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Effects of Tampering Heat Treatment on the Performance of Hardened S7 Tool Steel

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Abstract— Technological advancements increase the pressure on industrial activities where post processing activities like machining places high demand on tools with high performance and longer tool life. The unique mechanical and physical properties of tools are improved through heat treatment processes like tempering, hence, the effect of different tempering conditions on the performance of S7 tool steel was studied. Four S7 tool steel samples were subjected to different tempering conditions. One was used as-received while another was tempered without any heat treatment exposure. Other two samples were austinitized to 1050oC prior to quench-hardening in automobile lubricating oil. Among the two quenched samples, one was used in as-quenched condition while the other was tempered to 500oC before being cooled in still air. The four samples were subjected to tensile, hardness and metallographic analysis. Results showed that quench-hardening increased hardness by 91.17%. However, tempering the as-quenched sample reduced the excessive core hardness and surface microhardness by 14.04% and 16.11% respectively. Also, through tempering the hardened samples, the tensile strength, yield strength and Young Modulus were moderated by 89.26, 95.83 and 2.49% respectively. At these high mechanical properties, post-hardened tempering increased the ductility of the hardened sample by 33.33% leading to an improved toughness. Results also show a correlation between microstructural phase changes and mechanical properties. Metallographic studies revealed that transformation of retained Austinite to martensite within eutectic carbide matrix was responsible for the high mechanical properties obtained which must be tempered before use. Hence, tempering is highly recommended for hardened S7 tool steels.

Keywords— Tempering; heat-treatment; hardening; quenching; Tool steel.

I. INTRODUCTION

Despite how power tools have revolutionised the machining, manufacturing and construction industries, hand tools continue to dominate the tools market due to their durability, and performance. Most of them are made from tool steel grades with S7 being a popular grade known for its exceptional strength, hardness, shock and wear resistance. With this, S7 Tool Steel has remained the best choice for manufacturing of dies, forge, machine tools, center punch, chisels etc. To sustain their integrity when contacting a workpiece, intrinsic properties like physical, mechanical, tribological and thermal stabilities must be optimized with heat treatment the most popular processing method for tuning microstructural modification to suit desired performance over its life time. Tempering as a post heat treatment process has been presenting improved performance and extended tool life to high strength tool steels in recent times. However, the tempering practice offers different results in different heat treatment conditions and the foundry worker must be abreast with the right information as a guide to optimal results. Hence, in this study, the effect of tempering heat treatment on the performance of S7 Tool Steel was carried out to explore the wide range of options available from microstructural modifications. Tempering was chosen because it is a crucial post heat treatment process that relieves internal stresses thereby improves several physical and mechanical properties of materials. It involves heating the material to a predefined temperature, holding at that temperature over a predetermined duration then followed by a controlled cooling to facilitate the emergence of desired precipitates for improved performance. These improved performances are usually from three microstructure-based modification mechanisms. First, the relief of quenching-induced internal stresses thereby improving dimensional stability and mechanical properties like toughness, wear resistance, etc. Next is the precipitation and redistribution of secondary carbides within the matrix leading to improved microhardness and wear resistance. Another means that tempering improves tensile toughness and ductility is by the decomposition of the very brittle but hard as-quenched martensite into tempered martensite that possess higher toughness. With these, it can be seen that temper heat treatment offers improve intrinsic properties reflecting on the physical, mechanical, tribological and thermal stabilities of Tool Steels against the abrasive and shock impacts when they contact the workpiece. It is highly prohibited to engage in scrap development in manufacturing process (Elenwo et al., 2024). However, the volume of scrap and rejects increases due to blunt tool or excessively worn tools. Hence, the need to inculcate exceptional mechanical and physical structural performance on tool materials becomes a necessity to manufacturers. According to Shivashankar, et al., (2022), cutting tools must have higher hardness, strength and toughness than the workpiece. However, tools are constantly exposed to severe abrasive contact conditions that causes cracking, wear and plastic deformation all through their service life, (Podgornik, et al., 2013). Heat treatment is one of the established methods of improving tool steel properties, Shivashankar, et al., (2022) and the most of the mechanical properties rises from the evolution of martensitic microstructure.

