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To Study the Mechanical Properties of AISI H11 Tool Steel after Heat Treatment

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Abstract- Belonging to the class of chromium tool steels, AISI H11 possesses very good toughness and hardness, and is therefore suitable for hot metalforming jobs performed at very high loads. Mostly used in fabrication of helicopter rotor blades, H11 also has great potential as a die steel in hot-work forging and extrusion. This alloy steel can be heat treated to increase the service life and dimensional accuracy of the die and tooling. Main aim of the current investigation was to formulate an optimum heat treatment strategy for H11 steel, especially for hot work applications. High-speed milling and electric discharge machining were used to fabricate samples for tensile and impact testing. After various types of heat treatment (annealing, austenitizing, air cooling or oil quenching, single and double tempering), these samples were tested for hardness, toughness (impact), yield strength, tensile strength, and ductility. Microstructural analysis was also performed to analyze the effect of heat treatment on mechanical properties. As tempering temperature increases, hardness initially increases and then starts to gradually decrease; impact strength first decreases and then increases; and yield strength exhibits a fluctuating pattern of initial decline followed by an increase and another decrease. Even though H11 steel is highly suitable for both hot and cold-work, it is surprisingly not a common choice for metalworking dies and tools. Results presented here can encourage die designers and hot-work practitioners to explore the versatility of this tool steel, and to adopt appropriate heat treatment strategies for different applications.

***Keywords*:** H11 tool steel, hardness, toughness, tensile properties, optimum heat treatment, microstructure

I. INTRODUCTION

Tool steels used in machining and metal forming operations are generally high-alloy steels. Especially selected alloying elements ensure high levels of strength, toughness, and hardness, making these steels suitable for dies and cutting tools [1]. AISI H11 belongs to this group of high-grade steels, and is appropriate for both hot and cold-work processes. Being low in carbon and high in chromium content, it is categorized as a hot-work chromium steel (H10 to H19). Its elemental composition [2], in wt%, is (C 0.33-0.43, Mn 0.20-0.50, Si 0.80-1.20, Cr 4.75-5.50, Ni $<$ 0.3, Mo 1.10-1.60, V 0.3-0.6, Cu $<$ 0.25, P $<$ 0.03, S $<$ 0.03). Apart from high toughness and strength, it also possesses good ductility. These characteristics make it well-suited for specialty tools such as aircraft landing gears and helicopter rotor blades and shafts [3-5]. Even tghough it possesses the highest shear strength among tool steels, it is surprisingly not used much in hot metalforming [6].

H11 steel is well-suited for applications where thermal and mechanical sresses are high, such as hot forging and extrusion, and die casting. Dies and related tools in such environments are succeptible to changes in geometry and integrity owing to surface wear, micro-chipping or cracking, heat-checking, etc [7, 8]. Desired material performance needs to be improved, especially toughness and hardness. Toughness can guard against fracture relatesd failures [9], and hardness can prevent local plastic deformation that leads to variations in tool geometry [10, 11]. As toughness and hardness are inter-related to some extent, their optimum combination can be achieved through careful heat treatment [12].

II. HEAT TREATMENT

H11 steel samples for tensile and Charpy impact tests were prepared with the assistance of a regional precision die manufacturing plant, through EDM wire cutting and high speed milling. These samples were variously heat treated, as outlined below. After heat treatment, mechanical testing (tensile, impact, hardness) was carried out.

All samples were first *annealed* to get rid of any residual stresses or other material anomalies. The procedure consisted of preheating to 200°C and holding for 15 min; slow heating to 850°C; holding for 2 hr; slow cooling to 480°C; and then brisk cooling to room temperature. *Austenitizing* was the next step, consisting of preheating of furnace to 260°C; slow heating to 815°C and holding for 15 min; further slow heating to 1010°C; holding for 30 min. This was followed by *air cooling*: slow cooling until red heat is gone (by shutting off the furnace and opening the furnace door); taking the samples out and air-cooling to 65˚C. For *oil quenching*, hot samples were taken out of the furnace and submerged in oil bath until cooled to room temperature. For *tempering*, quenched samples are loaded into the furnace which is already set to the desired tempering temperature (450°C, 500°C, 550°C, 600°C, 650°C); held for 2 hours; removed from furnace and cool to room temperature. *Double tempering* consists of cooling single-tempered samples for at least one hour; placing them back in the furnace at the same temperature; holding for 2 hours; removing from furnace and air cooling to room temperature. All heat treatment routines followed standard guidelines for H11 tool steels [13, 14].

