EXPLORE
International Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444

International Journal of Engineering and Technology Volume 4 No. 5, May, 2014

Mechanical Properties Enhancement of Conventional Mild Steel For Fastener Application

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ABSTRACT

Due to the rampant brittle fracture of most mild steel fasteners, an innovative hardening process of microstructure modificaton is employed on conventional mild steel to enhance its mechanical properties. The steel specimens were subjected to inter-critical austenitising heat treatment in the temperature range of 800^0-950^0C and soaked for 30 minutes, quenched in water at ambient temperature and tempered at varying temperatures of 250^0, 350^0, 450^0 and 550^0C. Results of mechanical characterisation of the test specimens demonstrate improvement in ultimate tensile strength and impact energy by 58.3 and 53.8 percent respectively coupled with a modest increase in hardness from 25.7HRB to 37.5HRB. Contribution to improved mechanical properties stem from the inducement of fine needle-like lower bainite particles within the dislocation-rich ferrite matrix at 450^0C and 550^0C tempering temperature regime.

Keywords: *Mild steel, hardening, austenitising, mechanical properties*

1. INTRODUCTION

Mechanical joining of engineering components is commonly carried out using various types of materials. Besides welding and laser processes, fastening is another veritable joining technique depending on the service environment. Mild steel due to its availability coupled with a relatively low cost is often employed as metallic fasteners. However, the rampant brittle fracture of mild steel fasteners such as nails, screws, studs, etc on application of sudden load has become a growing concern (Teresa and Manuela, 2008). Various reasons have been adduced for the abysmal failure of mild steel fasteners in service. Hence, the imperative of devising a means by which the impact property and other relevant characteristics of conventional mild steel can be improved. Major impact toughness enhancement techniques that have been employed include alloying, heat treatment and most recently, impulse electric current treatment. Varied amounts of copper, titanium and nickel have been added to steel by quite a number of researchers to achieve improved impact toughness. In the work of Mone and Scott (2011), significant improvement in impact property was obtained as the copper content was increased from 0.2-1.5wt%.

Enhanced impact toughness was noticed from 0.25% copper and peaked at 1.5wt%. Philip and Richard (1970) achieved improved toughness as the silicon content was increased. Zirconium, titanium and nickel have also been employed by other researchers. Although the alloying technique of toughness enhancement has been found to be remarkably effective, the rather prohibitive cost implication has rendered the method unpopular except in situations where the service benefits by far outweigh the cost burden. High impulse electric current technique (IECT) was employed by to increase the impact toughness of low carbon steel (Stepanov, et al., 2007). The high-density current passed through the specimen seemed to affect only the grain size and not the morphology. Therefore contribution to improved toughness was reported to have been due to the homogeneous dispersion of grains within the matrix occasioned by the passage of impulse current. However, it has been observed that IECT toughness enhancement has limited applications especially in structural components.

The foregoing, properties optimisation techniques notwithstanding the heat treatment option of impact toughness improvement may be most versatile considering the volume of works carried out in that area. Heat treatment involves a cycle of heating and cooling that alters the material microstructures resulting in a modified mechanical properties. Of the various heat treatment methods, hardening through quenching followed by tempering has been established as the most effective method of enhancing the strength characteristics of metal and their alloy. According to Offor and Ezekoye (2011), improved notch impact toughness was exhibited by 0.14wt% carbon steel after being subjected to varied inter-critical (810^0C-890^0C) normalizing. Similarly, the hardening of HT 480 and HT 600 having 0.27wt%C (HT represents high tensile) and subsequent quenching in oil followed by tempering between 480ºC and 600ºC resulted in impact energy of 195J and 225J respectively (Muhammed; et al., 2011). One of the major processing parameters in hardening heat treatment is the tempering temperature. Rugly and Strohaecker (2004) worked on toughness improvement of low carbon steel independent of the austenitising temperature. The result established that a relatively high tempering temperature between 500^0C and 650^0C favours improved impact toughness. This was also corroborated by Danilo and Jaime, (2010) and further strengthened by the findings of Dosseth and Boyer, 2006 in which it was observed that tempering in the range of 250^0C-370^0C should be avoided to stem the phenomenon of temper embritlement. Considering all of the above, the issues germane in the heat treatment of low carbon steel for mechanical properties enhancement bore down to the interplay of three parameters namely the austenitising temperature, cooling rate as represented by the quenching medium and the tempering temperature. The need to establish a standard procedure for these processes for industrial application is imperative. This will ensure efficiency and cost effectiveness in the mass production of quality mild steel fasteners.

