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Heat Treatment of UNS T72305 Tool Steel: Effect on Mechanical and Microstructural Properties

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ABSTRACT
The effects of full annealing, quenching and temper heat treatments to achieve excellent tool performance were investigated with our results establishing a linear correlation between microstructural modifications and changes in material properties. Isothermal transformations show that full annealing with a resultant microstructure of proeutectoid ferrite and pearlite developed an extreme increase in ductility by 30% and 6.78% respectively in terms of percentage elongation in length (PEL) and percentage reduction in area (PRA) with a 0.27% drop in hardness. Full annealing also led to reductions in yield, ultimate and fracture strengths by 32.50%, 21.57% and 18.12% respectively. Also, quenching which produced martensite with some retained austenite offered a remarkable 6.85% rise in hardness as well as 56.86% in tensile and 83.74% fracture strengths with no observable yield strength. Practical limitations like cracks, reductions in PRA by 32.63% and PEL by 18.99% were improved by tempering. The tempered martensite with its precipitated cementite grains in a ferrite matrix gave rise to 15.19%, 26.50% and 39.91% increments in yield, ultimate and fracture strengths respectively. Moderate drops in hardness by 4.66%, PEL by 19.43% and PRA by 5.45% accounts for the excellent blend in properties responsible for the toughness, resistance to abrasive wear and thermal deformation especially at high operating speeds and feeds expected in the anticipated tool steel.
***Keywords**: Tool-Steel, heat treatment, metallography, microstructure, full-anneal, quenching, tempering, martensite, cementite.*

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I. INTRODUCTION:

Steel has remained the most widely used industrial material due to the broad range of properties and assorted microstructural varieties obtainable from its heat treatment processes[1]. As at 2012, the global steel production was about 1,547.8 MMT (Million Metric Tons) with China producing up to 46.30% of it[2]. Though Steel can be grouped due to the mode of processing yet the widely accepted grouping system has been based on the chemical composition where Steel is classified into four categories: carbon steel, alloy steel, stainless steel and tool steel.

Carbon steels comprise: ultra-low carbon steel (< 0.03% carbon), low carbon steel (0.04 to 0.15% carbon), mild steel (0.15 to 0.3% carbon.), Medium-carbon steels (0.3 to 0.6% carbon) and High-carbon steels (0.6 to 2% carbon). Alloy steels contain significant amounts of alloying elements while stainless steels are known for their Chromium and Nickel components that are responsible for the formation of thin and protective Chromium oxide that offer excellent corrosion resistance thereby making them stainless in aggressive environments. Alloy steels contain fair quantities of both Carbon and alloying elements but received the name as tool steel due to their use in tooling. Shape stability is an essential requirement for tool steels which is absolutely dependent on a high degree of hardness [3]. Hence, there is a need for the maintenance of their dimensional accuracy, resistance to abrasive wear and tear at contact surfaces in addition to the good blend of high strength, toughness, resistance to creep/deformation at elevated temperatures (hot hardness) as well as economics of manufacture at high speeds and feeds. This has placed high industrial demand on continuous improvement of tool steels both in alloying and processing so as to achieve functional tools and high-quality finished products.

The four major costs facing a final product in the manufacturing industry: costs on labour, material, production time and tooling affect the final price placed on the product; these costs directly impinge on the cutting tool[4, 5, 6]. Controlling these costs via heat treatment to increase the life and performance of cutting tools is a mutual benefit to both the user and manufacturer. Hence, to achieve desired production targets, reduce tool maintenance cost and scrap rates, the economy of cutting tool life becomes inevitable and this has recently attracted the attention of both the research and industrial communities at a global scale.

To reduce friction, wear and contact surface temperature, lubricants and forming oils have been used but their biodegradability and additional cost in the production cost still creates the need for rugged tool steels.