III. MECHANICAL TESTING

After these heat treatments, mechanical testing was performed on the samples to determine hardness, toughness, and tensile properties. Thorough surface cleaning of heat treated samples was carried out through stage-wise grinding, before testing for hardness on a digital Rockwell hardness (*HRC*) tester. Toughness (impact energy *CVN*) was determined on a Charpy impact tester. Tensile properties were measured on a 600-kN universal testing machine. Stress-strain curves were plotted to determine values of yield strength (σY), ultimate strength (σU), and ductility (% elongation). All reported values are an average of three different readings. ASTM standard test procedures [15-17] were followed for all mechanical testing.

IV. RESULTS AND DISCUSSION

Changes in mechanical properties of H11 samples due to the three types of heat treatment are discussed below: single and double tempering after air cooling (air-single and air-double), and double tempering after oil quenching (oil-double).

Variation of *hardness* against temper temperature is shown in Fig-1. Hardness initially increases and then steadily decreases with an increase in temperature. Samples tempered at 500°C exhibit the highest hardness value, maximum value being 50 *HRC* for the air-single case. The three curves are quite close to each other, signifying that the choice of heat treatment sequence does not lead to any noticeable difference in hardness behavior. Most of the common steels show a decrease in hardness with increasing temper temperatures. The increasing-decreasing pattern observed in Fig-1 is typical of high-strength hot-work tool steels, particularly for H-class steels such as H11 [18].

Effect of heat treatment on *toughness* (recorded in terms of impact strength *CVN*) is shown in Fig-2. As temper temperature increases, toughness first decreases and then increases; lowest *CVN* value occurring between 500°C and 550°C. The three curves are close to each other at low temperatures, but move apart as the tempering temperature increases. Lowest impact toughness is recorded for air-single samples. This mirror behavior to hardness variation is also characteristic of H-category tool steels [19]. The dip in toughness values of oil-double specimens after 600°C may be due to some experimental error; *CVN* should exhibit an increasing trend at higher tempers.

A typical *stress-strain curve* is shown in Fig-3, used for determination of tensile properties. Changes in *yield strength* (σY) with tempering temperature for the three types of heat rteatment can be seen in Fig-4. σY exhibits a somewhat fluctuating pattern; an initial decrease, followed by an increase, then a gradual decrease with increasing temper temperatures. Highest values of σY are observed for oil-double and air-double samples, in that order. At higher temper temperatures, maximum yield strength value (1400 Mpa) is exhibited by oil-double samples at 550°C. The three curves are generally set apart from each other, indicating a notable effect of heat treatment scheme on σY values.

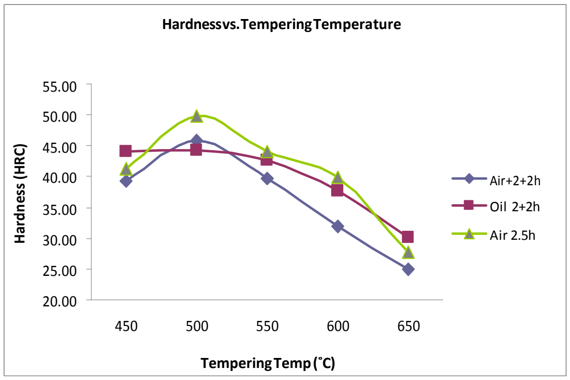

Figure-1 Variation of hardness against tempering temperature for different heat treatments

