Materials Science & Engineering A 706 (2017) 15–21

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Improved uniformity of hardness by continuous low temperature bainitic transformation in prehardened mold steel with large section

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ARTICLE INFO

Keywords:
Pre-hardened mold (PHM) steel
Quenching and tempering
Thermal expansion
Finite element modeling
Retained austenite

ABSTRACT

Expanding automobile industry energized the demand for large section plastic mold steel, large (465 mm × 1325 mm × length) pre-hardened mold (PHM) steel was trial-produced by quenching the forged slab at temperature between start (Ms) and finish (Mf) temperature of martensite, followed by tempering, according to the thermal expansion experiments and finite element modeling (FEM) of cooling rate from core to surface. Continuous low temperature bainitic transformation in PHM steel created high volume fractions of refined bainitic-ferrite laths, filmy retained austenite and dispersed carbides. Uniformity of microstructure and hardness, and the impact toughness of the PHM steel were remarkably superior to the one produced by conventional quenching & tempering (QT) process.

1. Introduction

The surging automobile industry energizes the production and consumption as well as the research of pre-hardened mold (PHM) steels [1]. PHM steel in delivered condition can be directly manufactured into mold cavity; it has advantages in wear resistance, hardness, weldability, machinability, corrosion resistance, and polishing property [2]. PHM steel occupies a large ratio in plastic mold productions. In response to the intense competition on technique and cost, large-section PHM steels were developed at the risk of quenching crack and hardness fluctuation [3], and conventional quenched & tempered (QT) treatment for pre-hardening was applied [3]. Thick PHM steels were quenched to temperature below start temperatures of bainite (Bs) to obtain bainitic microstructure. Appropriate cooling rate in core site of large PHM steels during quenching should be warranted to avoid the induction of ferrite or pearlite, as well as cracks causing by thermal stress. Microscopically, The coarser microstructure of bainitic ferrite and islands of martensite/austenite (M/A) would evidently deteriorate the over-all properties [4].

Novel low-temperature bainitic steel was reported by Bhadeshia et al. [5,6]. The excellent combination of strength and toughness of this steel is owing to the presence of nanoscale bainitic ferrite with high density of dislocation and interlaced filmy retained austenite, respectively. Recently, Wang et al. [7] proposed multi-step isothermal bainitc transformation in medium-carbon steel, and encouraging refined bainitic microstructure was presented. Moreover, Zhao et al. [8] found that bainitic transformation was accelerated significantly by the prior partial martensitic transformation.

In the present work, PHM steels with large section were treated by two separate processes, one was to quench the forged steel block to temperature between start temperature of bainite (Bs) and start temperature of martensite (Bs~Ms), followed by tempering treatment (the steel is designated as "QT" steel), the other one was to quench the forged steel block to temperature between start and finish temperatures of martensite (Ms~Mf), followed by tempering treatment (the steel is designated as "PHM" steel), with the aim to comparatively study the refinement mechanism of below-Ms quenching. The production process of QT and PHM was schematically illustrated in Fig. 1. In advance, the thermal expansion behaviors of austempering between temperatures of Bs and Mf were detected, and the cooling rates from core to surface of PHM steel during heat treatments were predicted by finite element method (FEM) at rehearsal. Specially, microstructures of as-treated PHM steel from core to surface, as well as intrinsic factors influencing toughness and hardness uniformity were investigated.