In industrialized countries, direct losses due to friction and wear has been estimated around 7% of their gross national product which has intensified the demand for innovative materials[7]. Their high alloying elements rich in carbide formers enables them to be efficient as cutters in drills bits, taps, punches, milling cutters, saw blades, knife blades, cutting hobs, reamers, injection molding tips, stamping, forging, threading and deep drawing dies as well as different lathe tool bits and agro-machine parts. These carbides are formed by a good blend of alloying and controlled heat treatment processes. Hence, the final properties of a steel sample depend on the microstructural arrangement of the size, shape and distribution of alloying elements in the ferrous matrix, hence, these properties can be manipulated through heat treatment [1, 8]as investigated in this study.

Heat Treatment is defined as a solid solution process of controlled heating of materials into solutionizing temperatures, soaking for even dissolution of solute atoms and for getting rid of temperature gradients (homogenization) and finally cooling at appropriate rates to modify their physical and mechanical properties through microstructural rearrangement. Material properties commonly adjusted through heat treatment includes strength, ductility, brittleness, toughness, removal of residual stresses, hardness and other tribological properties as well as improving the ease of forming and machinability. Fabrication and manufacturing processes like welding and machining causes unplanned heat treatment at localized regions like the heat affected zones which can alter the intended material properties. However, since heat treatment process are carried out at molten state (below the melting point) the process does not alter the product shape. The popular heat treatment processes available to tool steels are: Annealing, Normalizing, Hardening/Quenching and Tempering. These processes follow the three significant stages of heating, soaking and cooling to obtain the final structure and corresponding mechanical properties.

Heating into austenitic temperatures dissolves alloy carbides and limits primary austenite grain growths, soaking by holding at the austenitic temperature for some time to ensure full dissolution of solute atoms and to even out the temperature gradient between the surface and core followed by a controlled cooling [3]. Full annealing or simply annealing is the most preferred heat treatment process when a good balance between strength and ductility viz a vis toughness which it achieves by grain refinement of the ferrite- pearlite microstructure. Annealing is done by a gradual cooling inside the furnace with the popular aim being to restore ductility or remove residual stress induced during cold working. Normalizing as an air-cooled process foran intermediate increase in strength and hardness between annealing and quenching conditions due to its formation of pearlite.

Quenching or hardening is done by a rapid cooling in water, oils or salt baths to trap the solute atoms within the solid solution which gives rise to 100% martensite for smaller tools and martensite with bainite for larger ones. Quenching produces maximum strength and wear resistance at the expense of ductility, electrical conductivity and corrosion resistance. The reduced ductility mainly limits the applicability of quenched materials as structural engineering materials. The shortcomings of high brittleness of quenched materials can be moderated by tempering where the quenched material is slightly reheated to precipitate carbides and bainite in ferrite matrix [9] before cooling to ambient temperatures. Sometimes supplementary treatments like case hardening via carburizing or nitriding are used to further improve the tool surface performance.

As tool steels interact with other metallic surfaces on regular bases all their life, they are conditioned to required properties through these heat treatment process. Based on this, our study aimed at investigating the effects of these different treatments on the physical, tribological and mechanical properties of tools steels as literature reveals that further research is still needed in this area. To achieve this, our objective focusses on preparing the samples to standard heat treatment practices and mimicking ambient conditions similar to the service environments in which the actual tools will operate.

II. MATERIALS AND METHODS

2.1 Materials: Samples of scrap cutting tools were collected from manufacturing plants, fabrication workshops and tooling centers. The most scrapped tools were drill bits, saw blades and lath cutters.Drill bits were selected as they had the best shape for machining into the required tensile test sample.Four samples (one as control and three for heat treatment) were machined using a center lathe before alloy characterization was conducted to ascertain the elemental composition.

2.2 Method: Material characterization was conducted by energy dispersive X-Ray Fluorescence analysis using Oxford Instrument X-Met 7000 XRF Spectrometer (Oxford Instruments plc, England, UK) at different positions on the selected sample and was observed to be precise. The three samples(one left out as control) were charged into the laboratory Muffle furnace set to Autenitizing temperature of 1050^{o}C. These samples were held for 60 minutes to achieve a homogenized heat treatment and this soaking time was believed to get rid of temperature gradients due to structural variations and to avoid micro-segregation during cooling. One (the annealed sample) was left to cool in the furnace for 24 hours while the other two were quenchedin water at room temperature.