Several authors have studied the heat treatment of tool steels. For instance, Sun, et al, (2022) investigated the thermomechanical properties of additive manufacturing produced tool steels before heat-treating the components. They realized that the heat treatment improved the thermal conductivities with decreased anisotropy. Also, Momeni, et al., (2014) studied the influence that heat treatment has on mechanical properties of altered cast AISI D3 tool steels. Remarkable increase in wear resistance was achieved from the study. Likewise, Chen, et al., (2024), investigated the impacts of different austenitizing temperature on the microstructural behavior and structural performance of Cr–Mo–V hot work tool steels at different nitrogen contents. Their results showed that the primary microstructural phase was tempered martensite and that the higher the Nitrogen content the better the impact toughness which occurred more at increased austenitizing temperatures. These findings from existing literature that tempered martensite offer high mechanical properties, it calls for more attention to researchers in heat treatment and materials development. Hence, as the only way of generating a martensitic microstructure is through austinite transformation during quenching, (Ofner, et al., 2025), it becomes researchable to explore the potential of the quenching process and its post-quench temper heat treatment.

Aim of the study: The aim of the study was to evaluate the effect of the different tempering conditions on the properties of the S7 tool steel.

II. MATERIALS AND METHODS

Material preparation

To investigate the effect of different tempering conditions on the performance of tool steels, a high-speed tool speed sample designated as S7 was procured from the Port Harcourt Steel village as cylindrical rods of 10 mm and 50 mm diameter and length respectively. Compositional analysis was carried out to understand the elemental make up of the alloy through energy dispersive X-Ray Fluorescence analysis using Oxford Instrument X-Met 7000 XRF Spectrometer (Oxford Instruments plc, England, UK) at different positions on each rod sample and was observed to be precise. The result obtained is shown in table 1.

Table 1: *Chemical Composition of S7 Sample*

Element	C	Cr	V	W	Si	Mn	Cu	P	S
Wt %	0.55	3.50	0.30	1.0	0.60	0.80	0.25	0.03	0.03

Four samples in all were used. Sample SC was left out as a control while three were subjected to different conditions of tempering. Sample SAT was austinitized to 1050°C for 6 hours, held at that temperature and quenched in mineral oil. This sample was later tempered to 500°C. Sample SA was austinitized to 1050°C for 6 hours, held at that temperature and quenched in mineral oil without tempering operation. Finally, Sample ST was tempered to 500°C without a prior austinitizing heat treatment. These designations are tabulated in table 2:

Table 2: *S7 Sample Designations*

Sc	Control sample tested without heat treatment process
SAT	Austinitized to 1050°C, held at that temperature for 30 minutes and quenched in mineral oil. This sample was later tempered to 500°C.
SA	Austinitized to 1050°C, held at that temperature for 30 minutes and quenched in mineral oil without tempering operation.
ST	Tempered to 500°C without a prior Austinitized heat treatment.

III. DIFFERENT TEMPER HEAT TREATMENT CONDITIONS

While the first sample was labelled as the Control sample to be tested without heat treatment as SC, the second and third samples were charged into the laboratory Muffle furnace set to Autenitizing temperature of 1050ºC. The samples were held for 30 minutes under furnace temperature 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 of precipitates during cooling. At the end of the 30 minutes, the two austinitized samples was quickly transferred into a beaker containing mineral oil. These samples were allowed to remain in the quenchant until cooled to room temperature. One sample was labelled as the Austinitized sample quenched in mineral oil without tempering as SA while the other sample was marked as the Austinitized sample quenched in mineral oil and tempering as SAT and charged into the furnace with the fourth sample labelled as tempered without a prior Austinitized heat treatment as ST. These two samples were heated up to 500ºC, held at that temperature for 30 minutes for homogenization and allowed to cool in still air. After this, the four samples SC, SA, SAT and ST were subjected to mechanical uniaxial loading test to investigate the effect of the different tempering conditions on the properties of the S7 Tool Steel.

IV. MECHANICAL TESTING

From the rods, test samples were machined using a center lathe into 28 mm and 5 mm gage length and gage diameter respectively ready for physical, mechanical and morphological characterization.

From A grip section of 8 mm in both length and diameter were machined to enable holding grip within the chuck of a tensometer. The standard ASTM E8 procedure was followed as reported in Uchegbulam et al., 2019. To get rid of surface defects that may interfere with the expected results, the samples were ground and polished with abrasive papers of different grit sizes progressing from 220 up to 1200. On gripping the sample in the chuck of the Universal Testing machine to avoid bending stresses and to ensure uniform loading, a uniaxial tensile loading at a strain rate of 0.05 mm/mm per minute was applied. The loading was consistent until fracture occurred recording the force-extension results on a graph sheet attached to the extensometer drum. From the results, the ductility reported as percentage elongation in length, the Young's Modulus in GPa, Yield Strength (MPa) and Ultimate tensile strength (MPa) were recorded and presented.