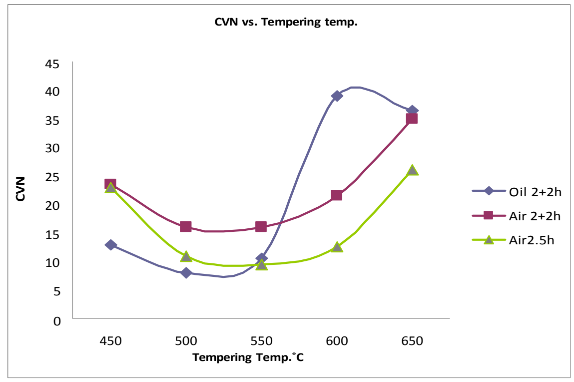

Figure-2 Variation of impact toughness against tempering temperature for different heat treatments

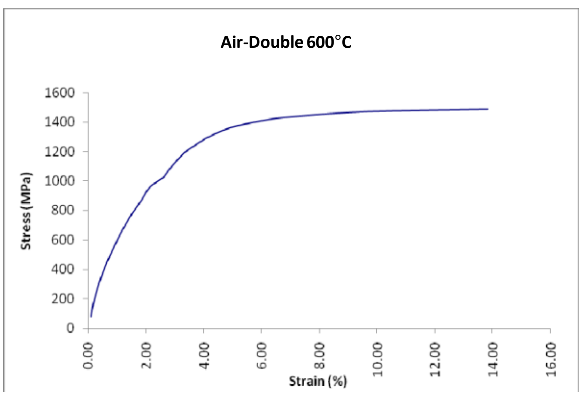

Figure-3 Stress-strain curve for one of the air-cooled double-tempered samples

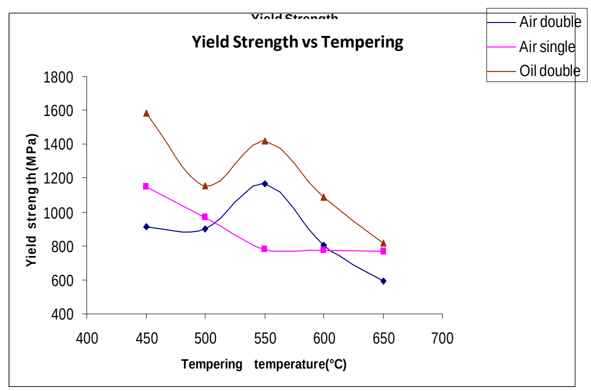

Figure-4 Variation of yield strength against tempering temperature for different heat treatments

Figure-5 shows the variation pattern of *ultimate tensile strength* (σU) against tempering temperature for different heat treatments. σU initially increases, reaches a maximum value, and then steadily decreases with a rise in temper temperature. The three curves are very close to each other, which implies that the effect of heat treatment type on ultuimate strength is not significant. Double tempering at 500°C after oil quenching yields the maximum value of σU (around 2100 Mpa). The variation trend for σU is almost similar to that of *HRC*, establishing that strength of H11 tool steel is directly proportional to its hardness, just as for other steels.

How *ductility* (% elongation) varies with temper temperature is shown shown in Fig-6. Up to the temper temperature of 600°C, ductility displays a steady decrease and then increases quite steeply. Air-single samples tempered at 600°C give the lowest ductility (around 12%). Other tool steels also share this variation trend; decrease followed by abrupt increase.

H11 steel is a good candidate for hot work applications, where tools experience both mechanical and thermal fatigue. They key to good performance and longer service life in such an environment is a good combination of high hardness and high toughness, for continued dimensional accuracy and resistasnce to fracture failure respectively. To make such a decision easier, Fig-7 plots the variation of *CVN* and *HRC* against tempering temperature on the same graph. Just like most steels, *hardness and toughness* for H11 samples show a mirror behavior (except in the > 600ºC range for oil-double samples); in regions where hardness decreaes, toughness increases, and vice versa.

