Effect of intercritical processing temperature on mechanical properties, microstructure and microhardness of ferrite - bainite medium carbon dual phase steels

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Abstract: This research focuses on the dual phase (ferrite and bainite) treatment for medium carbon steels containing same carbon content (different alloying elements) and mechanical properties, as well as microhardness and microstructure. Dual phase treatment is carried out by heating normalized specimen to intercritical temperature range (750, 770 and 790 °C), followed by isothermal holding in the bainitic temperature (350 °C) and cooling to room temperature in still air. The effect of chemical composition (alloying elements) of steel on the dual phase morphology intern on the mechanical properties like, tensile strength, elongation, hardness and impact energy is also presented. Mechanical property results are in par with the microstructure and microhardness of dual phase obtained. Lower intercritical temperature (750 °C) has resulted in lesser amount of bainite phase with poor mechanical properties in dual phase structure, whereas higher temperature (790 °C) increases bainite phase content with considerable improvement in mechanical properties. Microhardness data obtained supports the qualitative analysis of microstructure in all steels under consideration. It is found that intercritical temperature of dual phase treatment and material alloying elements are the major contributing factors on the dual phase microstructure and mechanical properties.

ABOUT THE AUTHOR

Our group’s research area is mechanical characterization and microstructure related study of ferrite - bainite medium carbon dual phase steels.

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PUBLIC INTEREST STATEMENT

The objective of manufacturing unit is to increase the production rate with reduction in production cost. To achieve this goal, high-speed machining is inevitable. High-speed machining without compromising the quality of the product is solely dependent on machinability. To improve machinability, it is desired to have high material removal rate with lower power consumption to enhance tool life with reduced surface roughness. Even small differences in the composition of the steel and alterations in phases can have a drastic effect on its properties. This phase modification is possible by heat treatment techniques. Dual phase with ferrite and bainite phase combination is having balanced tensile, hardness and toughness properties, which is ideal for the machinability improvement in medium carbon steels.
1. Introduction
The medium carbon steels with or without alloying elements (Cr, Mn, Ni, etc.) are most widely used steels for the construction of structural equipment due to its versatility in property alteration, flexibility for adoptability and reliability for the application. This implies that the carbon content in steel plays an important role in its application. The suitability of medium carbon steels for most of the applications is due to property enhancement through heat treatment (Avner, 2004). Heat treatment is a combination of timed heating and cooling applied to a particular metal or alloy in the solid state in such a way as to produce desired microstructure and the mechanical properties. Thus, the application of medium carbon low alloy steels with suitable heat treatment process gains importance in automotive structural applications like axles, bolts, crank shafts, connecting rods, torque tubes, etc. However, these steels are prone to poor machinability and show moderate strength and hardness in as-bought condition. This drawback is tackled by the addition of more number of suitable alloying elements in the balanced proportion to medium carbon steels and property enhancement by heat treatment.

The enhancement of properties of medium carbon steels (AISI1040, 4140 and 4340) is possible if the dual phase structure consisting of ferrite and bainite is obtained during heat treatment. The dual phase is obtained by heating steels in the intercritical temperature range for partial austenitization and then rapidly quenching in a suitable medium (Caballero et al., 2001; Kumar et al., 2008; Sharma & Rajan, 2010) above room temperature for considerable time. The dual phase treatment is the controlled hardening process, which gives the two-phase structure of hard bainite embedded in the soft ferrite matrix (Sharma & Rajan, 2010). Promotion of bainite structure in steel increases the tensile strength and hardness with increased absorbed energy in impact failure. Growth of bainitic microstructure, unlike martensite, leads to provide a better combination of strength and ductility at high bainite content.

In the present work, comparative study of the mechanical properties (tensile strength, ductility, hardness and impact strength) is performed for all three grades of steels (AISI1040, 4140 and 4340) partially hardened at three different intercritical temperatures. This will reveal the effect of different alloying elements like chromium, molybdenum and nickel on the dual phase properties (Fereiduni & Ghasemi Banadkouki, 2015; Hofinger et al., 2019; Sharma & Rajan, 2010). The ferrite-bainite microstructure of low alloy as dual phase structure plays a major role in structural application as well as automotive industries. From the last few decades, the mechanical properties of low alloy steels have significantly improved by subjecting them to different heat treatment methods. An optimum combination of mechanical properties can therefore be obtained in steels by development of dual phase microstructures (Li et al., 2015).