V. HARDNESS TESTING

The core hardness of the samples was carried out on flat surfaces of the samples according to ASTM E18 Standard. To ensure a smooth surface free of scales and dirt which may affect the expected results, the targeted surface was ground using Abrasive paper mesh 220 and 600 successively before polishing with 1200 and mesh. This was done without generating heat that may alter the microstructural arrangement of the samples. According to this ASTM standard, the ASTM E18 was suitable for S7 Tool Steel using Rockwell C scale (HRC). The diamond cone with 120° cone angle was used with 150 kgf and 10 kgf major and minor loads respectively. This test was conducted by initially applying the minor laod of 10kgf to establish a reference prior to applying the major load of 150 kgf for a 15 seconds dwell time. After this dwell time, the major load was removed and with the minor load still applied the indentation was measured. This was done in triplicate with the average recorded as the Rockwell hardness number (HRC).

Likewise, the surface microhardness of the S7 samples were measured using Vickers Hardness test in line with ASTM E92 standard. surface preparation to obtain a mirror-like finish was conducted. a diamond pyramid Vickers indenter with a 136° included angle. 1 kgf load for microhardness testing was pressed unto the Tool Steel surface for a 15 seconds dwell time. Using a Keyence microscope, the average lengths of the indentation diagonals were estimated and the Vickers Hardness Number (VHN or HV) is determined using the formula:

Where P = Applied Load (kgf)
d = Average lengths of the indentation diagonals (mm).

VI. METALLOGRAPHIC ANALYSIS

From each of the four samples, a small sample was cut after the tensile testing to prepare them for microstructural analysis based on the ASTM E3-11 standard. This was done by impregnating the cuttings in a phenolic powder using a digital mounting press. The compact help for gripping the sample while grinding them on a rotary grinding machine until the cutting was revealed and its surface ground into a fine surface finish prior to polishing on a Polishing machine to obtain a mirror-like surface. The repeated polishing advancing through different polishing emery cloths of different grit sizes continued until a mirror-like shiny surface was

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obtained showing that the sample was ready for etching. To reveal the microstructure of the samples, each of the prepared samples were dipped for 2 minutes into 2% Nital made by diluting 2% Nitric acid in 98% ethanol followed by rinsing in distilled water. This etched samples were oven dried for micro-examination in accordance with the ASTM E407 standard [12]. A metallurgical microscope set to 500 magnifications with its metallographic camera activated was used to view the microstructure of the samples. After fine resolution of the surfaces on the microscopic stage, micrographic images were captured and saved in Jpeg format for metallographic interpretation.

VII. RESULTS

Ductility as Percentage elengation in length

From the tensile tessting process conducted, it was observed that the different tempering conditions had significantly different effects on the samples tested as shown in figure 1,

The As-Received sample (SC) used as control which had neither heat treatment nor tempering exposure had the highest ductility of 14.03%. After tempering it to 500ºC as ST, the ductility reduced by 15.71%. The Quenching heat treatment as SA drastically reduced the ductility by 86.8

%. However, tempering it as SAT to 500ºC only affected the ductility by 25.71% reduction. With respect to the quenched sample, the lost ductility was increased by 33.33% through tempering heat treatment of the SAT sample.

This showed that though quenching reduces the ductility of Tool Steels but tempering improves the ductility of quenched Tool Steels.