One of the quenched samples(tempered sample) was later charged into the furnace for tempering up to 210^{o}C. After cooling, the samples were recovered from the different heat treatments and were subjected to uniaxial loading on aMonsanto tensometer including the control sample according to ASTM E8 / E8M-16a for standard tensile strength testing[10]. Results of the tensile test were interpreted as Stress-strain curves where the yield, ultimate and fracture strengths were presented in graphical format. Ductility (percent elongation in length and reduction in area) was also determined from dimensional changes of the gage length. A small sample was cut from each of the fractured sample after tensile testing to prepare them for microstructural analysis based on the ASTM E3-11 standard [11]. This was followed by impregnating the small cuttings in a phenolic powder to be thermoset using a digital mounting press for ease of handling while being ground on a hand grinding steel stand and polished in universal rotary polishing machine. The compaction was done by setting the mounting press to a pressure of 400bar to obtain a condensed sinter with the sample revealed at one end. These sinters (cuttings imbedded in phenolic thermoset) were ground progressively with different abrasive papers in decreasing coarseness (grit sizes: 240,320,400, 600, 800, 1000 and 1200). Grinding was done in sixty strokes of equal length in successive directions of 90^{o} to counter the grooves formed by the previous. This was done by advancing to the next smoother grit until contour-free and bright surface samples were obtained to prepare the samples for polishing. The rotary polishing machine with a surface Velvet cloth was wetted with a Diamond paste before it was electric powered with the sample placed tightly on the cloth. At 2 minutes intervals, the sample was turned in 90^{o} to facilitate polishing and to get rid of any micro-grove not removed during grinding. This offered a mirror-like shiny surface after repeated polishing showing that the sample was ready for etching. The clean samples were dipped for 2 minutes into 2% Nital made by diluting 2% Nitric acid in 98% ethanol followed by rinsing in distilled water before oven dried for micro-examination in accordance with the ASTM E407 - 07(2015)e1 standard [12]. The metallurgical microscope was set to 400 magnification with the camera activated. After setting the samples on stage and focused in turns, they were viewed and micrographs saved in Jpeg format for metallographic interpretation and further microstructural study.The experiments were concluded with a hardness test where the samples were indented using a Rockwell hardness testing machine at four locations and the average recordedfollowing the ASTM E18 - 19 standard [13].

III. RESULTS AND DISCUSSION

Results of the chemical composition (Table 3.1) from the XRF conducted shows the carbon and other alloying elements contributions to the tool steel composition. This instrument has a unique feature of displaying the alloy designation in the Unified Numbering System (UNS) grade on immediate detection with the probe. **Figure 3.1**shows the tensile test sample dimensions.

Element	Cr	Mo	Mn	V	Si	C	Ti	Al	Fe
%Composition	0.46	0.30	0.13	0.18	0.25	0.43	0.13	0.02	Rest
±	0.012	0.016	0.031	0.015	0.178	0.033	0.022	0.368	-

Table 3.1: Chemical composition of the studied tool steel

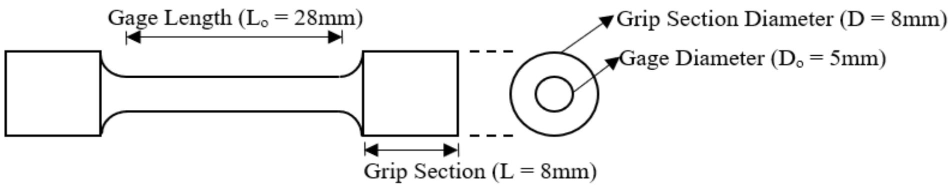


Figure 3.1: Dimensions of the tensile test sample as perASTM E8 / E8M-16a standard [10]

3.1 Mechanical properties

Engineering Yield, Ultimate Tensile and Fracture Strength Results and discussion:

Results from figures 3.2, 3.3 and 3.4 show the Stress-Strain results of the samples tested under different heat treatment. Figure 3.2 demonstrates the effect of full anneal heat treatment on the tensile properties of the tool steel tested with respect to the untreated sample. Comparing the two graphs: the yield, ultimate and fracture strengths were noticed to decrease by 32.50%, 21.57% and 18.12% respectively. Summary of the yield, tensile and fracture strengths of the full annealed samples compared to the untreated are shown in figure 3.4a.