2. EXPERIMENTAL PROCEDURE

2.1 Material

A commercial two-metre length of conventional hot rolled 12mm bar sample was acquired for the study. This type of material is preferred because the available hot rolled 6mm and 8mm bars that are most suitable for the study have been subjected to some degree of cold deformation during coiling for ease of shipment. This mode of handling is capable of tampering with the material's intrinsic characteristics hence, preference for a mild steel which has not been subjected to any form of mechanical deformation. The results of composition analysis on the bar sample obtained through a Quantometer model ARL 3460B is presented in Table 1.

Table 1: Elemental composition of mild steel sample

Element	C	Si	Mn	S	P	Cr	Ni	Cu	Pb	Mo	V	Fe
Wt.%	0.268	0.208	0.803	0.034	0.036	0.124	0.084	0.227	0.002	0.001	0.003	98.211

2.2 Specimens preparation and heat treatment

One of the as-received mild steel sample was mechanically cut using a hacksaw at ambient temperature and then shaped on a lathe machine to standard tensile test specimens. Both ends of the tensile test specimens were threaded to enable firm grip on the testing machine while the second sample was earmarked for a Charpy V impact test. Each of the specimens was machined to 10mm diameter and 60mm length with a 2mm deep 45^0 inclined V-notch at the centre. The prepared standard tensile and impact test specimens were austenised in a muffle furnace at temperatures which varied from 800^0C-950^0C. On attainment of the specified austenitising temperature the specimens were soaked for 25 minutes to ensure homogenisation and then quenched rapidly in a bath containing water. After five minutes, the specimens were brought out of water into the open air and the temperature was measured using a digital pyrometer. This was done to ascertain the degree of cooling achieved in order to correlate the type of microstructural transformation that had occured as indicated on a standard iron-carbon phase diagram. The specimens were then tempered at 250^0C, 350^0C, 450^0C and 550^0C and held for 20 minutes respectively.

2.3 Mechanical properties tests

The axial stactic flow stress data of the heat treated specimens was obtained using an Instron electro-mechanical tester and the data were used to evaluate the specimens tensile characteristics as shown in Figures 1-4. One fractured piece from each tensile test specimens was appropriately prepared for the evaluation of microhardness developed in the specimens using the 'B' scale Rockwell hardness tester and the result illustrated in Figure 5. The impact energy of the heat treated specimens was also determined using an Avery impact tester type 6703 model E742474. Each specimen was subjected to an impact load with a striking pendulum velocity of $5ms^{-1}$ while the energy (Joules) absorbed in fracturing each of the test specimens was recorded.

2.3 Microstructure Analysis

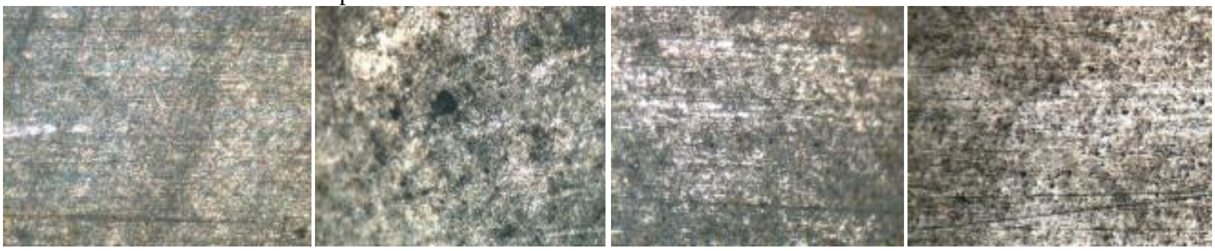
The test specimens were ground on a water-lubricated grinding machine using silicon carbide abrasive papers grade 240, 320, 400 and 600 grits in succession. Final polishing of the specimens was carried out with 0.5 microns chromic oxide powders. The mirrow like surfaces obtained were etched in 2% Nital solution for 30 seconds and rinsed in water while the microstructural features were examined under an optical microscope at x 800 magnification and the micrographs presented in Plates 1-4.

