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# Investigation of Enhancing Temper Resistance and Hot Hardness for Tool Steel

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***Abstract-*** Hot strength, temper resistance and low thermal expansion are a few amongst many desirable properties to ensure longer life for dies and punches in AISI type H tool steels, during hot forging. A compromise over hardness invariably reduces die and punch life during thermal fatigue and same applies for hardness on lower side. In this research work, optimum level of hardness and heat treatment parameters (hot strength, temper resistance, and thermal expansion for hot work die steel) is investigated by varying heat treatment variables for enhanced service life of dies and punches. Moreover, three different heat treatment techniques were adopted to attain an optimum level of microstructure and surface hardness in hot forging punches for hot-work tool steels. Considerable improvements were observed in surface micro-hardness. The choice of selected optimum parameters shows clear signs of improved service life for H13 tool steel during forging.

***Keywords-***Tools Steels; Heat Treatment; Hot Hardness; Thermal Fatigue; Forging.

## I. INTRODUCTION

Amongst forming techniques, hot forming is one of the oldest and important metal forming technologies which accounts for a large percentage of fabricated metal products. However, the metal industry today is very competitive and a metal former must carefully evaluate the costs of the operations necessary for converting each material into finished products. Therefore, the industry continuously strives to lower the production costs of each operation. The dies and punches play the most essential part in all types of hot forming operations, because it usually gives the object its final complex shape. Since, the die usually is expensive to manufacture, it therefore has a major influence on the production costs. Some metal workers even claims that a high-quality die with a long lifetime is the key for a successful and cost-effective production. Dies costs accounts for major portion of component final cost in a closed forging process as per Sirgaokar (2008) and Bayramoglu. The process of heat treatment followed by tempering process can provide answers to costly tooling and provide a viable option for production enhancement with available tool steels. The forging process on one end provide near net shape products at a faster production rate but also pose serious challenges due to extreme working temperatures at which tooling is exposed. The tooling thus used has to have optimum mechanical and microstructure properties to face extreme working and service environments.

## II. LITERATURE REVIEW

Forming techniques including hot forging and die casting are two popular ways of forming net and near net shaped components, since they are economical and high-speed methods. High quality of tool steels for dies and punches during hot forging process are therefore a pre-requisite for cost effective production [1].

The effect of annealing temperatures and post machining treatment on service properties and microstructure of steels has been investigated and reported by multiple researchers over the years but same investigation into an important category of tool steels .i.e hot working tool steels has not been carried out for hot forging applications. The literature is however available on various stainless steel grades with different level of investigation.

The effect of varying the levels of annealing on micro and macro properties of Boron steel used in hot stamping has been reported. The investigation reported that high temperature annealing decreases yield strength for these steels. The author goes on to report that tensile strength and hardness varies with the change of the same trend when annealing temperature changes. They reported that Boron steel grades tend to have dual regions of Ferrite and Pearlite below 760 °C of annealing temperatures. The steel tends to have more martensite if annealed at higher temperatures and thus has higher strength & hardness [2].

Hot work die steel, AISI H13 is an air/Oil hardening medium alloy steel with excellent strength during thermal shock as well as hardness retention at temperatures as high as 1000 0F or more. The chemical composition from various suppliers may have varying amounts of alloy contents which ultimately affect post heat treatment results and subsequent properties during service. The chemical composition is a clear indication of specific properties which make AISI H13 the material of choice during hot working. The hardening process by austenitizing followed by quenching process is however of prime importance for such tool steels and should therefore be carefully planned for optimum results. Generally, the factors which can affect specific properties of tool steels are as under;

a. Composition of tool steel
b. Shape & Size of part
c. Heat treatment sequence (Rate of heating, Heat treatment temperature, Soaking time and Quenching rate)
d. Grain size and Homogenous nature of austenite
e. Nature of quench media
f. Finish of parts post machining

Various investigations can be found in literatures which have reported material properties for such steels against heat treatment parameters but a limited work has so far been conducted specifically for AISI H13 tool steel in hot forging. In current work, heat treatment parameters and all possible factors which can possibly affect post-heat treatment results have been investigated. Figure 1, shows general heat treatment sequence for tool steels. The process involves pre-heating at uniform heating rate in two stages to subsequent holding or soaking of samples at austenitzing temperature. The process is followed by quenching and later on by series of tempers depending upon type of tool steel being treated.