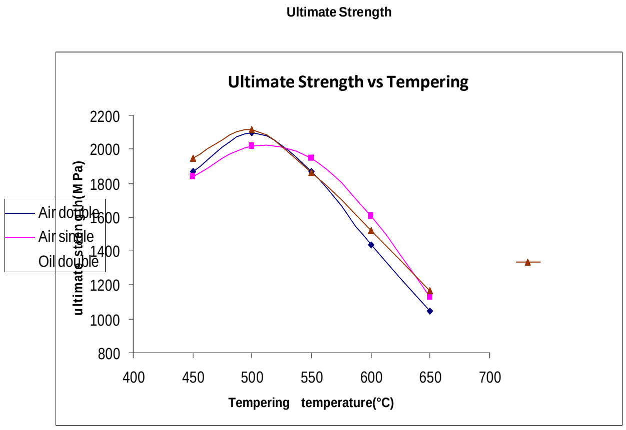

Figure-5 Variation of ultimate strength against tempering temperature for different heat treatments

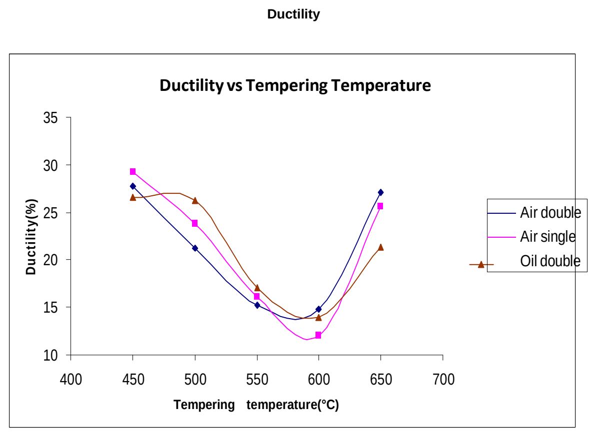

Figure-6 Variation of ductility against tempering temperature for different heat treatments