3. RESULTS AND DISCUSSION

3.1 Microstructure

Plates 1 - 4 show the micrographs of the mild steel specimens tempered at varying temperatures after drastic cooling in water from different austenitising temperatures. The mild steel under investigation contains 0.27 wt.% carbon, being an hypo-eutectoid steel consists basically two major micro-constituents which are ferrite and pearlite. However, when austenised and quenched drastically could not develop martensitic structure but varying volume fractions of lower bainite was induced. Though, the formation of lower bainite could not be verified empirically under an optical microscope as employed in this study, nevertheless, the level of undercooling administered on the specimens lay credence to the fact of bainite formation during the experiment. Bainite comprises of two different structures which are dislocation- rich ferrite matrix and cementite as the reinforcing phase (Bhadeshia, 2001). When compared with martensite , bainite grows at relatively high temperatures where the microstructure undergoes recovery during transformation. Improved mechanical properties compared to that of low alloyed steel are often conferred on mild steel as the cementite morphology progressively changes from coarse plate-like to fine needle-like crystals at varying

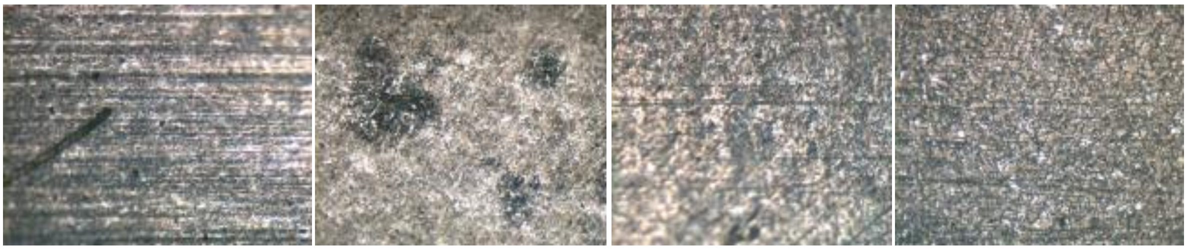
tempering temperatures. The mechanical properties are further enhanced as the induced stress within the dislocation- rich ferrite matrix is relieved upon tempering.
The micrographs in Plate 1 show the microstructures of specimens austenised at 800^0C and tempered after massive undercooling. At 800^0C, very low volume of austenite could have gone into solution and available for transformation hence the apparent absence low volume of lower bainite inducement for pearlite (Plate 1a).



(a) (b) (c) (d)

Plate 1: Micrographs of mild steel austenised at 800^0C, quenched in water and tempered at (a) 250^0C (b) 350^0C (c) 450^0C (d) 550^oC. The microstructures consist of fringes of lower bainite but a preponderance of pearlite showing progressive reduction in size as the tempering temperature increases.

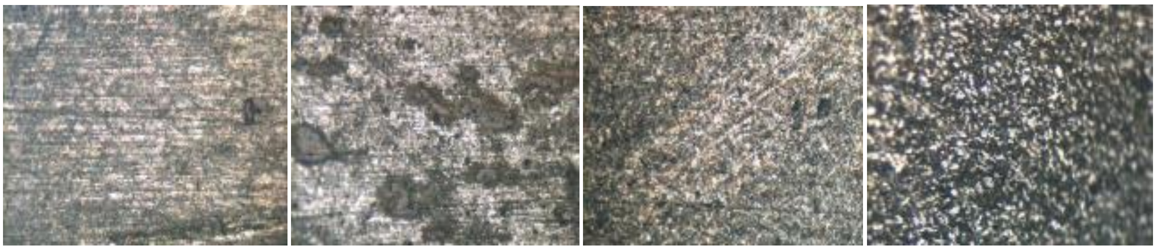
The plate-like pearlite formed was only modified into fine crystals as the inter laminar spacing is reduced as tempering temperature increased from 350^0C-550^0C (Plate 1c-1d). As the austenitising temperaature increased to 850^0C, more austenite was released into solution but still produced low volume of lower bainite carbide particles with higher fractions of cementite as the main structure shown in Plate 2(a-d) while the crystals size also reduces as tempering temperature increases. However, the volume of austenite in solution at 900^0C increased significantly and upon drastic cooling transformed predominantly into lower bainite.



(a) (b) (c) (d)

Plate 2: Micrographs of mild steel austenised at 850^0C, quenched in water and tempered at (a) 250^0C (b) 350^0C (c) 450^0C (d) 550^oC. The structure developed contain more lower bainite crystals compared to specimens austenised at 800^0C.

