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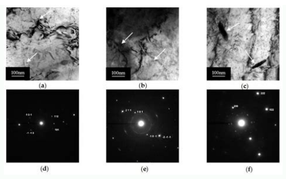

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Refined Bainite Microstructure and Mechanical Properties of a High-Strength Low-Carbon Bainitic Steel Treated by Austempering Below and Above M_S

Junyu Tian, Guang Xu, Mingxing Zhou, and Haijiang Hu*

Four isothermal heat treatment schedules are designed to study the effects of transformation temperature below and above martensite starting temperature (M_S) on bainitic transformation kinetics, microstructure, and mechanical properties of a low-carbon bainitic steel. The results indicate that the product of tensile strength and elongation (PSE) of tested steel do not show any improvement when the samples are austempered at a temperature below M_S. Finer bainite microstructure can be observed when the samples are austempered at a temperature below M_S, but the highest PSE is obtained in the sample austempered at a temperature above M_S (400 °C). Lower PSE of the samples transformed below M_S is mainly attributed to less bainite and retained austenite (RA) amount and more amount of athermal martensite, as well as the existence of carbide. In addition, with the decrease of the isothermal transformation temperature, the PSE first increases and then decreases. Different from austempering above M_S, when the sample is austempered below M_S, PSE decreases with the decrease of transformation temperature. Moreover, whether the treatment below M_S can improve mechanical property of bainitic steels depends on the composition of steels and transformation temperature.

1. Introduction

Since ultrafine or nanostructured bainitic microstructure with high strength and good toughness is discovered,[1,2] ultrafine bainitic steels have been universally applied in machinery, automobile, railway industries, and so on.[3–5] It has been reported that the final size of the bainitic plate is primarily controlled by two factors,[6] that is, the stability of austenite that limits the growth of bainite and the driving force for bainitic transformation. Generally, both factors are determined by the chemical composition and austempering temperature. The effects of austempering temperature above martensite starting temperature (M_S) on the transformation and microstructure of bainitic steel have been widely reported in recent years.[7–15] For further understanding the bainite transformation and improving the comprehensive property of bainite steels, some researchers used the isothermal transformation temperature below M_S. They based on the mechanism that lower transformation temperature can provide the larger driving force, which may be useful to obtain a finer microstructure.

Bohemen et al.[12] investigated the isothermal decomposition of austenite below M_S in a Fe–0.66C–0.69Mn (wt%) steel by dilatometry and microstructure examination and found that the austenite decomposes isothermally below M_S at a certain rate. Both dilatometry and microstructure (mixed martensite-bainite microstructure) strongly identified the formation of isothermal bainite below M_S. Similarly, Kolmskog et al.[13] directly observed the growth of bainite below M_S in Fe–0.51C–2.28Si–2.05Mn (wt%) steel by laser-scanning confocal microscopy (LSCM) and in situ simultaneous synchrotron X-ray diffraction and suggested that the C curve of bainite formation may be extended below M_S in a time–temperature–transformation (TTT) diagram. Additionally, the kinetics of the isothermal product formed below M_S temperature in Fe–0.32C–0.64Si–1.78Mn–1.75Al–1.20Co (wt%) steel were analyzed by Samanta et al.[14,15] They demonstrated that the Zener-Hillert model is too slow to match the observed kinetics at such a low temperature (below M_S). On the contrary, the kinetics of bainite formation with a displacive mechanism is in accord with the observed isothermal transformation kinetics below M_S. Therefore, they asserted that the isothermal product below M_S that interrupts the formation of athermal martensite is bainite.

Besides medium- and highcarbon steels, bainite transformation below M_S in low-carbon steels was similarly investigated. Silva et al.[16] studied the decomposition of austenite austempered below M_S in a low-carbon steel and observed the formation of bainite below M_S. Simultaneously, they used a nucleation-based transformation model to describe the kinetics of isothermal bainite formation below M_S. Additionally, Zhao et al.[17] elucidated that the bainite microstructure could be formed below M_S in a 0.15C (wt%) low carbon steel. They emphasized the result that compared with the conventional isothermal transformation process above-M_S, the below-M_S process refines effectively bainitic plates. They also claimed

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Effect of austenitization temperature on microstructure and mechanical properties of low-carbon-equivalent carbidic austempered ductile iron

