizing at 950 °C for 15 min followed by austempering at 270 °C for 30 min and subsequent water quenching to room temperature. Optical/electron microscopy along with X-ray diffraction was used to quantitatively monitor the size, morphology and distribution of the phase or phase aggregate. Significant improvement in nanohardness, wear resistance and elastic modulus and was observed in samples subjected to thermomechanical processing, as compared to that following the same austenitizing and austempering routine without hot deformation at any stage. However, improvement in the bulk mechanical property due to the present thermo-mechanical is lower than that obtained in our earlier study comprising cold deformation prior to austenitizing and austempering.

1. Introduction

SAE 52100 steel is a commercially available grade of high carbon and low alloy steel widely utilized for small, medium and large ball and roller bearings used in automobiles and medium and heavy duty machines and moving components [1]. Conventionally heat treated SAE 52100 steel has a tempered martensitic microstructure along with uniform distribution of primary iron/alloy carbides which provide resistance to both abrasive as well as adhesive wear encountered in bearing assembly and tools. However, heavy and intermittent loads of cyclic nature warrant greater tensile/impact strength and wear resistance [2]. Our prior studies were concerned with development of an improvised austempering routine for SAE 52100 steel to develop a bainite + martensite duplex microstructure [3,4]. We demonstrated that the SAE 52100 steel samples subjected to austempering would yield superior mechanical properties as compared to the normal quenched and tempered samples. It was also found that the ultrafine bainite + martensite duplex microstructure developed by cold deformation prior to austempering was more effective to improve the strength/impact properties as compared to similar duplex phase aggregate developed by usual austempering routine [4].

Extensive studies on the kinetics and growth mechanisms of bainite have been reported in the past. It is well known that bainitic nucleation takes place at prior austenite grain boundaries and the growth is restricted to within the same prior austenitic grain/region as bainitic transformation is an invariant plain strain type of a moving boundary transformation involving a large shear component [5]. Dislocations and residual stress within austenite aid nucleation of bainite, though the rate may be diminished due to the presence of the same defects. These two premises provide additional scope for further refining the bainitic sheaves in the bainite + martensite duplex microstructure. Such ultrafine duplex microstructure is extremely beneficial as a softer and thinner phase (bainite) alternated with a much harder phase (martensite) is conducive to enhance both strength and toughness in steel [6].

An approximate quantification of this effect can be obtained through Eq. (1) for overall yield strength (σ), proposed by Young and Bhadeshia [6], which is bears similarity with the conventional Hall–Petch relationship, but combines the effects of both substitutional and interstitial solid solution strengthening, work hardening, and second phase distribution, along with so-called grain size (here, sheaf-thickness) effect:

$$\sigma = \sigma_{Fe} + \sigma_c + \Sigma\sigma_{ss} + K_1(L_3)^{-1} + K_2\rho_d^{1/2} + K_3\Delta^{-1} \quad (1)$$

where, σ_{Fe} is the strength of pure annealed iron, σ_c is the contribution of solid solution strengthening due to carbon, $\sum\sigma_{ss}$ is the sum

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of contributions to solid solution strengthening from all substitutional solutes, L_3 is the ferrite plate thickness, ρ_d is the dislocation density, Δ is the average distance between primary carbide particles and K_1, K_2, K_3 are material constants.

As already mentioned, we attempted in one of our earlier studies to decrease the austenite grain size by prior cold deformation of the samples before austenitizing [4]. In this approach, the residual dislocations increased the driving force for recrystallization during austenizing and resulted into smaller grains of austenite, which in turn, enhanced the bainitic nucleation density and rate. These results corroborated earlier studies that had indicated, while refinement in the austenite grain size could aid heterogeneous nucleation kinetics of bainite [7], the overall reaction kinetics, however, could be retarded due to physical restriction to sheave growth by grain boundaries [8].

In the present study, we explore the feasibility of further refining the bainitic sheaf length/width by thermomechanical processing (hot deformation) during various stages of austenitizing prior to austempering of SAE 52100 steel. The hot deformation of the relatively softer austenite may generate dislocations, some of which can act as potential nucleation sites for new austenite grains (grain refinement) during austenitizing itself, or provide nucleation sites for bainite during subsequent austempering.

Thermomechanical processing is an established route for altering the microstructure and mechanical properties of steels. Micro-alloying elements and recrystallization behavior can significantly influence the morphology, size and distribution of the phase aggregate so as to obtain the desired range of properties and performance. Hot deformation of SAE 52100 steel has been attempted earlier. Among the earliest studies, Wadsworth and Sherby [9] have reported the effect of chromium on the pinning effect of ferritic grains during the thermomechanical processing 52100 steel. McNelley et al. [10] have studied the effect of isothermal warm rolling of martensitic as well as pearlitic aggregate in SAE 52100 steel. The precipitation kinetics of the carbides is found to be greatly influenced by the thermomechanical treatments at 650 °C.