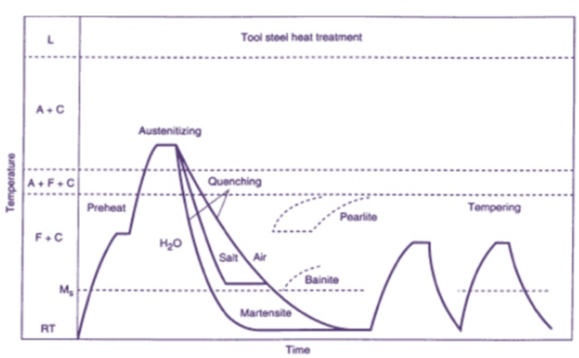



Fig 1: Heat treatment sequence for Tool Steels

H13 tool steel like all die steels is subjected to prior heating before hardening process. This treatment termed as pre-heat is necessary to ensure that all sections of material are evenly heated and also to stabilize the material before exposing it to higher austenitic temperature [3].

In another research on similar steel, effect of annealing temperatures on properties and microstructure was investigated. Reportedly, by increasing the inter-critical annealing temperature the austenite volume fraction decreases (it has relationship with the amount of martensite after quenching) which results in increase of ultimate strength and ductility reduction is marginal. In low inter-critical annealing temperature (770 ˚C) small amount of austenite are formed and cementite spherodising in pearlite, results in a small distribution of austenite which can successfully create fine grain martensite distribution [4].

The high hardening capability of tool steels is the main reason behind suppressed formation of perlite at various cooling rates. Likewise, except for heavy sections with slow cooling rates, the formation of Bainite is also suppressed. The complex nature of formation of Carbides on austenitic regions close to boundaries cannot be controlled during slow cooling. These carbides tend to weaken tool steels through reduced fracture toughness and hence, lower performance of steels particularly H13 [5,6].

Heat treatment of hot working tool steels requires sophisticated control of various aspects of pre-heating, heating, soaking and quenching. The same is followed by multiple tempering sessions to achieve desired hot toughness properties [7]. The reported results for same die steels have projected 2 to 3 tempers post heat treatment and an immensely improved die life has been reported but finest result were attained by weld overlay of the die contact surfaces with cobalt base welding electrodes. [8]. The pre-heating temperatures of up to 850 $^{0}$C and austenitizing temperatures of 950 $^{0}$C to 1000 $^{0}$C have been reported to be suitable for various grades of hot working tool steels [9, 10].

Heating of tool steels to achieve austenitic region is one of the most critical steps in heat treatment. Alloyed elements tend to distribute themselves between matrix of austenite and carbides. The wear resistance and grain size is controlled by these retained carbides. Smaller grain sizes and large fractions in volume for these carbides tend to control grain growth of austenite more effectively. The higher heating temperatures or cycles tend to dissolve retained carbides and thus cause cementite precipitation on cooling. It results in coarsening of grain boundaries at austenitic regions. It is therefore advised to avoid high heating temperatures during post machining treatments to safeguard retained austenite from dissolving and also to prevent grain growth. Similarly, really slow quenching can result in formation of carbides at grain boundaries which is also a major reason for irregular failures of tool steels [11].

The past research in hot working tool steels has been focused primarily on general mechanical properties modification for these steels but no work has reported for a specific industrial application. The few researchers such as Arif et el. have focused on hot extrusion application but no specific industrial investigation into H13 application for hot forging has been reported. Considering its unique application in defense industry for forging, the same steel grade needs specific attention. The complexity of its heat treatment to obtain optimum level of hardness, hot strength and thermal fatigue resistance; an investigation at a national level industry has been considered necessary [12].

Hot working tool steel grades contain alloying elements such as Chromium, Tungsten, Vanadium, or Molybdenum in relatively large quantities. High alloy contents enable these steels withstand extreme hot working service temperatures and retention of hardness at elevated temperatures [13]. Treatment of such hot working tool steels thus, plays a pivotal role in defining service life of dies and punches as well as quality of forging thus produced. Steels which need to maintain certain mechanical properties at high temperatures require resistance to temper for strength and durability. The capability of few elements to boost carbide formation after appropriate heat treatment therefore requires optimum choice of treatment parameters. Selection of particular hot work tool steel for forging therefore depends on mechanical and thermal fatigue, plastic deformation and wears resistance [14]. The most commonly used hot-work tool material is AISI category H13, which quite suitably serves the purpose during hot working [15].