2. Materials and experimental procedures

Two 25 t ingots with a chemical composition of Fe-0.2C-0.2Si-1.6Mn-1.03Cr-0.25Mo-0.12Ni (wt%) was smelt in electric arc furnace, followed by ladle refining and vacuum degassing. Specimens with a size Φ4 × 10 mm were machined for thermal expansion experiments conducted on Bähr 805A dilatometer. The AC_3, AC_1, Bs, Ms and Mf temperature of the steel were detected to be 860 °C, 770 °C, 450 °C, 372 °C

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http://dx.doi.org/10.1016/j.msea.2017.08.104
Received 15 July 2017; Received in revised form 23 August 2017; Accepted 24 August 2017

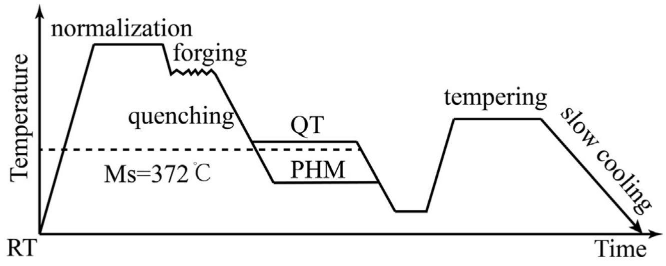

Fig. 1. Schematic illustration of heat treatment processes for QT and PHM steels.

and 256 °C, respectively.

Vickers hardness values were the average of 5 tests. Impact toughness (a_{kv}) measured at room temperature was averaged from 5 tests, using V-notched samples of size of 10 × 10 × 55 mm^3 according to the standard ASTM E23. Microstructures were examined by optical microscopy (OM, NIKON MA100), scanning electron microscopy (FEG-SEM, JEOL JSM-7600F operating at 15 kV) and transmission electron microscopy (TEM, JEM-2010 operated at 200 kV). OM and SEM specimens were mechanically polished and etched with 4% nitric acid solution. TEM observation was carried out on thin foils electropolished at − 30 to − 20 °C using 4% perchloric acid solutions. SEM and OM micrographs were used to determine the distribution, size (width and thickness), morphology and volume fraction of each phase. The average thickness of lath-like phases was determined using the mean linear intercept $L = \pi t/2$ method in a direction normal to the plates [7]. The volume fraction of austenite at room temperature was determined by X-ray diffraction (XRD) with Cu-Kα radiation using a D/max-2550 X-ray diffractometer based on a direct comparison method of the integrated intensity of $(200)\gamma$, $(220)\gamma$ and$(311)\gamma$ austenite peaks and $(200)\alpha$ and $(211)\alpha$ ferrite peaks [9].

3. Results and discussions

3.1. Thermal expansion experiment

In order to study the bainitic transformation behavior by experiments on Bähr 805A dilatometer, Φ4 × 10 mm samples were heated at a rate of 5 °C/s to 910 °C and held for 900 s, then quenched to 380 °C, 350 °C and 320 °C and held for one hour, respectively, finally quenched at 5 °C/s to room temperature. The samples were designated as QT380, QT350 and QT320, respectively.

The dilation-temperature and dilation-time curves of QT380, QT350 and QT320 are plotted in Fig. 2. Three dilation-temperature curves appeared to be linear until cooling down to the isothermal temperature; it indicates that the quenching rate was high enough to avoid transformation before tempering. For the above-Ms process, when quenched to 380 °C for one hour, evident isothermal expansion was visible (Fig. 2a). The corresponding dilation-time curves (Fig. 2b) show a continuous expansion at 380 °C, indicating the occurrence of time-dependent bainitic transformation. In comparison, for the below-Ms tempering, it can be seen that time-dependent bainitic transformation also occurred below-Ms at 350 °C and 320 °C (Fig. 1b), but these were preceded by martensitic transformation. It can be seen that there was no incubation period for bainitic transformation in QT350 and QT320, and bainitic transformation occurred as soon as the tempering temperature was reached. Through microstructural observations by OM and SEM, QT350 has ~ 55% martensite and ~ 45% bainite, and formation of ~ 40% bainite exhausted ~ 28 s. Whilst QT320 has ~ 79% martensite and ~ 21% bainite, and ~ 19% bainite exhausts 270 s. It means that as quenching temperature decreased from 350 °C to 320 °C, the transformation rate of bainite in QT320 was about one twentieth of QT350. The present result suggests that the bainitic transformation process at temperatures below Ms was postponed by the prior formed martensite. The results is in contrary to the findings by Zhao et al. [8], they observed the period for bainitic transformation was shortened by decreasing below-Ms tempering temperature. This is probably due to the fact that the hydrostatic pressure helps to stabilize the retained austenite, since it hinders the austenite-to-bainite transformation [10]. Furthermore, owing to the formation of prior martensite, additional dislocations would be introduced into the residual austenite, and these dislocation structures are believed to mechanically stabilization of retained austenite [11]. There might be also some other factors that also influence the kinetics of bainitic transformation, which needs to be studied further.