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Abstract: The wear resistances of austempered ductile iron (ADI) were improved through introduction of a new phase (carbide) into the matrix by addition of chromium. In the present investigation, low-carbon-equivalent ductile iron (LCEDI) (CE = 3.06%, and CE represents carbon equivalent) with 2.42% chromium was selected. LCEDI was austenitized at two different temperatures (900 and 975°C) and soaked for 1 h and then quenched in a salt bath at 325°C for 0 to 10 h. Samples were analyzed using optical microscopy and X-ray diffraction. Wear tests were carried out on a pin-to-disk-type machine. The effect of austenitization temperature on the wear resistance, impact strength, and the microstructure was evaluated. A structure-property correlation based on the observations is established.

Keywords: low carbon equivalent ductile iron (LCEDI); carbidic austempered ductile iron (CADI); wear test; austenitization temperature; impact strength

1. Introduction

Austempered ductile iron (ADI) is a low cost material well known for its high tensile strength and toughness [1]. It is also known for its high fatigue strength and excellent wear resistance [2–4]. Additionally, ADI has a high strength-to-weight ratio, which makes it a candidate material to replace forged steels in many applications.

The mechanical properties of ADI are attributed to its matrix. The matrix of ADI consists of acicular ferrite and carbon-stabilized austenite. Gatin and Mannheim [5] reported that, while working on the wear characteristics of ADI, the austenite phase in the micro-structure of ADI is converted into martensite under an applied load. This phenomenon is called the strain-induced/stress-assisted phase transformation of retained austenite into martensite (SITRAM/SATRAM) [6–7] and it is similar to that observed in transformation induced plasticity (TRIP) steels. Thus, ADI becomes harder with application of a load. This property of ADI makes it an ideal choice for applications that requires high wear resistance and toughness. Zimba *et al.* [8] have suggested that ADI is useful for the components of earth-moving machines. However, ADI has a limitation: its modulus is low compared with that of steel. The graphite volume fraction in ADI is approximately 12%–15% [9]. Consequently, the Young's modulus (E) of ADI is 176 GPa, whereas that of steel is 205 GPa [10]. Thus, heavier and larger sections of ADI are required to deliver same rigidity as a steel component. This limitation is one of the constraints faced by design engineers attempting to reduce the weight of components and make machines more efficient. This problem of low modulus of elasticity can be overcome by reducing the graphite volume fraction in ADI. Low-carbon-equivalent ductile iron (LCEDI) contains C and Si in concentrations much lower than those in conventional ductile iron (DI). Thus, their carbon-equivalent (CE) is much lower compared with that of conventional DI. Their modulus of elasticity has also been reported to be higher than that of DI [10]. The response of low-carbon-equivalent irons to austempering treatment has been well established [11–12]. These alloys have been reported to exhibit better wear resistance than ADI, and this enhanced wear resistance has been attributed to presence of ledeburitic carbides [13].

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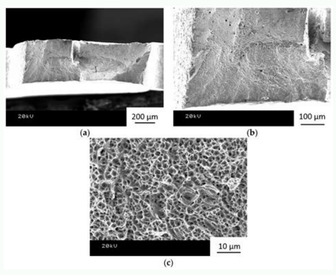