Li et al. (2015) conducted continuous annealing simulations using a continuous mechanical thermo-annealing simulator. Isothermal holding times of 5, 60, 180 and 480 seconds at an intercritical annealing temperature of 820 °C were used to investigate the evolution of the microstructure and mechanical properties of dual phase steel (DPS). Due to the presence of the phases, the ferrite-bainite DPS was characterized by a high strength and low yield ratio. The results suggested that long holding periods at intercritical temperatures may not be acceptable since there is no appreciable improvement in microstructure over time. This simulator is conducive to the mass production of DPS. Y. Cao et al. (2015) investigated the effect of strain rate of the low carbon DPS and annealing temperature on the mechanical properties. Material was strained to 3.5% and then annealing treatment was carried out at 180 °C for 30 min. Uniaxial tensile tests were used to assess the behaviour of the material in the automotive application. In DPS, increase in YS and UTS
is observed with increased strain rate or decreased annealing temperature. Also, reduction in elongation was observed with increase strain rate.

M. Basiruddin et al. (2018) carried out mechanical characterization of low carbon steels under different heat treatment cycles by developing F-B microstructures. Two different types of heat treatments, namely step-cooling (SC) and intermediate cooling (IC) treatments, were carried out on the as received material. Higher improvement in strength and toughness noticed in IC treatment compared to SC treatment. Fine film-like structure with large orientation difference across the ferrite-bainite interface boundaries not only increased the strength but also resulted in frequent deflection in cleavage crack propagation path, which improved the low temperature impact toughness and reduced the ductile to brittle transition temperature (Cao et al., 2015; Basiruddin et al., 2018).

The initial room temperature structure like, annealed, normalised hot rolled or cold rolled has got tremendous effect on the heat treatment result especially, phase morphology and bulk mechanical properties. For all standard tests, refined grain steels (normalised) are used to get consistent interchangeable properties. Novelty of the work lies in two folds, viz., first, use of standard refined (normalised) grained steel for dual phase treatment and, second, linkage of microstructure and microhardness to correlate the tensile and toughness property of DPS in all dual phase conditions for all three grades of steel.

2. Materials and methods

2.1. AISI1040 steel
AISI1040 steel is also known as EN 8 steel. It is an alloy-free medium carbon, moderate strength steel, generally seen in hot or cold rolled as well as normalized conditions. It is commonly available in untreated conditions in shapes like hot or cold rolled circular cross section, hot drawn or turned with cylindrical shapes, flats and plates. It can be simply turned under annealed condition. Axles, gears, bolts, shafts and studs are the automobile components made out of AISI1040 steel.

2.2. AISI4140 steel
AISI4140 (EN 19) steel is low chromium and molybdenum steel, generally used in machining industry for shafts, spindles and gears. It is harder and stronger steel compared to AISI1040 steel due to the presence of alloying elements like chromium and molybdenum (carbide formers). These alloying elements act as ferrite stabilizers, which make the steel easily machinable in annealed condition and provide excellent room temperature wear resistance. Its application is highly diversified and is broadly used in gas and oil industries.

2.3. AISI4340 steel
AISI4340 (EN 24) steel is generally called as nickel-chromium–molybdenum high tensile strength steel and has carbon content ranging from 0.38 to 0.43 wt.% and is termed as a medium carbon alloy steel. This type of steel finds its application in critical components of aircraft, which are subjected to high operating stresses such as landing gears and in commercially available components such as connecting rod, crankshaft and heavy duty axles, which demand high resistance to wear and deformation.

Raw steels are purchased from local steel market with initial condition as as-cast. Table 1 shows chemical composition of all three steels as obtained by Optical spectroscopy analysis method.