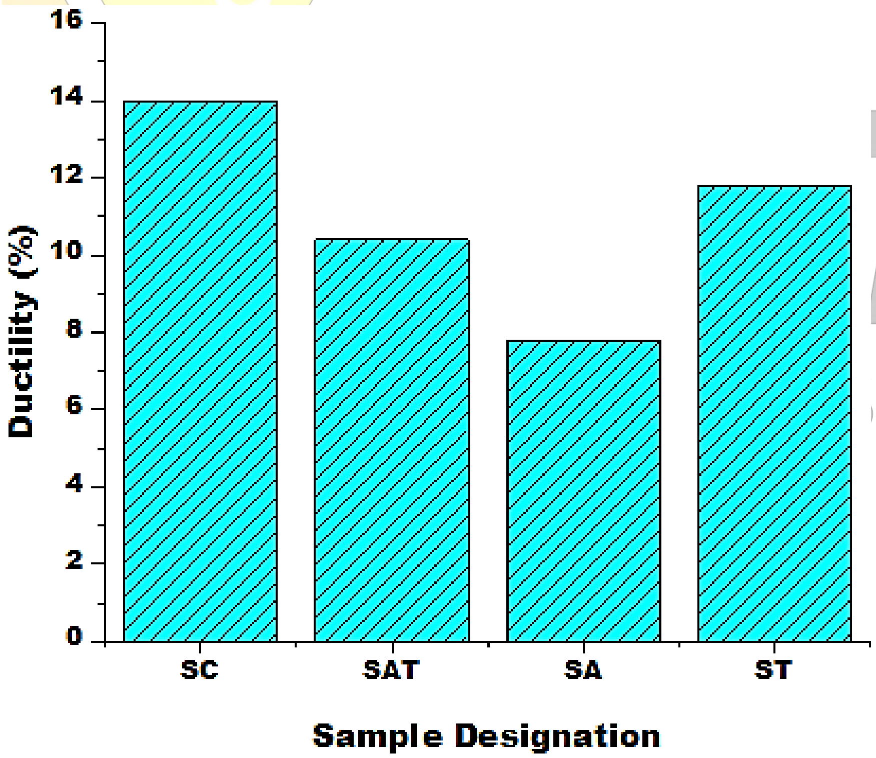

Figure 1: *Effect of different tempering conditions on the ductility of S7 Tool Steel*

VIII. ULTIMATE TENSILE STRENGTH, YIELD STRENGTH AND YOUNG MODULUS OF S7 TOOL STEEL

From figure 2, it can be noticed that the different tempering conditions affected the properties of the Tool Steel samples. Slightly tempering the As-received sample SC to 500ºC as ST increased the tensile strength, yield strength and Young Modulus by 26.90, 12.50 and 0.50% respectively. Likewise, by quenching the heat-treated tool steel samples as SA increased the tensile strength, yield strength and Young Modulus by 54.01, 73.61and 1.49% respectively.

However, by tempering the quenched sample to 500ºC as SAT, the tensile strength, yield strength and Young Modulus were reduced by 89.26, 95.83 and 2.49% respectively.

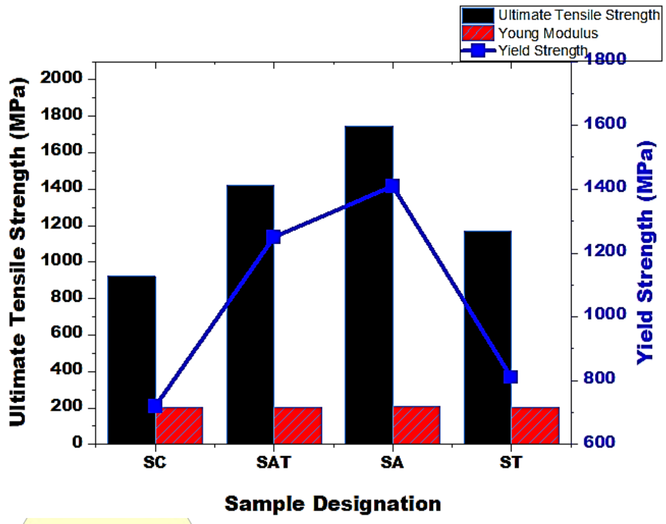

Figure 2: *Effect of different tempering conditions on the Ultimate Tensile Strength, Yield Strength and Young Modulus of S7 Tool Steel*

IX. HARDNESS TESTING

Similar to the mechanical properties, the Rockwell Hardness Scale C values of the As-Received sample SC shown in figure 3 was increased by 32.35% as the sample was tempered as ST without austinitizing heat treatment. The core hardness value was further increase by 91.17% by austinitic heat treatment prior to quenching in the SA sample treatment. However, the core hardness of the quenched sample was slightly reduced by 67.65 % as it was tempered as SAT. This shows that quenching heat treatment adversely affects the core Hardness of Tool Steels but tempering the quenched sample moderates the hardness. Likewise, the same trend was observed in the surface microhardness when measured with Vickers hardness method.