Table 1 shows the microstructure and performance of QT380, QT350 and QT320 steels. As tempering temperature decreased from 380 °C to 320 °C, statistic results shows that the width of bainitic ferrite (BF) had decreased from 228 nm to 125 nm, whilst the average size of blocky island of martensite and austenite (M/A) decreases slightly. It is in consistent with the findings by Wang et al. [7]. The fluctuation of Vicky hardness of QT320 was detected to be more steady than QT350, the primary cause is the spacing of BF was narrowed by decreasing tempering temperature, and the hardness of bainite rised to the level of tempered M/A. For three experimental steels (QT380, QT350 and QT320), the increase of impact toughness and hardness caused by the below-Ms austempering treatments is evident. The impact toughness of QT380, QT350 and QT320 was 25 J cm^{-2}, 30 J cm^{-2} and 31 J cm^{-2}, whilst the Vickers hardness of QT380, QT350 and QT320 increased from 322 kg/mm^2, 328 kg/mm^2 to 342 kg/mm^2. The volume fraction of retained austenite also increased from 3% to 5%, and the level of

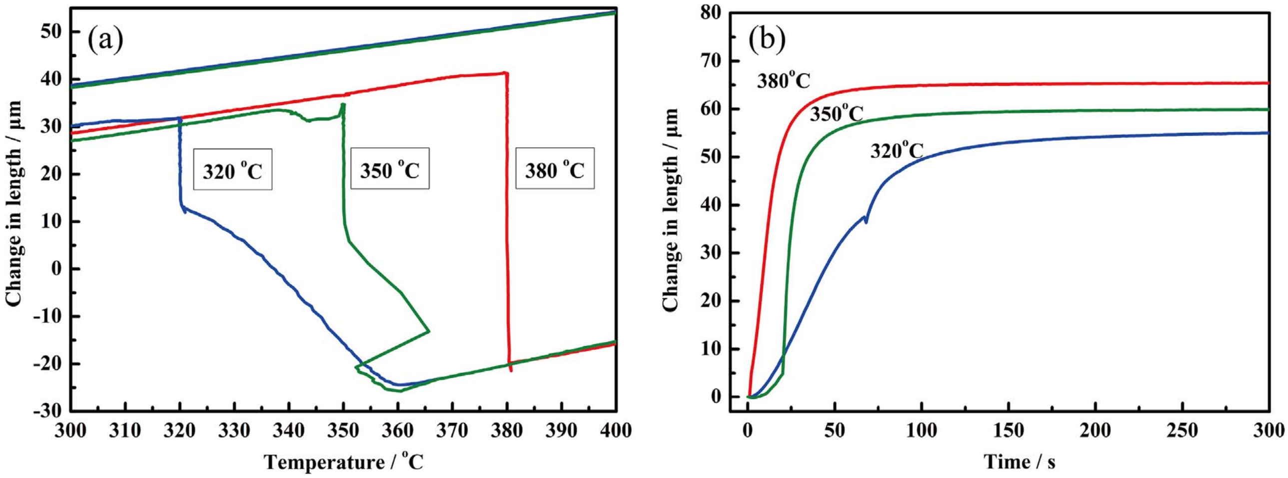

Fig. 2. Dilation- temperature (a) and dilation-time (b) curves of QT380, QT350 and QT320.