2.4. Heat treatment
The various test specimens prepared for determining the mechanical properties such as tensile strength, hardness and impact strength are subjected to normalizing (Figure 1, Path A-B-C-D) heat treatment to analyze the effect of standard refined room temperature structure on the said mechanical characteristics. The combined heat treatment cycle used to carry out the normalizing and DPS
Heat treatment is shown in Figure 1. The muffle furnace having a range of operating temperature from 300 to 1000 °C is used for heat treatment. Normalising is carried out for all the specimens by heating to supercritical temperature (900 °C) for 2 hours followed by air cooling.

Initially, samples are heated in a muffle furnace to the predetermined austenitisation temperature (900 °C). The process AB represents the heating steps for austenitisation process. The samples are held at the austenitisation temperature for the fixed duration of 2 hours. The process BC represents the holding time. This time duration is known as austenitisation time. After isothermal holding for 2 hours, specimens are quickly taken out from the furnace for air cooling to get fine pearlite as room temperature structure. In Figure 1, Path A-B-C-D is normalizing; E-F-G-H-I-J is dual phase treatment.

Furthermore, normalized specimens are subjected to dual phase treatment by partially austenitising at intercritical temperatures of 750 °C for 2 hours, followed by quenching and maintaining in a salt bath at 350 °C containing equal proportions of molten sodium nitrate and sodium nitrite mixture isothermally for 30 minutes followed by air cooling to room temperature. The same procedure is performed for at 770 and 790 °C (Sharma & Rajan, 2010). Tensile, impact and hardness tests are carried out on all the specimens in normalised and dual phase conditions.

Table 1. Composition of AISI1040, AISI4140, and AISI4340 steel

| Type of Steel | C    | Mn   | Si    | Cr   | Mo   | Ni   | Fe    |
|---------------|------|------|-------|------|------|------|-------|
| AISI 1040     | 0.39 | 0.72 | 0.10  | 0.03 | 0.02 | 0.02 | balance |
| AISI 4140     | 0.39 | 0.65 | 0.21  | 0.93 | 0.23 | 0.02 | balance |
| AISI 4340     | 0.39 | 0.70 | 0.25  | 0.80 | 0.25 | 1.85 | balance |

Figure 1. Heat treatment procedure for ferrite-bainite dual phase structure (Sharma & Rajan, 2010).
2.5. Mechanical testing
The tensile strength, hardness, ductility and impact energy of the various specimens are determined by carrying out the appropriate tests.

2.6. Hardness (Rockwell hardness) test
The ASTM E18-02 standard specimens are prepared. The bar stocks are cut in to 25 mm length using power blade hacksaw. The facing operation is carried out on CNC turning centre. Hardness test is carried out using Rockwell hardness testing machine (Akash industries model, A1-Twin).

2.7. Tensile test
Tensile specimens are prepared as per ASTM E8M standard. Turning operation is carried out on CNC turning centre. Computer controlled Tensometer (Kudale instrument) is employed for tensile test. Specimen is clamped between the jaws of the tester and then load is applied till it fails. The load verses displacement graphs are analyzed, and corresponding values of the percentage elongation and UTS are recorded.

2.8. Impact (Charpy) test
Specimens are prepared as per ASTM E23-020 standard-Type A. The bar stocks are first cut in to 112 mm length using power blade hacksaw. Facing and plain turning operations are carried out on CNC turning centre.

2.9. Microstructure examination
The microstructure of all the heat treated samples are obtained for analyzing the different phases and its effect on the mechanical properties of the material. The specimen was subjected to micro finishing with conventional polishing and sonication as first step, followed by etching. The samples are polished using various grades of emery papers to get mirror like finish without any micro scratches. The polished samples are properly etched using nital (100 ml ethanol + 5 ml nitric acid) to highlight the different phases. SEM (Model- JEOL JSM 840A) was used to obtain the microstructure of the samples.

3. Results and discussion

3.1. Hardness
Hardness variation in different heat-treated conditions is similar to UTS trend. Accordingly, normalized condition shows lesser hardness than dual phase condition in all the steels (Figure 2). Higher bulk hardness in dual phase condition is due to the morphology of bainite phase (Mohammad & Ekrami, 2008; S. S. Sharma Gurumurthy et al., 2020; Saeidi & Ekrami, 2009). Higher hardness in alloy steel is due to the dissolution of carbide forms (Cr & Mo) in the lattice (Avner, 2004). Low temperature processed DPS shows lesser hardness, and it is due to the lesser wt.% of bainite formed (lever rule). As the dual phase processing temperature increases, more and more wt.% of austenite forms. It results in more wt.% bainite on austempering. The degree of fineness of individual phases in bainite and degree of orientation mismatch distorts the lattice to increase the strain energy. This increases internal energy to enhance the hardness of steel (Zhou et al., 2014).