Chung [11] has demonstrated that a significant improvement in fatigue strength of SAE 52100 steel is possible by introducing bainitic instead of martensitic microstructure through suitable heat treatment of the initial ultrafine ferrite and carbide aggregate obtained through thermomechanical processing. The argument put forward is that the bainitic plates can alter the crack path and delay or inhibit the fatigue crack growth propagation. In our present study we have utilized thermomechanical processing with a similar objective. The spherodized annealed SAE 52100 steel is hot deformed during the various stages of heat treatment where grain refinement is expected to occur through recrystallization during the austenitization. Thus three different thermomechanical routines are attempted with the sole objective of refining the microstructure for improved mechanical properties.

In the present study, we intend to investigate the microstructural evolution and its influence on mechanical properties at appropriate stages of thermomechanical processing followed by controlled austempering. It may be noted that similar thermomechanical processing (hot deformation) of austenite followed by austempering for improving both strength and toughness has not been reported in the literature for SAE 52100 steel or similar low carbon and high alloy steel.

2. Experimental

2.1. Material and heat treatment cycles

Cylindrical rod samples of 4 mm diameter and 250 mm length of spherodized annealed SAE 52100 steel having a nominal composition of 1.1%C, 1.46Cr, 0.27%Si, 0.33%Mn, 0.14%V, 0.04%Ni, 0.02%P and rest Fe (in wt%) were subjected to thermomechanical processing as shown in Fig. 1. In the first cycle the samples were subjected to 5% tensile deformation in the austenite (γ) + ferrite (α) region (between Ac_1 and Ac_3) at 700 °C. Subsequent to this deformation the samples were austenitized at 950 °C for 15 min and quickly transferred to a salt bath furnace for austempering at 270 °C and isothermally aged for 30 min followed by water quenching to room temperature. This cycle will be described throughout the article as Cycle ‘A’. In the second cycle the samples were austenitized at 950 °C for 15 min, cooled in the same furnace at 1 °C/s to 850 °C and subjected to 5% tensile deformation. Subsequently the sample was immediately transferred to a salt bath furnace maintained at

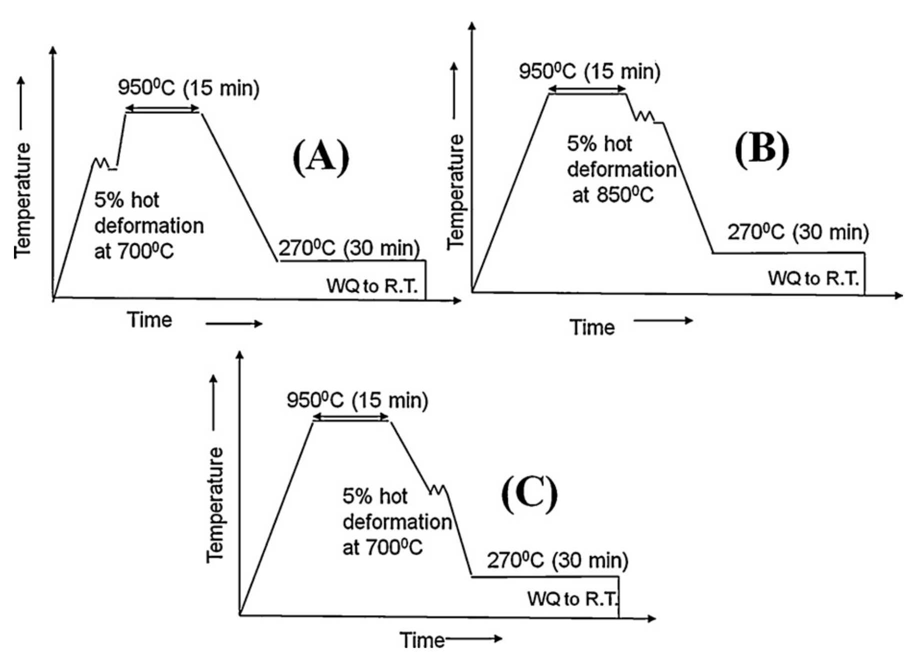

Fig. 1. Schematic diagram of the three different thermomechanical processing (5% tensile hot deformation) cycles applied to SAE 52100 steel. (Cycle ‘A’, Cycle ‘B’ and Cycle ‘C’.)