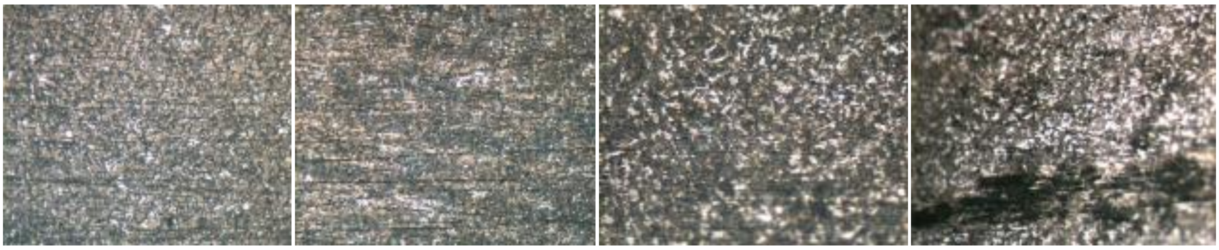
Plate 3(a-d) shows the microstructures of the specimens exhibiting fine crystals of bainite with their apparent size reducing as tempering temperature increases. The specimen tempered at 350^0C, Plate 3(b) however, appears to be out of trend with other specimens in term of crystal morphology assuming a structure whose crystals coalesced into a large body. This can be explained in the light of literature which has established the occurrence of structural reversion in plain carbon steels within 300^0C-350^0C tempering temperature (Henkel and Pense, 2002). The coalsced particles referred to as ε-carbide usually manifest in the form of film at the grain boundaries. This phenomenon has not been sufficiently explained scientifically hence the need for caution when tempering within that temperature regime.



(a) (b) (c) (d)

Plate 3: Micrographs of mild steel austenised at 900⁰C, quenched in water and tempered at (a) 250⁰C (b) 350⁰C (c) 450⁰C (d) 550ºC. The microstructures consist of lower bainite showing needle-like carbide particles whose size reduces as the tempering temperature increases except at 350⁰C..

Further increase in austenite volume that transformed occurred at 950⁰C which translate into significant increase in the fractions of lower bainite carbide particles induced in the specimens on quenching. As shown in Plate 4(a-d), the microstructures contain more needle-like crystals compared with those specimens austenised at 900⁰C.



(a) (b) (c) (d)

Plate 4: Micrographs of mild steel austenised at 950⁰C, quenched in water and tempered at (a) 250⁰C (b) 350⁰C (c) 450⁰C (d) 550⁰C. The microstructures consist of lower bainite particles whose size reduces as the tempering temperature increases except at 350⁰C..

3.2 Tensile strength

The tensile strength characteristics demonstrated by the mild steel specimens after tempering are shown in Figures 1 (a-d). Figure 1a illustrates the tensile behaviour of the steel austenised at 800⁰C. Compared with 558.3MPa demonstrated by the control sample, the treated specimens exhibited varied ultimate tensile strength (uts) with respect to the tempering temperatures translate to 778.1MPa followed by 745.5MPa, 469.8MPa and 183.2MPa respectively at 450⁰C, 550⁰C, 250⁰C and 350⁰C tempering temperatures. The emerging trend in specimens' uts behaviour shows that strength increases concommitantly with tempering temperature.

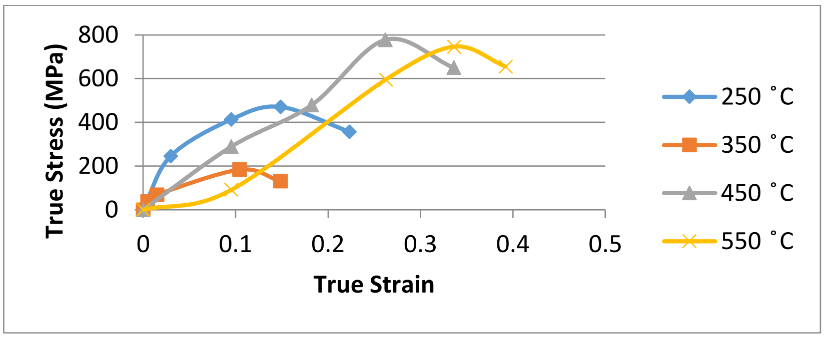


Figure 1a: Effect of tempering temperature on the tensile behaviour of mild steel austenised at 800⁰C