Open Open AccessFeature PaperArticle Gipimme, Department of Materials Engineering, Engineering Faculty, Universidad de Antioquia, Calle 67 No. 53-108, Bloque 18, Oficina 240, MedellÃÂn 050010, Colombia MATERALIA Research Group, Department of Physical Metallurgy, National Center for Metallurgical Research (CENIM-CSIC), Avenida Gregorio del Amo, 8, 28040 Madrid, Spain Authors to whom correspondence should be addressed. Metals 2020, 10(5), 635; Received: 13 April 2020 / Revised: 10 May 2020 / Accepted: 12 May 2020 / Published: 14 May 2020 Carburizing implies the existence of a carbon gradient from the surface to the core of the steel, which in turn will affect both the critical temperature for austenite formation and the kinetics of the bainitic transformation during the austempering treatment. Therefore, for future development of carbo-austempered steels with nanobainitic microstructures in the case, it is key to understand the effect of such carbon gradient has on the final microstructure and the mechanical properties reached by the heat treatments used. This work was divided into two parts, firstly two alloys with similar carbon content to those at the surface and center of the carburized steel were used to establish the optimal heat treatment parameters and to study bainite transformation kinetics by high resolution dilatometry. In a second step, a carburized alloy is produced and subjected to the designed heat treatments, in order to evaluate the microstructure and mechanical properties developed. Results thus obtained are compared with those obtained in the same carburized alloy after following the most common quench and temper treatment. Conceptualization, O.R.-D. and R.A.-S.; investigation, O.R.-D.; project administration, C.S.-G.; Supervision, R.A.-S., J.A.J. and C.G.-M.; writing¢ÃÂÂoriginal draft, O.R.-D., R.A.-S., J.A.J. and C.G.-M.; writing¢ÃÂÂreview & editing, O.R.-D., R.A.-S., J.A.J. and C.G.-M. All authors have read and agreed to the published version of the manuscript.This research was funded by the CODI-Universidad de Antioquia.The authors want to thank Phase Transformation and XRD Laboratories at the National Center for Metallurgical Research-CENIM-for the support provided for the experimental development of this work.The authors declare no conflict of interest. Figure 1. Relative change in length (RCL) as a function of T during 0.18 Ã°ÂC/s heating up to 1000 Ã°ÂC and subsequent cooling down to room temperature, 100 Ã°ÂC/s, for both alloys. Figure 2. Light optical micrographs of austenitized and quenched samples: (a) 0.76 wt.% C alloy after austenitized at 900 Ã°ÂC/30 min and for the 0.29 wt.% C (b) austenitized at 900 Ã°ÂC/30 min, (c) austenitized at 830 Ã°ÂC/15 min. Etched with Picral. Figure 3. Theoretical Nehrenberg [19] and experimental Ms temperature as a function of carbon content in austenite, CÃ³Â. Figure 4. For the case steel (0.76 C wt.%), relative change in length (RCL) curves as a function of temperature and time for the different Tiso-tiso (a) and (b) for TÃ³Â = 900 Ã°ÂC and (c) and (d) TÃ³Â = 830 Ã°ÂC. Figure 5. For the core steel (0.29 Cwt.%), relative change in length (RCL) curves as a function of Temperature and time for the different Tiso-tiso (a) and (b) for TÃ³Â = 900 Ã°ÂC and (c) and (d) TÃ³Â = 830 Ã°ÂC. Figure 6. Secondary electron SEM images of the microstructure of the alloy with 0.76% of C, after austenitization at 830 Ã°ÂC/15 min., and treated isothermally at (a) 250 Ã°ÂC/480 min., and (b) 300 Ã°ÂC/240 min. Where Ã³Âret is austenite and Ã±Âb bainitic ferrite. Figure 7. Secondary electron SEM images of the microstructure of the alloy with 0.29% of C, after austenitization at 830 Ã°ÂC, and treated isothermally at (a) 250 Ã°ÂC/480 min., and (b) 300 Ã°ÂC/240 min. and austenitization at 900 Ã°ÂC, and treated isothermally at (c) 250 Ã°ÂC/480 min., and (d) 300 Ã°ÂC/240 min. Where Ã±Â is 3ÎT)%.tw(C .tnemtaert lamrehtosi eht fo erutarepmet eht ot erutarepmet gnizitinetsua eht morf etar gnilooc eht si osiRC .semit evitcepser eht rof dnats osit dna 3Ît saerehw,ylevitcepser,erutarepmet gnirepmetsua dna noitazitinetsua eht rof sdnats osiT dna 3ÎT erehW .tset lamrehtosi rof snoitidnoc tnemtaert taeH) dna sM detamitsE .ecafrus tenirubrac eht morf htped htiw noitubirtsid tnetnoc nobra C .9 erugiF .leets esac)b(dna eroc rof)a(:noitidnoc T&Q eht fo erutcurtsorcim eht fo segami MES nortcele yradnoceS .8 erugiF .etirref citiniab si b± dna etinetsua + etisnetram si± 3 (min)CRiso (Ã°ÂC/s)Tiso (Ã°ÂC)tiso (min)0.29900153525048030024083025048030024 00.769002504803002408302504803002400.769002504803002408302504803002400 Table 5. Microstructural characterization data from the samples isothermally transformed. Where, VÃ³Â and CÃ³Â stand for the volume fraction and carbon content of austenite measured by XRD. VÃ±Â is the fraction of proeutectoid ferrite measured by point counting. From dilatometric curves the martensite start temperature, Ms and fraction of martensite VÃ±Â¢ÃÂÂ are derived. Fraction of bainitic ferrite VÃ±Âb = 100 ¢ÃÂÂ (VÃ³Â + VÃ±Â + VÃ±Â¢ÃÂ²Â). Finally, tÃ±Âb and tÃ³Ât stands for the bainitic ferrite and retained austenite thin film thicknesses, respectively. Alloy C (wt.%)0.290.76 Isothermally treated samplesTÃ³Â(Ã°ÂC)/tÃ³Â(min)900/15830/15900/15830/15Tiso(Ã°ÂC)/tiso(min)250/480300/240250/480300/240250/480300/240250/480300/240tÃ±Âb (nm)168 Ã±Â 13250 Ã±Â 13135 Ã±Â 15170 Ã±Â 1658 Ã±Â 696 Ã±Â 1854 Ã±Â 6102 Ã±Â 18tÃ³Ât (nm)146 Ã±Â 14195 Ã±Â 1590 Ã±Â 14140 Ã±Â 1044 Ã±Â 670 Ã±Â 1045 Ã±Â 965 Ã±Â 11VÃ±Âb (Vol %)25.534.525.358.585.583.386.785.1VÃ±Â¢ÃÂ²Â (Vol %)705636-----VÃ±Â (Vol %)--32.3 Ã±Â 333 Ã±Â 3----VÃ³Â (Vol %)4.5 Ã±Â 39.5 Ã±Â 36.7 Ã±Â 38.5 Ã±Â 314.5 Ã±Â 316.7 Ã±Â 313.3 Ã±Â 314.9 Ã±Â 3CÃ³Â (wt.%)1.54 Ã±Â 0.121.67 Ã±Â 0.121.63 Ã±Â 0.120.79 Ã±Â 0.121.03 Ã±Â 0.121.24 Ã±Â 0.121.20 Ã±Â 0.121.33 Ã±Â 0.12HV10490 Ã±Â 9440 Ã±Â 7380 Ã±Â 6340 Ã±Â 8579 Ã±Â 4513 Ã±Â 5576 Ã±Â 6510 Ã±Â 10Ms (Ã°ÂC)356374291----- Table 6. Mechanical properties in carburized steel under different processes. Q&T: quenching and tempering; YS: yield strength; UTS: ultimate tensile strength; TE: total elongation; V-notch: impact energy. TÃ³Â/tÃ³Â (Ã°ÂC/min)Tiso/tiso (Ã°ÂC/min)YS (MPa)UTS (MPa)TE (%)V-Notch (J)900/15Q&T846 Ã±Â 13911 Ã±Â 156.0 Ã±Â 0.54 Ã±Â 0.5900/15250/4801220 Ã±Â 71310 Ã±Â 168.0 Ã±Â 0.46 Ã±Â 0.4300/2401025 Ã±Â 261110 Ã±Â 178.5 Ã±Â 0.48 Ã±Â 0.8830/15250/4801289 Ã±Â 51390 Ã±Â 269.0 Ã±Â 0.29 Ã±Â 0.3300/4801106 Ã±Â 111179 Ã±Â 2510 Ã±Â 0.212 Ã±Â 0.4 Ã©Â 2020 by the authors. Licensee MDPI, Basel, Switzerland. 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24/06/2022 · The service performance of single crystal blades depends on the crystal orientation. A grain selection method assisted by directional columnar grains is studied to control the crystal orientation of Ni-based single crystal superalloys. The samples were produced by the Bridgman technique at withdrawal rates of 100 μm/s. During directional solidification, the directional … Heat treating (or heat treatment) is a group of industrial, thermal and metalworking processes used to alter the physical, and sometimes chemical, properties of a material.The most common application is metallurgical.Heat treatments are also used in the manufacture of many other materials, such as glass.Heat treatment involves the use of heating or chilling, normally to … Wrought iron is an iron alloy with a very low carbon content (less than 0.08%) in contrast to that of cast iron (2.1% to 4%). It is a semi-fused mass of iron with fibrous slag inclusions (up to 2% by weight), which gives it a "grain" resembling wood that is visible when it is etched, rusted, or bent to the point of failure. Wrought iron is tough, malleable, ductile, corrosion resistant, and ...

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