Tool steels should not be oxidized by excessively heating them in an open environment or in a furnace. The category of H13 tool steel also tends to de-carburize as a result of oxidizing phenomenon [16].

Currently, these articles describe standard heat practice of operation followed then in industry for hot work tool steel, and their influence on hardness and effect of heat treatment parameters. AISI H13 Tool steel is widely used due to its popularity in terms of high hot hardness, mechanical strength, significant resistance to shock, thermal fatigue and high toughness. During forging process, dies are subjected to frequent temperature cycles. To maintain detailed profile geometry, and to ensure repeated use of the die, which are sensibly heat treated and surface hardened to get an optimum mixture of high hardness and toughness.

The steels are then subjected to austenizing temperature where ferrite transforms into austenite if held for specific time at same temperature. The alloying elements in tool steel start to re-arrange themselves in a much softer iron phase. The time for which steels are held at critical temperature is known as soaking time.

Tool steels in general and few grades such as the one used in current work have such a wide critical temperature range that they can be regarded as "programmable". They can be adjusted for variety of properties combinations such as higher toughness, higher hardness and more wear resistance. The customizable properties of tool steels therefore require intensive investigation to reach the right combination of properties for specific application. The attainment of an optimum austenitic temperature for a particular composition of tool steel along with appropriate soaking time is the key goal in current work.

## III. Materials and Methods

The investigated material used in commercial grade AISI H13 steel, typically used in forging industries. Optical emission spectroscopy was used to confirm material chemical composition and to ensure that the specimens to be machined are of AISI H13. The steel chemical composition in mass percentage as obtained from optical spectroscopy is shown in Table I.

TABLE I
CHEMICAL COMPOSITION OF USED AISI H13 TOOL STEEL

| % C | % Si | % Mn | % Cr | % Ni | % Mo | % V |
|---|---|---|---|---|---|---|
| 0.39 | 1.0 | 0.4 | 5.2 | 0.3 | 1.4 | 0.9 |

### *3.1 Annealing Process*

The material was obtained in annealed condition. The annealing process as described by supplier constitutes soaking the material at about 850 $^0$C in an induction heating furnace and allowing sufficient time for thorough heating followed by furnace cooling at a rate of 20 $^0$C per hour till 600 $^0$C and subsequent air cooling to complete annealing process. The post annealing hardness was recorded as 202 VPN.

### *3.2 Stress Relieving*

It is generally advisable for tool steels to be stress relieved as, all tool steels and particularly AISI H13 is quite sensitive to distortion during hardening if post-machining stress relieving is over-looked. The specimen were heated to about 700 $^0$C in an induction furnace and allowed 2 hours per inch of time at this temperature before allowing it to air cool.

### *3.3 Sample Preparation*

The punch specimens were prepared by machining. The material in round was machined by turning to its close to final size of 65 mm thickness before heat treatment. Final sizes of punches however require post-heat treatment grinding operation. The scope of current work includes machined samples with grinding allowance of 0.5 mm each. Five different types of samples were prepared with specific identification engraved on each. The samples were heat treated by varying critical temperatures, soaking time, quenching media and tempering temperatures.

Fig 2: Forging Punch after Heat Treatment

The detail of samples is as follows;

TABLE II
LIST OF PREPARED SAMPLES ALONG WITH DESIGNATIONS & TREATMENTS

| Sample Sr. No. | Sample Identification | Sample Treatment |
|---|---|---|
| Samples category 1 | Designated as, C-81 | Soaked at 1030 $^0$C for 90 minutes, Air Quenched and Cyanided & Double tempered at 500, 550 $^0$C . |
| Samples category 2 | Designated as, O-81 | Soaked at 1010 $^0$C - 1050 $^0$C for 90 minutes & Oil Quenched &Double tempered 500, 550 $^0$C . |
| Samples category 3 | Designated as, A-81 | Soaked at 1010 $^0$C - 1050 $^0$C for 90 minutes, air Quenched & Double tempered at 580, 620 $^0$C. |
| Samples category 4 | Designated as, J-81 | Soaked at 1010 $^0$C - 1050 $^0$C for 60-90 minutes, air quenched & Double tempered at temperatures 600, 650 $^0$C . |
| Samples category 5 | Designated as, R-81 | Soaked at 1010 $^0$C - 1050 $^0$C for 60-90 minutes, oil quenched & Double tempered at higher temperatures 600, 650 $^0$C . |

*3.4 Hardening Process*

The specimens were subjected to different heat treatments. The parameters of heat treatment such as; austenitizing temperature, soaking time, quenching media and tempering temperatures were varied to reach an optimum combination of heat treatment conditions which best suit hot forging.