Figures 1(b-d) present a similar trend in term of the specimens uts behaviours at differnt austenitising temperatures. However, the uts values at the various tempering temperatures are quite close (see Figure 1b). This might be due to improvement in homogeneity of the specimens microstructures ocassioned by the increase in tempering temperature from 450^{0}C-550^{0}C. Compared to others, the specimens austenised at 900^{0}C and 950^{0}C demonstrate peak uts values from 778.1-883.5MPa (Figure 1d). However, the only behaviour that appears to be out of trend is observed with the specimen tempered at 350^{0}C.

It is evident in Figures 1a-1d that at all austenitising temperatures, tempering at 350^{0}C gave rise to the least uts values. This behaviour becomes more pronounced in Figures 1c and 1d where it is observed that the characteristic necking phenomenon of a ductile material undergoing tensile loading is conspicuously absent (Table 2). This may be due to the established structure embrittlement on tempering of plain carbon steels between 300^{0}C and 350^{0}C leading to the formation of ε-carbide in form of film at the grain boundaries which impairs strength (Barranco, et al; 1992).

Table 2: Comparative ultimate tensile strength (uts) of specimens tempered at 350^{0}C

Austenitising temp. ^{0}C	800	850	900	950
UTS, MPa	183.2	478.6	Brittle	Brittle

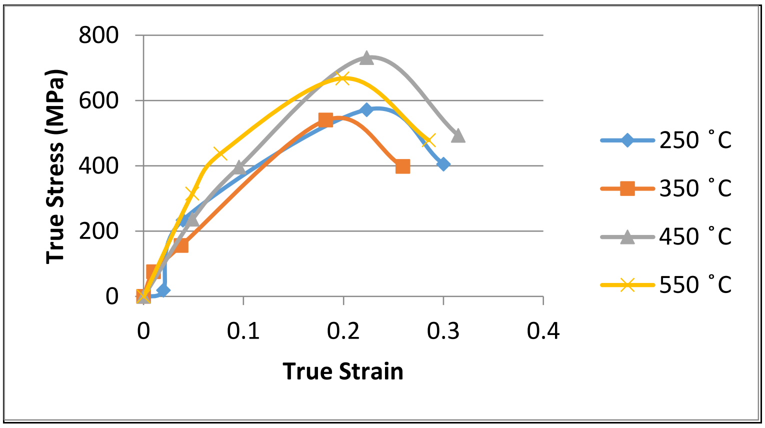


Figure 1b: Effect of tempering temperature on the tensile behaviour of mild steel austenised at 850^{0}C

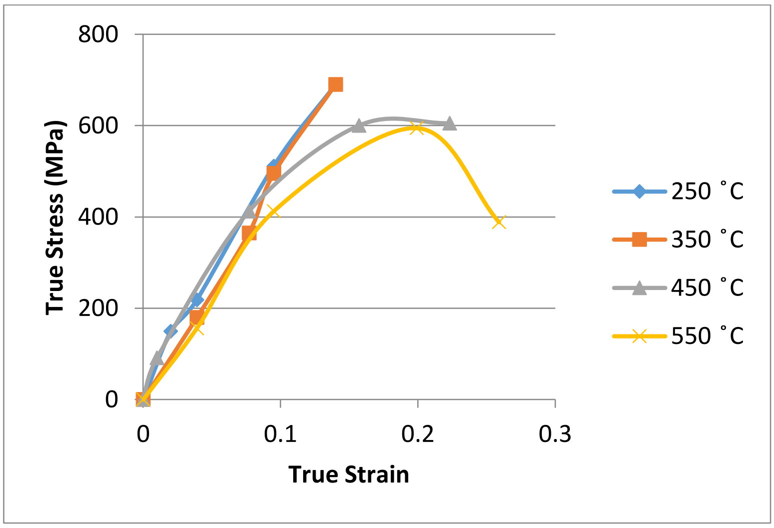


Figure 1c: Effect of tempering temperature on Effect of tempering temperature on the tensile behaviour of mild steel austenised at 900^{0}C