3.2. Tensile strength
The UTS of AISI1040 and 4140 increases gradually, whereas in AISI4340 steel, the increase is drastic in dual phase condition with respect to the increase in intercritical temperature. Among all three steels, normalized one shows lesser strength compared to dual phase conditions. In dual phase condition, AISI4340 shows excellent UTS among other grades. The difference in UTS between the two consecutive temperatures processed DPSs show maximum between 770 and 790 °C as compared to that obtained between 750 and 770 °C.
In normalized condition, AISI1040 steel shows lower UTS compared to that of AISI4140 carbon steel. This increased strength in AISI4140 steel is due to the ferrite stabilizers (Cr and Mo) present, which promotes an increase in bainite quantity at room temperature, even though distorts the ferrite matrix (Cao et al., 2015; Li et al., 2015). But in the dual phase condition, this difference increases with increase in austenitisation temperature. This behavior clearly shows ferrite stabilizers role in bainitic transformation for increasing strength (Figure 3). The plain carbon steel (AISI11040) is less sensitive to UTS increase in all heat treatment conditions as compared to AISI4140 and 4340 steels. The alloy steel is very sensitive to UTS, especially in the dual phase condition. In AISI4340 steel, when the intercritical temperature increases from 750 to 790 °C (40 °C difference), UTS increases by 1.5 times. The carbide former (Cr and Mo) elements have greater impact in distorting the growing axes of ferrite and carbides, so that degree of fineness and degree of orientation mismatch between ferrite and carbide is very high, reflected as increased strain energy in the lattice to record excellent UTS (Basiruddin et al., 2018; Mohammad & Ekrami, 2008). Also, nickel present in it increases hardness, hardenability and strength. The lattice distortion in bainite formation is due to the synergetic effect of two transformation mechanisms like, diffusion controlled (decomposition of austenite) and shear (diffusionless to form supersaturated phase) (Avner, 2004; Tang et al., 2018; Zhou et al., 2014).

3.3. Elongation
The ductility of the normalized (fine pearlite) specimen (Figure 4) is maximum compared to F-B conditions. F-B conditions, as the dual phase processing temperature increases, ductility decreases. This is due to the formation of increased amount of bainite phase. Bainite is distorted phase with less ductility (Sharma & Rajan, 2010). In alloy steels, the solubility of carbide formers in ferrite of bainite phase increases the degree of distortion, which decreases the ductility. In the lattice, high degree of fineness of two phases and degree of orientation mismatch distorts the phases to the larger extent. The combined effect is reflected as total reduction in ductility (Cao et al., 2015; Avner, 2004; Basiruddin et al., 2018; Caballero et al., 2001; Fereiduni & Ghosemi Banadokouki, 2015; Hofinger et al., 2019; Kumar et al., 2008; Li et al., 2015; Min et al., 2012; Mohammad & Ekrami, 2008; S. S. Sharma Gurumurthy et al., 2020; Saeidi & Ekrami, 2009; Sharma & Rajan, 2010, 2010). Ductility of alloy steels in all heat-
treated conditions is higher than that of plain carbon steel in the respective condition of heat treatment due to ferrite stabilizer (Cr) dissolution in ferrite (B. M. Gurumurthy et al., 2020; Qu et al., 2012). The decreasing trend in all the three steels is almost similar.

3.4. Impact strength
Dual phase condition shows slightly poor impact resistance than normalized condition. The decreasing trend in the impact strength with the increase in intercritical temperature is similar to that of ductility trend. AISI4340 steel shows better toughness among three categories in all the conditions (Figure 5). The reduction in toughness value in dual phase condition is due to the transformation mechanism of bainite (both diffusion controlled and shear) and morphology of two phases present in it (Movahed et al., 2009). Continuous reduction in the toughness value with increase in the wt.% of bainite content by increasing the dual phase treatment temperature can be attributed to the orientation scatter of ferrite and cementite in bainite (Ogunmefun et al., 2019). Analysis of all three grades of DPS in respective shows 15–40% decrease in toughness compared to normalized condition.