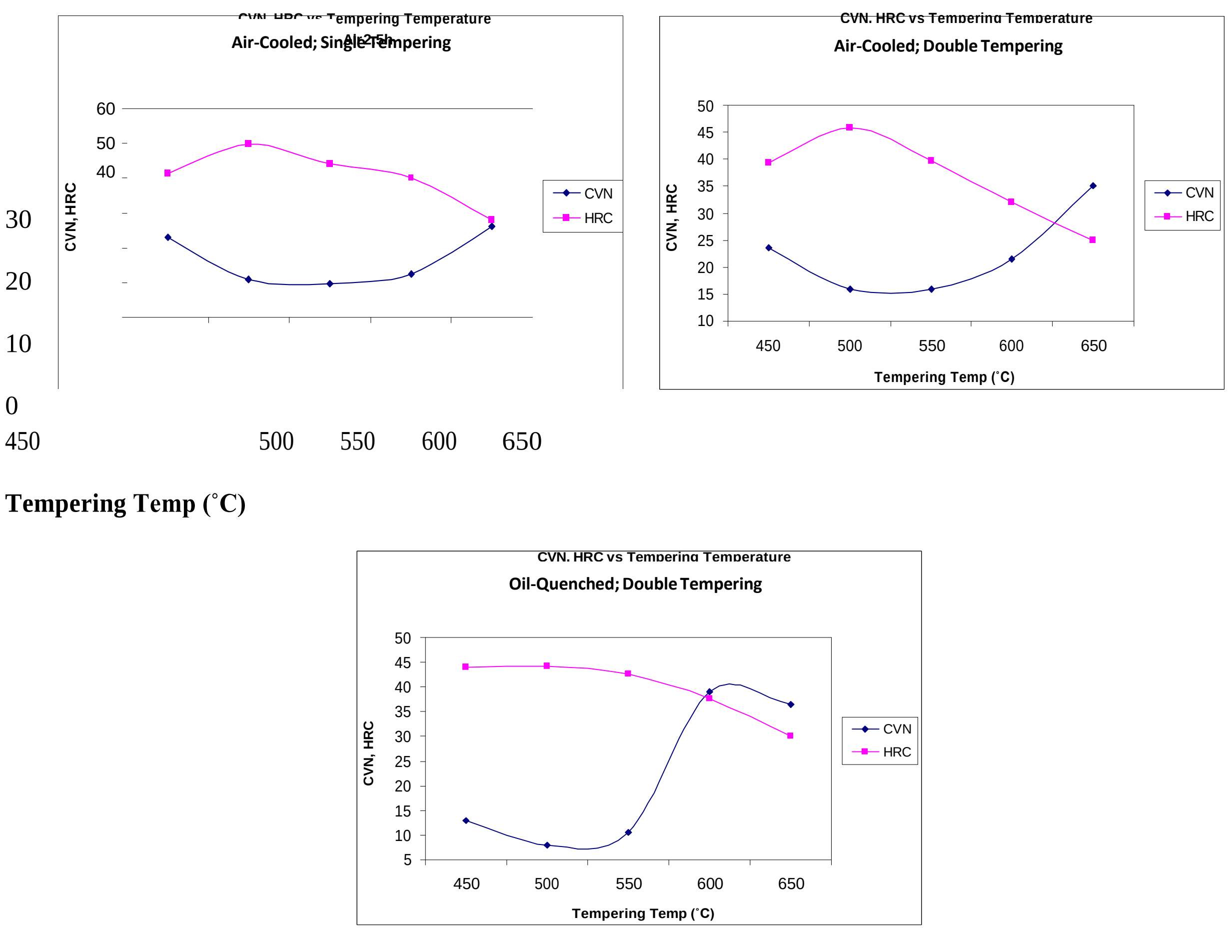

Figure-7 Variation of toughness and hardness against tempering temperature for the three heat treatments

Microstructure of some of the heat treated H11 samples is shown in Fig-8. In the case of air-cooled samples single-tempered at 550ºC, one can observe tempered martensite structure with uniform distribution of carbide particles in a ferrite matrix. When tempered at 650ºC, the samples show tempered martensite with some carbide particles. More ferrite tempered martensite can be seen in air-double samples at 550ºC compared to air-single specimens at the same temperature. Double tempering at 550ºC for oil-quenched samples yields coarser martensite structure. These changes in microstructure are in sync with the variation of hardness, toughness, yield strength, and ductility shown in the figures above.

An obvious choice for high values of hardness and toughness appears to be tempering at 600°C for oil-double samples; Fig-7. However, there is a need for deeper analysis. This temper temperature yields the lowest value of ductility; Fig-6. This translates into low formability and the possibility of crack formation, both undesirable from a manufacturing viewpoint. This tempering would also result in very low values of yield strength and tensile strength, as shown in Figures 4 and 5. This can lead to premature die failures due to factors such as excessive plastic deformation, inaccuracies in die shape and dimensions, and surface wear in the die bearing region [20]. On the other hand, tempering at 550°C can yield much higher values for hardness, yield strength, tensile strength, and ductility. One should not worry too much about the rather low toughness at this tempering. We know that tool steels exhibit an increase with increasing operating temperature [18, 19]. This means that in the case of hot metalforming, for which H11 steel is a suitable candidate, actual *CVN* value would be much higher than the room-temperature value. Hardness however would be lower at higher working temperatures. The cardinal rule for hot-work tool steels is that high-hardness is far more important than high-toughness. We can therefore conclude that the *optimum heat treatment strategy* for H11 tool steel is oil-quenching followed by double-tempering at 550°C.