Following different parameters of heat treatments were varied to attain various microstructures of martensite as indicated in table II;

- Variation of Austenitic Temperature
- Variation of Soaking Time
- Variation of Quenching Media
- Effects of Case Hardening
- Effects of Tempering Parameters

*3.4.1 Pre-Heating*

The hardening process started with two-stage pre-heating. The first pre-heat was heating the samples at a uniform rate up to 650 $^0$C for 2 hours and in second stage up to 850 $^0$C for 1 hour in an induction heating furnace.

*3.4.2 Austenitizing*

The samples were shifted to Neutral $BaCl_2$ molten isothermal salt bath having hardening temperature for austenitizing. The hardening process was carried in an Upton salt bath furnace where, the samples were rapidly heated to critical temperatures ranging from 1010 $^0$C to 1050 $^0$C for various samples. The critical temperature or austenitic temperature for sample materials was varied for observing changes in microstructure and hence, hardness which would ultimately affect service life of forging punches. Similarly, soaking time was varied from 60 minutes to 90 minutes for different samples.

*3.4.3 Quenching*

Austenitizing is followed by a quenching process. It is a process in which rapid cooling allows tool steels to cool below critical temperature in an appropriate cooling media. The rapid cooling causes alloying elements to be trapped in tough iron base. Too slow a cooling rate would cause lower hardness and too rapid cooling would result in cracks due to stresses. Commonly, various cooling media are used for quenching tool steels such as; water, oil, air, salt baths and vacuum. The selection of quenching media however, depends on many factors such a type of tool steel, dimensions of component to be quenched and most importantly, the properties which are required. Each cooling media has its own cooling rate and a right choice of cooling media is as important in tool steel post-heat treatment properties as any other factor already discussed.

Quenching was carried out using Oil, Air and Salt bath with varying cooling rates for different samples. Salt bath at 550 $^0$C was used during salt quenching followed by air cooling to room temperature.

*3.4.4 Tempering*

Quenching of tool steels is followed by tempering process. It is a process whereby hardened and brittle tool steel is re-heated to relieve stresses, control hardness and convert any retained austenite into martensite. Tempering is usually done at a temperature far below critical temperature of steel and tempering time is a function of section thickness of part. Longer tempering times are required by larger components. However, tool long an exposure would surely stress relieve components but at the cost of hardness reduction. The samples were shifted to tempering as soon as they became hand warm. The samples were tempered at varying temperatures ranging from 400 $^0$C to 650 $^0$C. Two tempering cycles were adopted for samples and in between cycles, it was ensured that the sample got completely cooled before it was place in for another cycle.

*3.5 Surface Treatment*

Cyaniding was carried out for one of the samples to induce a layer of Carbon and Nitrogen into surface of sample for enhanced hardness over the surface. The sample was immersed in a cyanide salt bath at 850 $^0$C. The process results in better surface hardness due to formation of additional carbides and nitrides. The bottleneck in such treatments however is limitation of surface depth up to which enhanced surface hardness can be achieved and hence a limitation in terms of process efficacy on punch performance is clearly assessed.

*3.6 Hardness Testing*

The hardness values were measured after hardening and also after tempering by Vickers hardness measuring machine. The measurements were re-validated by taking average of at least five values for each punch. Similarly, hardness values were recorded post-forging operation for each punch sample to witness any possible change in hardness and also to observe various levels of thermal fatigue resistance by same material under different heat treatment conditions. Figure 3 below shows a specimen for hardness testing for all samples.