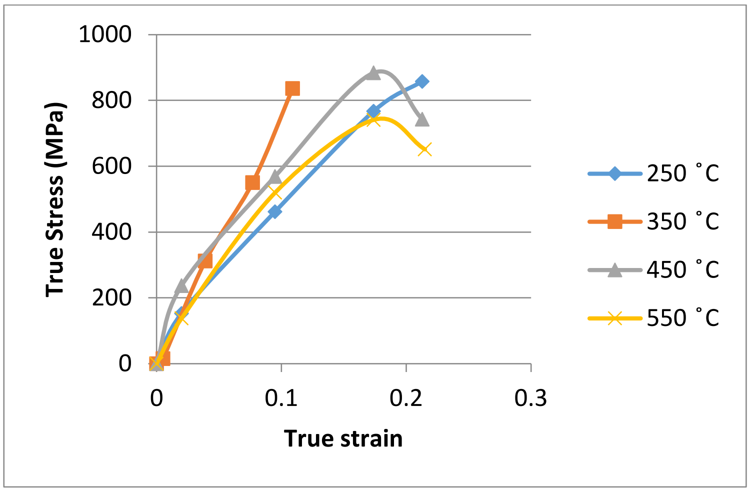


Figure 1d: Effect of tempering temperature on the tensile behaviour of mild steel austenised at 950^0

Further, the embrittlement effect of tempering between 300^{0}C and 350^{0}C is heightened at 900^{0}C and 950^{0}C austenitising temperatures as shown in Figures 1c and 1d respectively. This stemmed from increase in the formation of ε-carbide within the specimens matrices causing substantial distortion at the grain boundaries. In general, the overall behaviours of the specimens with regard to tensile characteristics is predicated on three parameters namely; volume of austenite available for transformation, morphology of precipitates developed and size as well as the distribution of the particles within the matrices. The dynamics involved and the influence of these parameters are already discussed under microstructre.

3.3 Impact strength

The effect of quenching and tempering on impact behaviour of the specimens is illustrated in Figure 2. At the various austenitising temperatures (800^0-950^{0}C), the specimen tempered at 350^{o}C exhibits the least impact energy (84.6J) while the highest impact energy of 146.7J is observed at 550^{0}C tempering temperature. Generally, Figure 2 shows a progressive increase in impact energy as tempering temperature increases from 250^{o}C to 350^{o}C, 450^{o}C and climaxed at 550^{o}C.

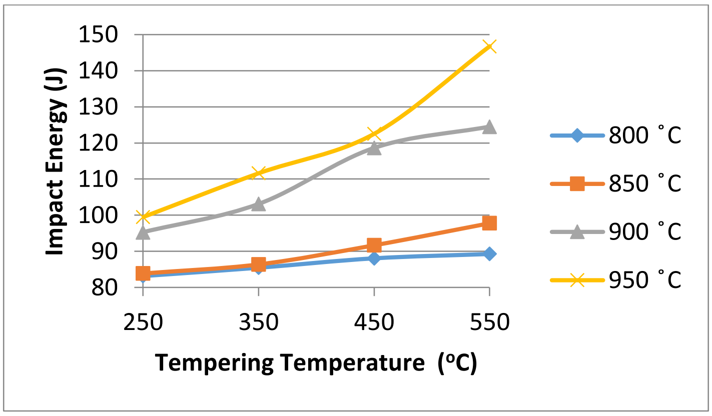


Figure 2: Effect of tempering on the impact energy of mild steel austenised at varying temperatures

This behaviour can be explained in relation to the microstructural changes that often take place as a non-equilibrium plain carbon steel is subjected to varying tempering temperatures. As the tempering temperature increases, extra motive energy is made available in addition to the lock-up stress in the material consequent to quenching thereby providing the kinetics for huge structural transformation capable of impacting the materials'mechanical properties.

Enhancement of impact property is imperative because fasteners are required to exhibit adequate resistance to dynamic loading to stem their susceptibility to brittle failure and warpage during installation. This has been long discovered by Hehemann, et al., 1956 to be feasible through skilful modification of the lower bainite crystal morphology on tempering. Thus, as the crystals morphology transformed from plate-like to needle-like at a lower tempering temperature of 250^{o}C, the brittle nature of the as-quenched structure also changes concommitantly. Further changes in morphology developed into fine crystals coupled with homogeneous dispersion as tempering temperature increases. This structure supports reduction in differences between ductility aad strength resulting to improved toughness as indicated by the increase in the amount of energy (from 105J to 146.7J) absorbed prior to fracture. As opined by Vijendra (2007) this can be attributed to a drastic reduction in dislocation density occasioned by annihilation brought about by diffusion of particles at higher tempering temperature between 350^{0}C and 550^{0}C.