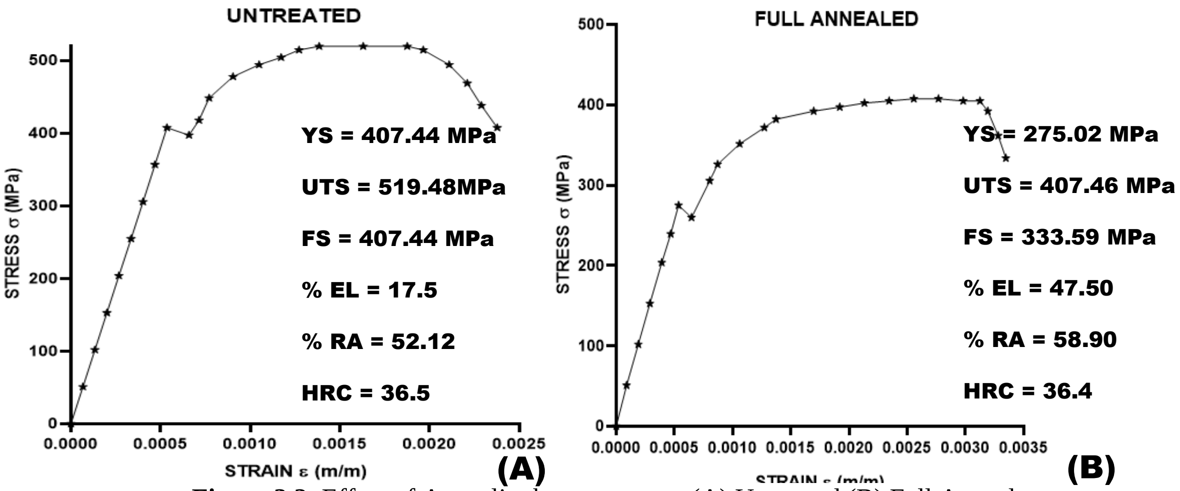


Figure 3.2: Effect of Annealingheat treatment (A) Untreated (B) Full Anneal

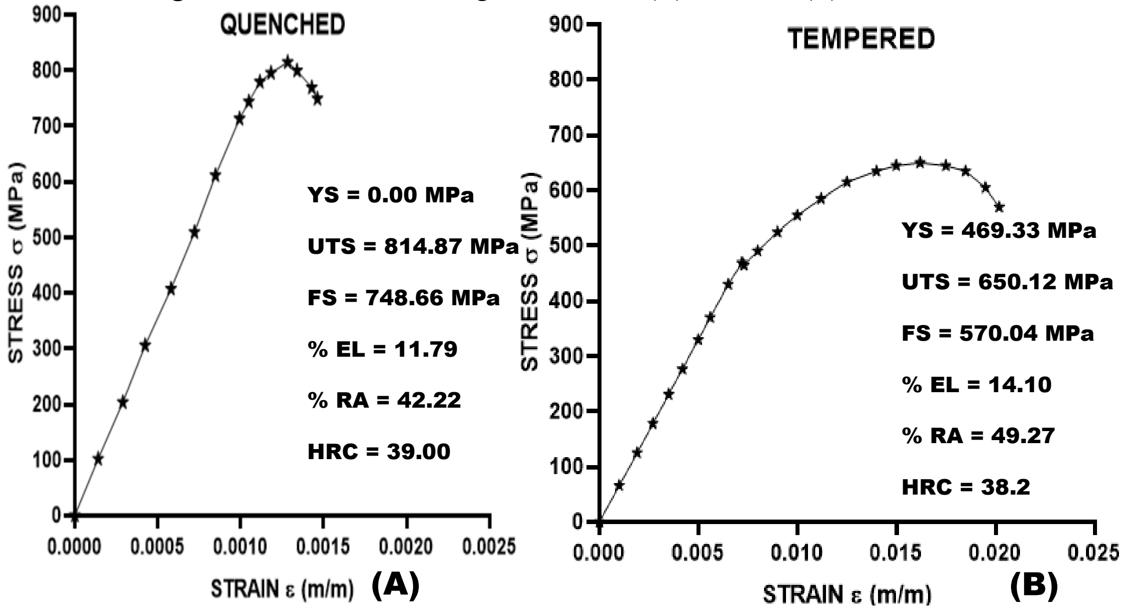


Figure 3.3: Effect of other heat treatments (a) Quenching (b) Tempering

The effects of Quenching and Tempering are shown in figure 3.3. It was noticed that Quenching increased the ultimate and fracture strengths by 56.86% and 83.74% respectively compared to the untreated sample in figure 3.2 with no well-defined point of yield strength. Remarkably, the effects of tempering by reheating the hardened alloy sample up to 210^{o}C before final cooling was noticed to improve the toughness, hence, practical use of this hardened sample.

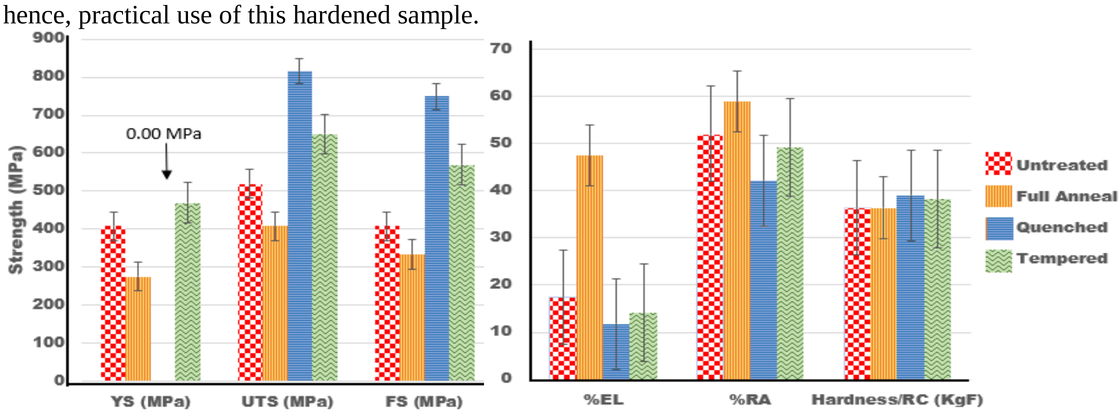


Figure 3.4: Summary of results: (a) Yield Strength YS, Ultimate Tensile Strength UTS and Fracture Strength FS (b) Ductility in Percentage elongation in Length EL, Percentage Reduction in Area RA and Rockwell Hardness RC

Results showed that the tempering process increased the ultimate and fracture strengths of the untreated sample by 26.50% and 39.91% respectively which were lower than the results from the hardened conditions with a noticeable yield strength at 469.33 MPa.

Hardness and Ductility Results and discussion

From figures 3.2b and 3.4b, full annealing was noticed to display least hardness with0.27% reduction in hardness compared to the untreated sample. However, it maintained highest ductility of 30% and 6.78% respectively in percentage elongation in length (PEL) and percentage reduction in area (PRA) compared to the untreated sample. Quenching demonstrated the highest hardness with a 6.85% rise in hardness with the ductility being adversely reduced by 32.63% and 18.99% in terms of PEL and PRA respectively making the sample very brittle. Moderate drops in hardness by 4.66% and ductility by 19.43% and 5.45% in percent elongation in length and percent reduction in area respectively were identified in the tempered sample which are ideal for tool steels unlike the 32.63% and 18.99% obtained in the quenched condition.