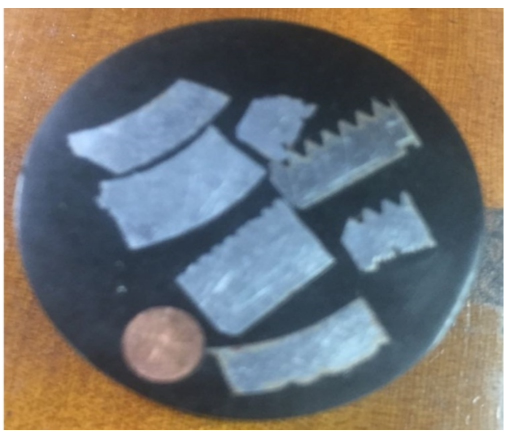


*Fig 3: Hardness Testing Samples*

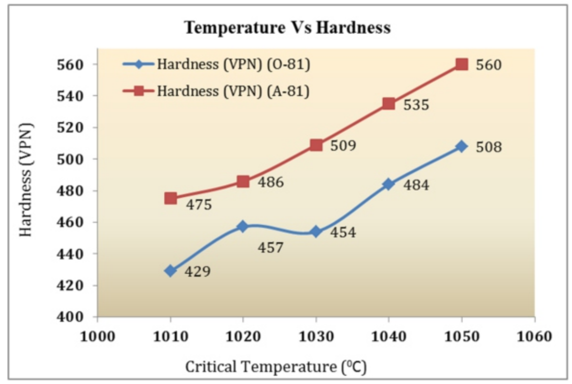
*3.7 Microstructural Characterization*

Scanning Electron Microscopy (SEM) was used at 10 µm magnification to identify various microstructures obtained after varying heat treatment parameters on

samples. The microstructure post-forging operation was also investigated for possible clues which could help us improve service life of punches.

## IV. Results and Discussion

The samples having difference in quenching media but for same austenitizing temperatures show varying hardness values. Hardness values for both oil and air quenched samples designated as O-81 and A-81 respectively indicate successive increase in surface hardness values for an increase in critical temperature from 1010 to 1050 $^0$C. The effect of austenitizing temperature on hardness for air hardening sample is more evident as compared to oil hard sample. Graph 1 indicates a clear difference in surface hardness for two different quench Medias.




*Graph 1: Austenitizing Temperature Vs Hardness for Oil (O-81) and Air hard (A-81) sample*

The increase in hardness with increasing hardening temperatures is associated with the fact that it induces higher amounts of carbides to be taken into the solution. On the other hand, an increase in austenitic temperature would allow more alloy content to be dissolved into iron matrix and thus; causing a decrease in toughness due to comparatively lower iron base.

The performance of air hardened punches at lower austenitizing temperatures indicated superiority over oil quenched punches. However, air hardened punches at higher austenitizing temperatures with highest of hardness should apparently have the best possible performance but the forgings produced as a service life indication revealed an altogether different result. The performance of air hardened samples at higher critical temperature despite better hardness was really poor and barely 40 forgings could be achieved before hardness loss at the surface. The O-81 category of oil hardened punches at similar austenitizing temperatures however showed much better performance with 60 forgings.

The possible explanation for performance difference between two differently quenched samples is that the punches had comparatively large section thickness for air quenching to attain thorough conversion of austenite to martensite. The air quenched samples therefore could only achieve a surface hardness higher than oil quenched samples but overall martensitic grain structure could not be attained. The surface hardness of air quenched samples quickly decreased during extreme forging temperatures as well as heating and cooling cycles. The distribution, grain size and homogeneity of carbides formed after heat treatment are vital to optimum performance of AISI H13 tool steels during forging. The evenly distributed carbides and minimum retained austenite predominantly evident due to oil quenching could be seen in fig 4.

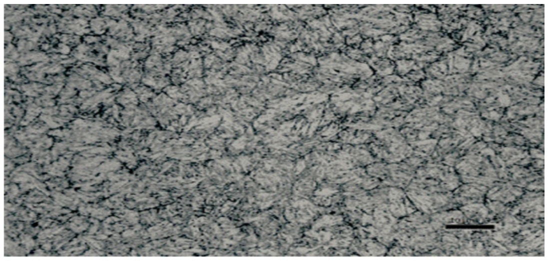


*Fig 4: Micrograph at 10 µm magnification for H13 in Oil Quenched and tempered state*

The microstructure after forging for the same sample shows clear signs of carbide dissolution and increased ferrite. Traces of carbide regions could also be seen in fig 5. The black morphological regions belong to Chromium carbide precipitates as the dissolution range for Chromium carbides is quite higher than working temperature range in forging.