3.5. Microstructure analysis
The SEM micrographs of DPS showed the microstructure that consists of mainly ferrite and bainite in all the three variety of steel samples, as shown in (Figures 6–Figures 8). During the dual phase treatment, the nature and quantity of ferrite and bainite phases are varying with respect to heat treatment temperatures. In all the DPSs, the microstructure at higher temperature (790 °C) shows more bainite phase compared to lower temperatures (750 and 770 °C). With the increase in intercritical temperature not only the grain size increases but also wt. % of austenite increases. On bainitic transformation, the same austenite transforms into lower bainite showing fine distribution of ferrite and cementite in the colonies (Cao et al., 2015; Sharma et al., 2018). Hence, at 790 °C, almost complete bainite phase is observed in all the steel categories with traces of fine-grained pro eutectoid ferrite (Figures 6–8).
The SEM micrographs of AISI1040 steel shows well defined polygonal colonies of bainite and proeutectoid ferrite. As the intercritical temperature increases, the bainite region also increases. This argument is well supported by hardness and strength test results. In AISI4140 and 4340 steels, similar result of microstructure as that of AISI1040 steel is observed. DPS treated at 750 °C shows well distinguished ferrite and bainite colonies, whereas with an increase in austenitisation temperature, proeutectoid ferrite region decreases. Hence, quantity of bainite increases. The
Figure 6. Ferrite-bainite DP structure of AISI1040 steel at (a) 750, (b) 770 and (c) 790 °C.
microstructural (SEM) results of AISI4140 and 4340 steels are almost similar with respect to pattern of ferrite and bainite colonies are concerned.

3.6. Microhardness of DPS
As intercritical temperature increases from 750 to 790 °C more austenite forms, accordingly, ferrite quantity decreases. The number of zones showing bold numbers in each category also increases with the sacrifice of ferrite zones. As more and more austenite forms on heating to higher intercritical temperature, austenite is depleted with carbon compared to low temperature (750 °C) treated DPS. Inturn, martensite forms with lower carbon showing reduction in the hardness values. Similarly, ferrite also depletes in carbon as the intercritical temperature of DPS increases, showing reduced hardness at higher DPS temperature (Das et al., 2019; Ghaheri et al., 2014; Samadi Shahreza et al., 2013). Correspondingly, higher hardness values are observed in AISI4140 and 4340 steels. Increased hardness is due to the alloying elements present in these steels which promotes bainite content compared to unalloyed steels. Figure 9 reveals that the variation in hardness is within 6 VHN, indicating that the result is fairly good to accept. Totally, 20 spots randomly selected for hardness locations in each microstructure of DPS. The number of spots related to ferrite and bainite out of 20 total spots in each case is converted into percentage, which is representing approximately the volume percentage of phases present in DPS. From the bar charts (Figure 9(a,c,e)), we can conclude that as the wt.% of alloying elements increases, hardness of ferrite and bainite increases. Similarly, Figure 9(b,d,f) shows that bainite content in steel increases as the number and content of alloying elements increases. Accordingly, ferrite quantity decreases. This microhardness result correlates the microstructure obtained (Figures 6–8). As the dual phase temperature increases more number of harder bainite phase are seen, as shown in Figures 7–9.