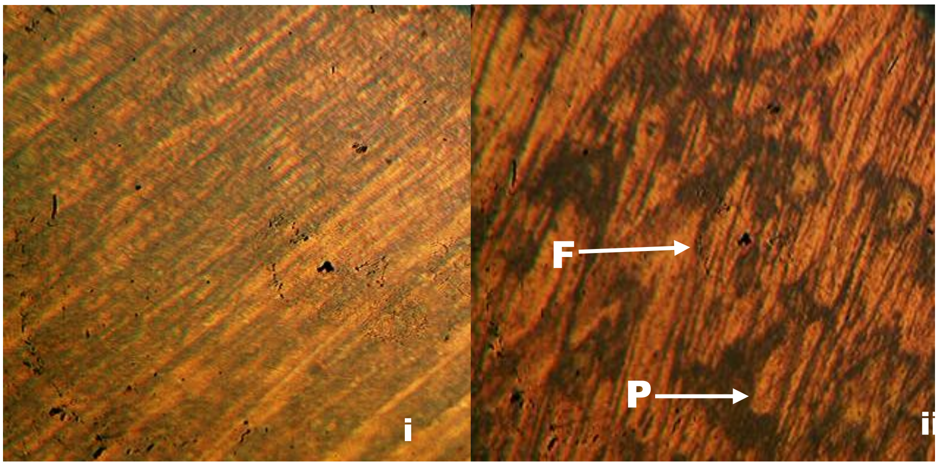
3.2: Microstructural characterization

Microstructural Results and discussion:

Microstructural results in figure 3.5 demonstrates the effects of the different heat treatment processes. The annealed sample shows proeutectoid ferrite (F) within colonies of pearlite (P). Hardened (Quenched) sample showing residual Austenite (A) entrapped within Martensite interlaths (M), tempered martensite showingCementite (C) as finely dispersed precipitated carbide particles resulting from the decomposition of retained austenite (A).

Full Annealing: The kinetics and thermodynamics of this full annealing are favored by the presence of alloying elements which triggers the diffusion of proeutectoid ferrite and activates the decomposition of the parent austinite phase. The isothermal transformation of Austenite gave rise to nucleation of metallic carbides (cementite) in a ferrite matrix diffusing from preferred locations like inclusions and austenite grain boundaries[14]. These dual phases continued as cooperative growth within the austenite resulting into their (cementite and ferrite) alternating layers leading to the lamellar appearance of pearlite. Hence, the slow cooling rate in the muffle furnace during the full annealing process led to a microstructure of proeutectoid ferrite (F) and pearlite (P) as shown in figure 3.5ii. Hence, the black components of figure 3.5ii are high concentrations of cementite (Iron carbide, Fe_3C) in pearlite while the white component is due to ferrite which is not necessarily from pearlitic ferrite alone but a combination of proeutectoid ferrite and pearlitic ferrite.

Ferrite is known to be very soft and ductile while cementite is hard, strong and brittle[1]. The high ferritic content of this resultant microstructure accounts for the reduced yield, tensile and fracture strengths as well as hardness with increased ductility in line with results from [15] which will lead to accelerated wear[16] as a tool steel. Based on this, full annealing is recommended from this study as an intermediate heat treatment process ideal for forming and machining purposes.



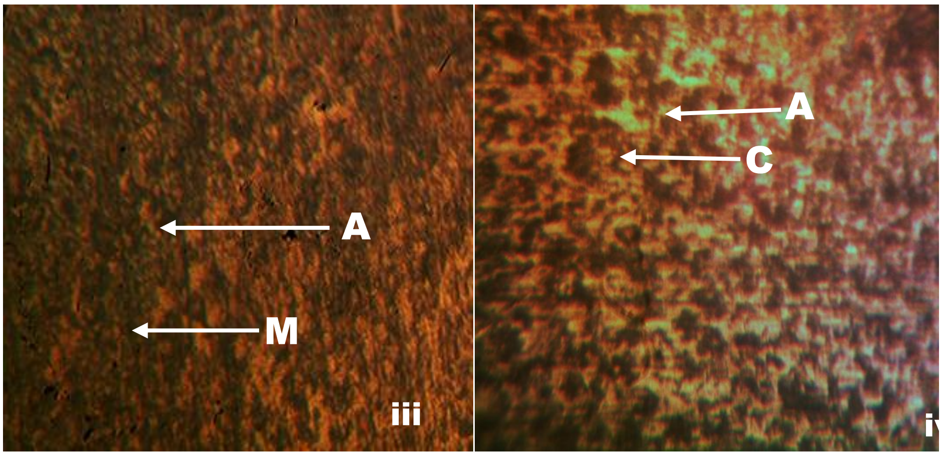


Figure 3.5: Micrographs: (i) Control, (ii) annealed, (iii) quenched and (iv) temperedsample (x400)