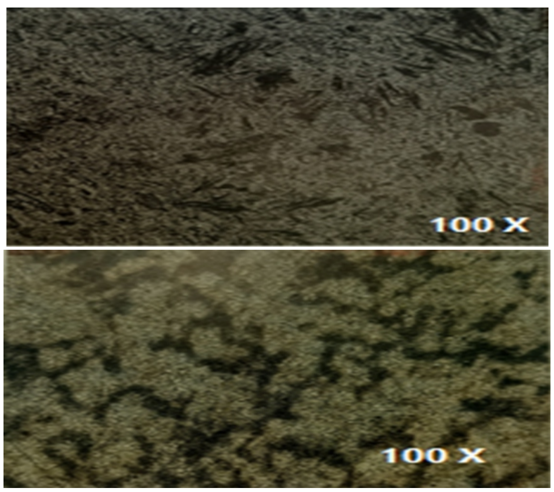



*Fig 5: Micrographs at 100X for Punch sample after forging*

The retained Chromium carbides thus enable punch to sustain extreme working temperatures. It can therefore be deduced that Chromium Carbides are mainly responsible for hot work strength and hardness retention in AISI H13 tool steels during forging operation.

Although, both types of punches were soaked for same time and at same critical temperatures of 1050 $^0$C; the in-service performance lag in air hardened samples is also due to the fact that exposure to higher temperatures during austenitizing and comparatively slow cooling rates in air cause de-carburization of such tool steels. The de-carburization causes lower hardness, embrittlement and grain coarsening.

The punches are water cooled immediately after each stroke, causing repeated heating and cooling cycle for punch material and therefore triggering thermal fatigue in thicker & partially martensitic sections of punches. It is worth mentioning here that the temperature during hot forging was recorded to be 620 $^0$C. Whereas, the punches were tempered at temperatures of 500 and 550 $^0$C for first and second tempers respectively. As a result of tempering process, the hardness decreases whereas; service life hardness retention depends heavily on tempering temperatures. If the temperature during forging exceeds considerably than temperatures during tempering, it would cause softening of punches and thus, deformation.

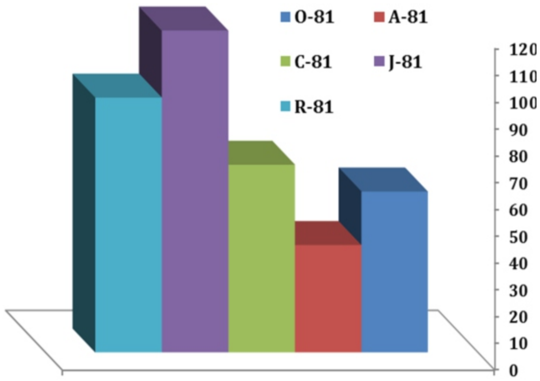
Soaking time on the other hand, also plays a vital role in defining an appropriate transformation of austenite into martensite. Too long an exposure at austenitic temperature would cause tool steel to de-carburize and too short an exposure would cause partial transformation. Soaking time of 90 minutes for 65 mm thickness of punch samples was found to have no considerable effect in either 0-81 or A-81 category of samples.

The sample treated at 1030 $^0$C, air cooled and subsequently cyanided showed clear signs of hardness improvement. The improved hardness is clearly associated with addition of Nitrogen into the surface of sample and subsequently formation of Nitrides. Similarly, addition of Carbon during same process enhances probabilities of formation of Carbides within surface treated sample. The temperature of 1030 $^0$C during heat treatment is not as high as to cause previously reported de-carburization in H13 tool steel. The sample therefore indicated an enhanced surface hardness as compared to other samples. The hardness of C-81 punch was recorded to be 595 VPN and double temper at 500 and 550 $^0$C limited it to 563 VPN. The punch also indicated somewhat improved service life and number of forgings enhanced to 70. The improved punch life can be explained by the fact that alloying elements in such hot work tool steels tend to have nitride formations which are hard and tend to contribute to thermal fatigue during service. It is clearly observed that avoiding excessively high hardening temperature coupled with surface treatment results in high surface hardening which can assist in thermal fatigue resistance of sample at elevated service temperatures.