In the same vein, the amount of austenite transformed is more at 950^{o}C austenitising temperature thereby impacting directly on the fraction of crystals transformed and dispersed within the matrices. Since the crystals assumed fine size as from 450^{0}C-550^{0}C tempering temperatures, large number of grain boundaries are induced thereby enhancing both strength and toughness.

3.4 Hardness

The extent of hardness induced in test specimens is illustrated in Figure 3. The Figure shows that hardness generally increases in tandem with tempering temperature but a dip occurred at 350^{0}C. The change in trend arose from the abrupt structural reversion in structure whereby needle-like bainite crystals transformed to ε-cementite which weakens the structures at the grain boundaries.

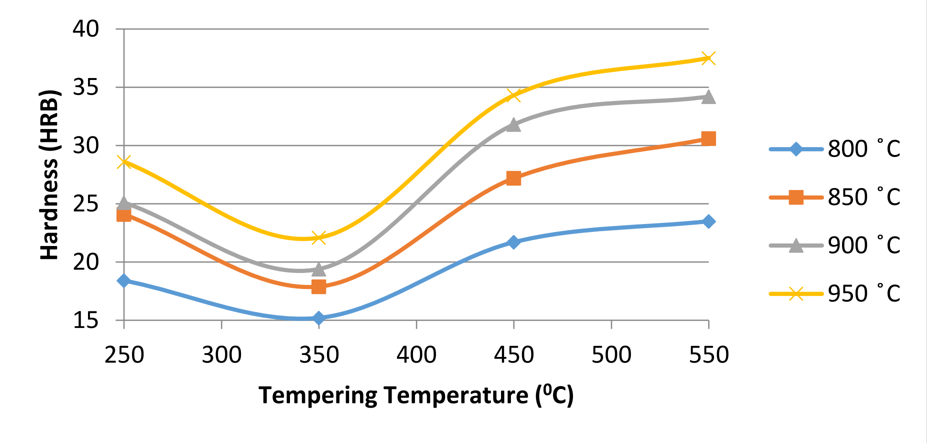


Figure 3: Effect of tempering on the hardness of mild steel austenitised at varying temperatures

However, modest increase in hardness occurred as the tempering temperatures increased to 450^{0}C and peaked at 550^{0}C. This is attributed to the development of fine needle-like bainite precipitates which gave rise to more grain boundaries and a plethoral of dislocations hence increase in hardness. Thus, reversion of the plate-like pearlite crystals developed at 250^{0}C to a matrix riddled with ε-carbide particles at 350^{0}C tempering temperatures is responsible for the dip in hardness. According to Franscisca, et al., 2004, at higher tempering temperatures of 450^{0}C and 550^{0}C increase in nucleation rate leads to microstructural refinement where most of the ε-carbide particles are disolved paving the way for transformation into fine bainite particles. The presence of these particles actually hightened resistance to dislocation motion within the structure hence, increase in hardness from 25.7HRB to 37.5HRB.

Similarly, the large volume of austenite available for transformation at higher austenitising temperatures of 900^{0}C and 950^{0}C may have been responsible for the significant increase in hardness observed with the specimens at these austenitising temperature regime. The development of sufficient hardness in fasteners is desirable as it enhances resistance to lateral tearing or shearing as the fastener is being forced into the components it holds together.

4. CONCLUSION

The feasibility and modalities for enhancing the mechanical properties of mild steel for fastener application have been investigated. From the results and their analyses, the following conclusions are made:

1. The effect of structure-property relationship came into fore by the inducement of fine needle-like bainites which gave rise to enhanced mechanical properties.
2. Austenitising temperature is a key factor in mechanical property enhancement as it impacts significantly on the volume of austenite available for transformation prior to massive undercooling.
3. The tempering temperature of the as-quenched structure exerts huge influence on the morphology of lower bainite crystals developed which invariably determined the mechanical properties.

Improvement in mechanical properties of the mild steel occurred through the processing parameters of 900^{0}C-950^{0}C, 450^{0}C-550^{0}C austenitising and tempering temperatures respectively coupled with drastic cooling rate of 235^{0}C.s^{-1} .

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