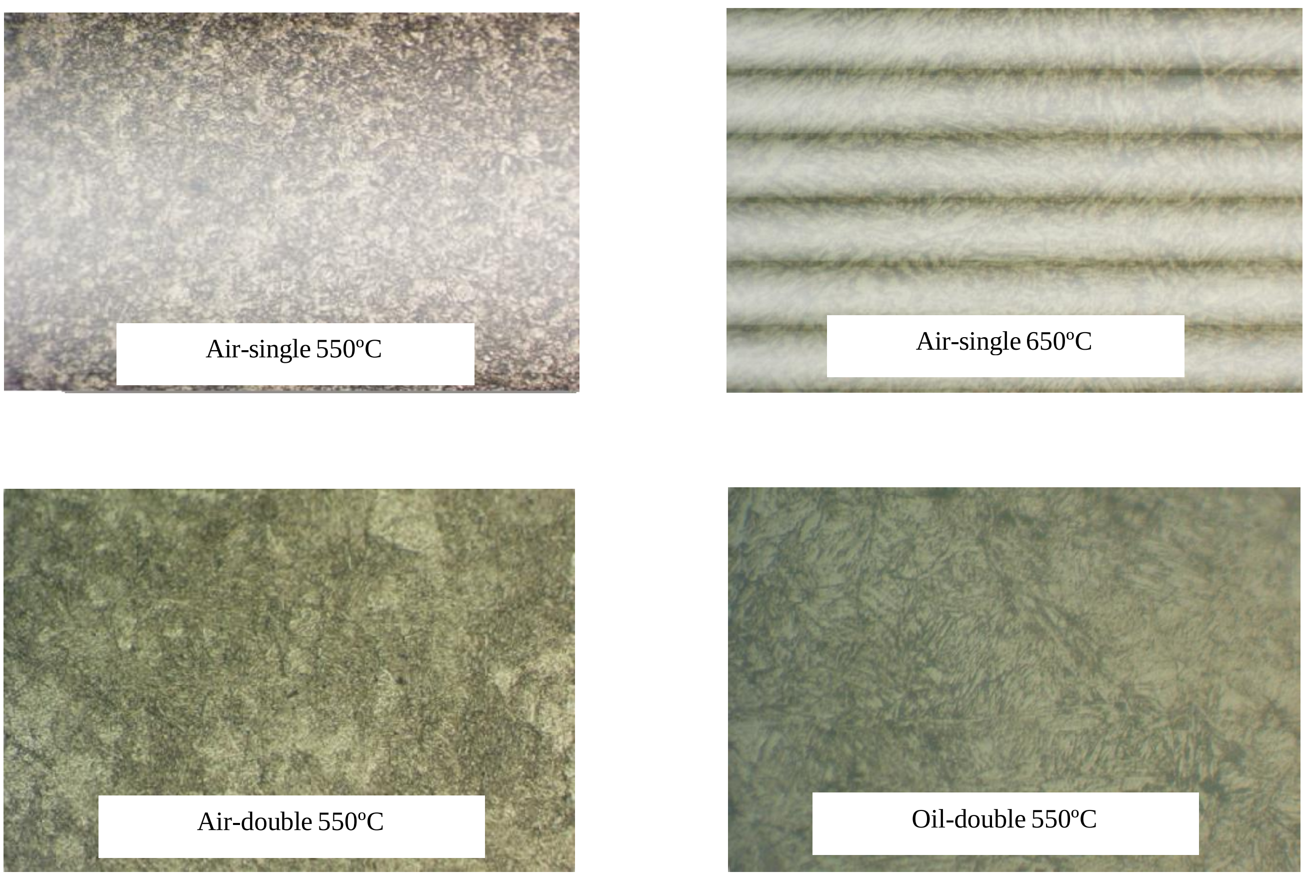

Figure-8 Microstructure of H11 steel samples after different heat treatments

V. CONCLUSIONS

Tensile and V-notch impact specimens of H11 steel were precision fabricated. These samples were variously heat treated: air and oil quenching followed by single and double tempering. Heat treated specimens were subjected to mechanical testing at room-temperature for determination of Rockwell hardness, Charpy impact toughness, yield strength, ultimate strength, and ductility. Variation of microstructure with heat treatment was also studied. Analysis of test results leads to the following major observations. HRC initially increases, followed by a gradual decrease. CVN shows a mirror behavior of initial decrease and later increase. σY shows a fluctuating behavior of decreases-increase-decrease. Like hardness, σU first increases and then decreases. Ductility decreases in a gradual manner, and then starts to increase sharply after 600ºC. Rather than double-tempering at 600°C (giving highest combination of hardness sand toughness), most optimum heat treatment schemes is found out to be double-tempering at 550°C for oil-quenched samples. This would result in the most suitable combination of hardness, toughness, yield strength, tensile strength, and ductility for hot metalworking.

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