4. Conclusion
All the three grades of hypoeutectoid steels are successfully heat treated to obtain dual phase (ferrite+bainite) structure by undergoing normalising path. Hardness, tensile and impact resistance are used as output mechanical characteristics. Microstructure study is used to confirm the type of phase present in dual phase condition. Microhardness analysis is used as an additional tool for approximating the quantity of phases formed by dual phase treatment. Based on the experimental results, the following conclusions are chalked out. An increase in dual phase treatment temperature increases the bulk hardness in all the steels, showing excellent result in steel containing more number of alloying elements (AISI4340). It is observed that hardness and UTS increase trend remains same in DPS. In AISI4340 steel, when the intercritical temperature increases from 750 to 790 °C, UTS increases by 1.5 times. The ductility of the normalized (fine pearlite) specimen is maximum compared to dual phase condition. In dual phase condition, as the dual phase processing temperature increases, ductility decreases for all the steels. Ductility of alloy steels in all heat-treated conditions is higher than that of unalloyed steel due to ferrite and austenite stabilizers. Normalized condition shows better impact resistance than dual phase condition. The decreasing trend in the impact strength with the increase in intercritical temperature is similar to that of ductility trend. AISI4340 steel shows better toughness compared to other steels in the respective heat treatment conditions Analysis of all three grades of DPS in respective shows 15–40% decrease in toughness compared to normalized condition. SEM micrographs of AISI1040 steel shows well defined polygonal colonies of bainite and proeutectoid ferrite. As the intercritical temperature increases, the bainite region in the given focussed area also increases. AISI4140 and 4340 steels show similar results in microstructure as that of AISI1040. An increase in intercritical temperature leads to decrease in proeutectoid ferrite regions. AISI4340 and 4140 steels show more bainite in all DPS condition compared to that of AISI1040 steel.
Figure 7. Ferrite-bainite DP structure of AISI4140 steel at (a) 750, (b) 770 and (c) 790 °C.
Figure 8. Ferrite-bainite DP structure of AISI4340 steel at (a) 750, (b) 770 and (c) 790 °C.
Figure 9. (a), (c), (e) Microhardness and (b), (d), (f) shows the hardness of ferrite and bainite at different zones (20 zones) of AISI 1040, 4140 and 4340 DPS steels, respectively.
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References
Avner, S. H. (2004). Introduction to physical metallurgy. McGraw Hill.
Basiruddin, M., Alam, I., & Chakrabarti, D. (2018). The role of fibrous morphology on the Charpy impact properties of low carbon ferrite-bainite dual-phase steels. Materials Science and Engineering: A, 716, 208–219. https://doi.org/10.1016/j.msea.2018.01.041
Cobalero, F. G., Bhadeshi, H. K. D. H., Mawella, K. J. A., Jones, D. G., & Brown, P. (2001). Design of novel high strength bainitic steels: Part 1. Materials Science and Technology, 17(5), 512–516. https://doi.org/10.1179/02670830110150348
Cao, Y., Ahlström, J., & Karlssön, B. (2015). The influence of temperatures and strain rates on the mechanical behavior of DPs in different conditions. Journal of Materials Research and Technology, 4(1), 68–74. https://doi.org/10.1016/j.jmrt.2014.11.001
Das, A., Tarafder, S., Sivaprasad, S., & Chakrabarti, D. (2019). Influence of microstructure and strain rate on the strain partitioning behaviour of DPs. Materials Science and Engineering: A, 754, 348–360. https://doi.org/10.1016/j.msea.2019.03.084
Fereiduni, E., & Ghosami Bonodkouki, S. S. (2015). Improvement of mechanical properties in a dual-phase ferrite-martensite AISI 1014 steel under tough-strong ferrite formation. Materials & Design (1980–2015), 56, 232–240. https://doi.org/10.1016/j.matdes.2013.11.005
Ghaheri, A., Shafaei, A., & Honarmand, M. (2014). Effects of intercritical-temperatures on martensite morphology, volume fraction and mechanical properties of dual-phase steel obtained from direct and continuous annealing cycles. Materials & Design (1980–2015), 62, 305–319. https://doi.org/10.1016/j.matdes.2014.04.073