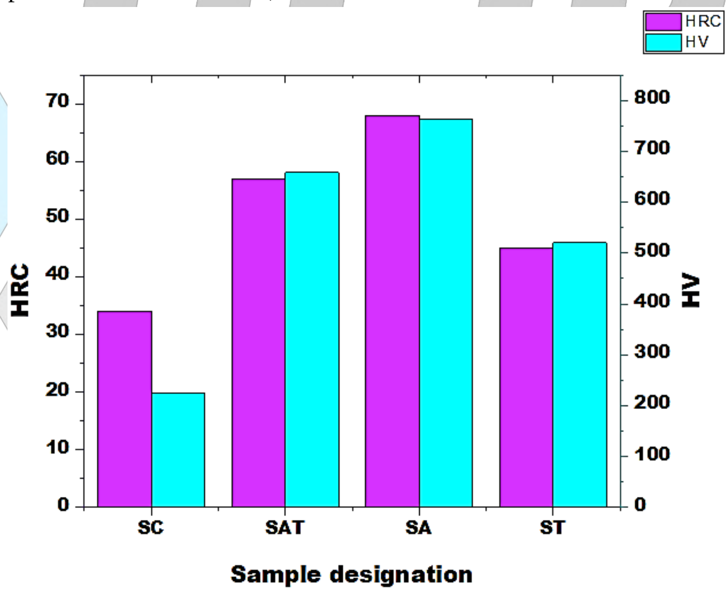

Figure 3: *Effect of different tempering conditions on the Hardness of S7 Tool Steel*

From the micrographs in figure 4, it can be noticed that the as-received sample SC in plate A had a finely dispersed gray phase in a white matrix. As it was tempered to 500ºC, both phases became coarse in plate B where the sample was tempered as ST. There was a possibility that this tempering heat treatment must have relieved internal stresses being the primary reason why the tensile strength reduced compared to the control sample SA. With respect to the quenched sample, the excessively core hardness was decreased by 14.04% and surface microhardness by 16.11% through tempering heat treatment of the SAT sample. This showed that though quenching increases the hardness of Tool Steels leading to higher tendencies to wear but tempering moderates the hardness of quenched Tool Steels.

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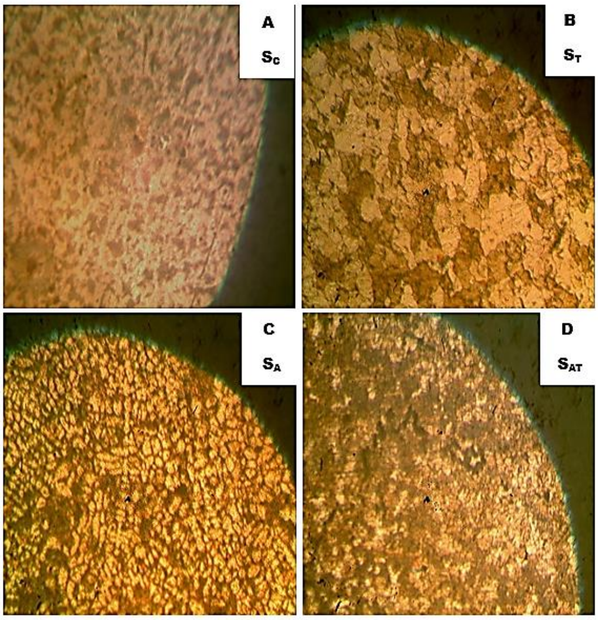

Plates; A, B, C and D, are Optical Micrographs of different tempering conditions on S7 Tool Steel at 500X magnification (a) Control sample tested without heat treatment process (SA) (b) Tempered to 500ºC without a prior Austinitized heat treatment (ST) (c) Austinitized to 1050ºC for 6 hours, held at that temperature and quenched in mineral oil. This sample was later tempered to 500ºC. (SAT) (d) Austinitized to 1050ºC for 6 hours, held at that temperature and quenched in mineral oil without tempering operation (SA).

Furthermore, austenitinitc heat treatment prior to quenching led to the finest grainsize of the gray phase in plate C. This offered the highest tensile strength and this treatment is suspected to engage the transformation of dissolved austenite phase into Martensite.

Hence, the gray phase is believed to be martensite in a whitish Carbide matrix. In this untempered condition, the martensitic microstructure was responsible for the high ultimate tensile strength, yield strength and young modulus.

Since martensite is a hard and brittle phase, this can be linked to the reason why sample SA had the highest Rockwell Hardness value and highest brittleness, that is, lowest ductility. In plate D, where sample SA was tempered into SAT, it was noticed that the gray phase grew in grainsize. It was believed that this tempering must have relieved quench-induced residual stresses leading to reduced tensile strength and improved ductility than in the as-quenched condition.

X. CONCLUSION

The present study focused on the effects of different tempering conditions on the microstructure, hardness, modulus, ductility, tensile and yields strengths of S7 tool steel. The elemental composition of the tool steel was ascertained for ease or result reproducibility. Cylindrical rod samples were machined into tensile test samples and were subjected to different tempering conditions. Results showed that the tempering heat treatment can improved the ductility of quenched tool steel samples with reduced effect on the young modulus, tensile strength and yield strength. Microscopic evaluation linked the tempering effect to the retained austenitic transformation into martensitic phase in eutectic carbide matrix.

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