Quenching: The extremely fast cooling of the austenite phase denied the solute carbon atoms enough time to diffuse out of the austenite crystal lattice. Since the ferrite matrixwas body centered cubic lattice with less interstitial space compared to the parent austenite's face-centered cubic (FCC) crystal lattice, the ferrites turned out to be distorted with surplus carbon as solute atoms in the solid solution. The resultant lattice structure shrinked in two cubic sides (a and b) and stretches along the third plane (c) with ($a=b\neq c$), a crystal lattice known as body-centered-tetragonal (BCT) lattice structure of martensite (M) (figure 3.5iii) as supported by[1].

This Martensite was composed of carbon atoms supersaturated in a ferrite matrix and as the transformation is difficult to control, cooling down to room temperature reserves some retained austinite(A) as shown in figure 3.5iii. This transformation was nonequilibrium and diffusionlessin line with[17];hence it was metastable at room temperature since the rapid cooling rate bypassed the equilibrium phases obtainable and also denied the solute atoms the time to diffuse into stable interstitial lattice positions. This supersaturation led to solid solution strengthening whilethe asymmetry in BCT lattice structure caused insufficient number of slip systems leading to increased resistance to deformation. Also,the elastic strained condition generated a high dislocation density and with the less slip planes to slide on due to BCT lattice structure,reduced the material's response to shear (ductility). All these conditions contributed to the overall Martensite's high strength, hardness and reduced ductility demonstrated in figures 3.3 and 3.4a in line with previous findings [8, 18, 19].

Tempering: Though the extremely high strength and hardness obtained from the martensite were desirable for the anticipated tool steel yet the brittle nature will cause severe abrasive wear making it less useful in several practical applications. In addition, the lattice distortions and supersaturated solid solution must have incurred both internal stress and surface cracks that will also limit its structural performance as supported by[1]. Tempering heat treatment was deployed to redistribute the trapped carbon atoms which restored some ductility and relieved the suspected internal stresses. In so doing, this reheat up to 210^{o}C where austenite reappearance was neither thermodynamically supported nor kinetically encouraged, instead forced the decomposition of some of the martensite. Through this, the microsegregation of the excess carbon solutes out of the Martensite solid solution and transformation of the retained austenite jointly precipitated as cementite grains (C) in the ferrite matrix (figure 3.5iv). In the long run, this reinstated equilibrium conditions, relieved internal stress and established material toughness but reduced hardness and strength from the parent martensite metastability.Our findings in line with previous results [16] demonstrated that tempering offered an excellent blend between toughness,strength, ductility and hardness which provided the required resistance to abrasive wear and deformation at elevated temperatures (hot hardness) especially at high operating speeds and feeds expected in the anticipated tool steel.

IV. CONCLUSION

It was clear that the alloying elements added an advantage to the kinetics and thermodynamics of the isothermal heat treatments investigated. We noticed that full annealing extremely increased the ductility with a corresponding drop in hardness as well as reduction in yield, tensile and fracture strengths. These were attributed to the dominance of soft ferrite from both the pearlite and proeutectoid ferrite compared to the hard and strong pearlitic cementite. Furthermore, quenching produced martensite with some retained austenite resulting to an exceeding rise in the hardness as well as tensile and fracture strengths with no observable yield strength. These introduced cracks due to induced stress as well as adverse effects on the ductility which made the material to be too brittle for several practical applications. To reduce these limitations, tempered martensite which composed of precipitated cementite grains in a ferrite matrix gave rise to a moderate rise in yield, tensile and fracture strengths in addition to sufficient hardness and ductility. These good blend of temper results were below the properties from quenching but greater than the full annealed condition which offered a high level of overall material toughness for the anticipated tool steel. From this study, we recommend these three heat treatment processes for general tool steels in the sequence of full anneal for forming and machining purposes, quench to obtain the desired high strength, resistance to abrasive wear and thermal deformation (red hotness) and finally temper to restore the required toughness and mechanical stability.

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Disclosure

The authors report no conflicts of interest in this work.

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