Table 3 presents an overall summary of punch hardness profiles against service life for each category of heat treated punch samples.

TABLE:3
HARDNESS VS PERFORMANCE FOR ALL SAMPLES

| Punch Designation | Hardness (VPN) | Performance (Number of forgings) |
|---|---|---|
| O-81 | 508 | 60 |
| A-81 | 560 | 40 |
| C-81 | 563 | 70 |
| J-81 | 545 | 120 |
| R-81 | 505 | 95 |




Graph 2: Performance Comparison between samples

Graph 2, indicates the same performance comparison between various samples. The results are an indicator of an optimum heat treatment which imparts a balance of hardness, suitable microstructure and toughness for punches to have a longer thermal fatigue life as well as high temper resistance. The later primarily due to the fact that double temper at temperatures close to service temperatures enables hardness retention for considerably longer durations and hence, a longer service life for forging punches. The considerably lower hardness due to higher tempering temperatures enhances toughness which for tool steels generally rises during hot working [7, 8] and therefore, a compromise over toughness can be made by reducing tempering temperature to have higher surface hardness values without compromising over toughness.

## V. Conclusion

The attainment of critical transformation temperature (austenitic temperature) as well as holding time plays a key role in defining final hardness and mechanical properties of tool steel. Multiple tempers for such steels however ensure that the retained austenite that gets converted to martensite after first temper gets tempered before being in service. A compromise over either hardness or toughness should be made in order to optimize the right heat treatment strategy which in current work was found out to be air cooling and a closely defined tempering cycles which best suit service life conditions. The enhanced service life and an increased forgings production at elevated temperatures provide a clear evidence of suitability of heat treatment strategy adopted for J-81 sample. The surface hardening process also provides a promising option in terms of enhanced surface resistance to wear and deformation but lack of sufficient depth is one of probable cause due to which production life of C-81 sample was recorded lower than J-81 sample. The extreme temperatures during service as well as abrasion cause surface treated sample to deform after 70 forging cycles.

## VI. Recommendation

The heat treatment parameters most suited to working conditions such as used in current work where service temperatures can cause cyclic heating and cooling of AISI H13 tool steel is to adopt an austenitizing temperature of 1040 $^{0}$C followed by an air cooling with double temper at 600 and 650 $^{0}$C. The optimized conditions therefore contribute to grain refinement and resultantly, improved service life of forging punches.

## VII. Nomenclature

| Name | Symbol | Units |
|---|---|---|
| Weight | W | N, Kgs |
| Length | L | Meter (m) |
| Temperature | °C | °C |
| Magnification | µ m | µ m |

## VIII. Acknowledgment

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Annex-A

## IRON CARBON PHASE DIAGRAM AND DEFORMED SAMPLE

Iron Carbon phase diagram serves as a reference for all heat treatments related to ferrous alloys. All steels thus can be heat treated depending upon the Carbon content.

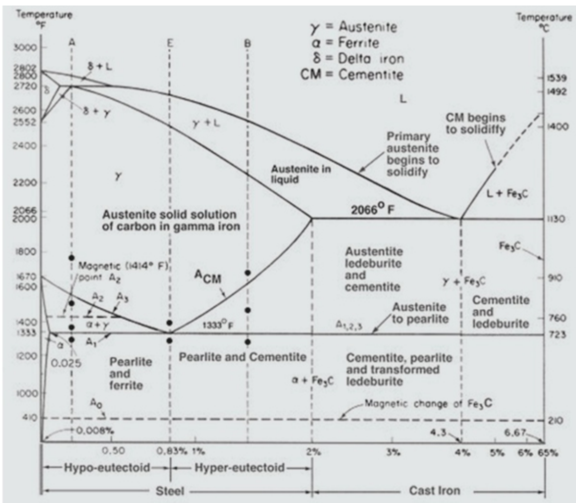


Fig 6: Iron Carbon Phase Diagram

## USED SAMPLE (DEFORMED)

The oil hardened sample O-81 after being used in hot forging and deformed was used to check microstructure of punches. The micrographs were used to determine what kind of possible changes in morphology take place during service.

Fig 7: Deformed sample of AISI H13 tool steel