Gurumurthy, B. M., Shivaprakash, Y. M., Sharma, S., Kini, U. A., & Mathur, R. (2020). Mechanical characterization of dual phase and austempered aisi 1040 normalized steel. International Journal of Mechanical and Production Engineering Research and Development, 10(2), 247–258. https://doi.org/10.24247/jmpera202022
Gurumurthy, S. S. S., Achutha, K. U., Sharma, S., Kini, A., Shettar, M., & Hiremath, P. (2020). Microstructure authentication on mechanical property of medium carbon low alloy duplex steels. Journal of Materials Research and Technology, 9(3), 5105–5111. https://doi.org/10.1016/j.jmrt.2020.03.027
Hofinger, M., Staudacher, M., Ognianov, M., Turk, C., Leitner, H., & Schnitzer, R. (2019). Microstructural evolution of a dual hardening steel during heat treatment. Micron, 120, 48–56. https://doi.org/10.1016/j.micron.2019.02.004
Kumar, A., Singh, S. B., & Roy, K. K. (2008). Influence of bainite/martensite-content on the tensile properties of low carbon dual-phase steels. Materials Science and Engineering: A, 474(1–2), 270–282. https://doi.org/10.1016/j.msea.2007.05.007
Li, Z., Wu, D., Li, W., Yu, H., Shao, Z., & Luo, L. (2015). Effect of holding time on the microstructure and mechanical properties of dual-phase steel during intercritical annealing. Journal of Wuhan University of Technology-Mater. Sci. Ed, 30(1), 156–161. https://doi.org/10.1007/s11595-015-1118-5
Min, J., Lin, J., Li, F., & Li, F. (2012). On the ferrite and bainite transformation in isothermally deformed 22MnB5 steels. Materials Science and Engineering: A, 550, 375–387. https://doi.org/10.1016/j.msea.2012.04.091
Mohammad, R. A., & Ekrami, A. (2008). Effect of ferrite volume fraction on work hardening behaviour of high bainite Dual Phase (DP) steels. Materials Science and Engineering A, 477(1–2), 306–310. https://doi.org/10.1016/j.msea.2007.05.051
Movahed, P., Kolahgar, S., Marashi, S. P. H., Pourjavadi, M., & Parvin, N. (2009). The effect of intercritical heat treatment temperature on the tensile properties and work hardening behavior of ferrite-martensite dual-phase steels. Materials Science and Engineering: A, 518(1–2), 1–6. https://doi.org/10.1016/j.msea.2009.05.046
Ogunmefun, A. O., Jamiru, T., Sadiku, E. R., Obodele, B. A., & Olorundaisi, E. (2019, October). Intercritical annealing temperature: Influence on the mechanical properties of low alloy dual-phase Fe0.08 C0.4 Mn Steel. In 2019 Open Innovations (OI) (pp. 141–146). Open Innovations (OI): IEEE.
Qi, S., Zhang, Y., Pang, X., & Gao, K. (2012). Influence of temperature field on the microstructure of low carbon microalloyed ferrite-bainite dual-phase steel during heat treatment. Materials Science and Engineering: A, 536, 136–142. https://doi.org/10.1016/j.msea.2011.12.090
Soeidi, N., & Ekrami, A. (2009). Comparison of mechanical properties of bainite/ferrite and bainite/ferrite dual phase 4340 steels. Materials Science and Engineering: A, 523(1–2), 125–129. https://doi.org/10.1016/j.msea.2009.06.057
Samadi Shahreza, Z., Dini, G., & Taheriolahzadeh, A. (2013). Improving the microstructure, mechanical and magnetic properties of AISI 4340 steel using the heat treatment process. International Journal of Iron & Steel Society of Iran, 10(2), 18–22. http://journal.issiran.com/article_10652.html
Sharma, C. P., & Roján, A. S. T. V. (2010). Heat treatment principles and techniques (2nd ed.). PHI publication.
Sharma, S., Gurumurthy, B. M., Kini, U. A., Hegde, A., & Patil, A. (2018). Mechanical characteristics evaluation of dual phase and related hardening techniques on AISI 4340 steel. Journal of Mechanical Engineering and Sciences, 12 (4), 4018–4029. https://doi.org/10.15282/jmes.2018.03.0049
Tang, C. J., Shang, C. J., Liu, S. L., Guan, H. L., Misra, R. D. K., & Chen, Y. B. (2018). Effect of volume fraction of bainite on strain hardening behavior and deformation mechanism of F/B multi-phase steel. Materials
Zhou, W. H., Wang, X. L., Venkatsurya, P. K. C., Guo, H., Shang, C. J., & Misra, R. D. K. (2014). Structure–mechanical property relationship in a high strength low carbon alloy steel processed by two-step intercritical annealing and intercritical tempering. Materials Science and Engineering: A, 607, 569–577. https://doi.org/10.1016/j.msea.2014.03.107