



Heat treatment of a hot-work die steel

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ABSTRACT

Purpose: This paper reports results of in-house experimentation and an exhaustive literature search on heat treatment of H13 tool steel. Heat treatment strategy practiced by the industry is described in detail. Effect of various types of heat treatment on fracture toughness and hardness is also analyzed.

Design/methodology/approach: Because of its versatility and wide applications, aluminum has been dubbed as the metal of the millennium. Commercial extrusion of aluminum alloys is a cyclic hot-working process. The magnitude of the thermal and mechanical stresses generated in the die and relevant tooling is therefore a major factor in extrusion. The die and mandrel (used for hollow profiles) are the most important tools subject to wear and are, at the same time, the most highly stressed tools in extrusion. For reliability and durability of an extrusion die, the load carrying capacity of the tool steel, its high-temperature fatigue properties, and its wear resistance become critically important. To withstand large stresses, the steel should have high strength and toughness, and to resist wear it should have high hardness and surface integrity. This combination of high toughness and high hardness is usually achieved through specific heat treatment and surface hardening sequences.

Findings: Toughness (expressed in terms of plane-strain fracture toughness K_{IC} or Charpy impact energy CVN) and hardness (HRC) of H13 steel vary in a nonlinear manner against tempering temperature. Toughness shows a decreasing-increasing trend, while hardness exhibits an opposite increasing-decreasing pattern with increasing tempering temperature.

Research limitations/implications: Optimum heat treatment strategy for commercial aluminum extrusion dies (H13 steel) appears to be tempering in the 525-550°C temperature range, to get the best combination of high toughness and high hardness

Originality/value: Experimental data from closely monitored heat treatment and mechanical testing has been added to the available published data. Careful and judicious extrapolation-intrapolation has also been carried out to complete the data matrices. Analysis of the resulting variation patterns provides a good scientific foundation for devising an optimal heat treatment strategy.

Keywords: Heat treatment; Hot extrusion die; H13 tool steel; Fracture toughness; Impact energy, Hardness

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Hot extrusion is one of the most commonly used bulk forming processes, used to generate a wide variety of aluminum alloy profiles (ranging from simple to very complicated solid and

hollow shapes) in the construction, automobile, aerospace, and other industries. Commercial aluminum extrusion almost universally uses H13 steel dies. Recent studies show that the most frequent mechanisms of die failure are fracture, wear, and deflection [1]. During commercial aluminum extrusion (billet by billet extrusion), dies are subjected to continued temperature

cycles. Coupled with high extrusion pressures, this can result in ultimate failure due to fatigue fracture or excessive plastic deformation. On the other hand, friction at the die-billet interface (known as the bearing) generates a high amount of wear. To maintain precise profile geometry, and to ensure repeated use of the die (long service life), dies are carefully heat treated and surface hardened to obtain an optimum combination of high-hardness and high-toughness. A thorough knowledge of these material properties, and their variation under different heat treatments and operating temperatures, is therefore critical.

Resistance of a material to fatigue failure is known as toughness, and is measured in terms of the material property known as plane-strain fracture toughness (K_{IC}). Since K_{IC} testing is complicated and costly, Charpy impact energy (CVN) is generally used as an alternate measure of fracture toughness. Wear resistance of a material is commonly represented by its hardness (Rockwell hardness HRC), especially hot hardness. To gauge the performance of a die against the three dominant failure modes of fracture, deflection and wear, knowledge of K_{IC} (or CVN) and HRC of the die material is essential.

The current paper describes standard heat treatment practices followed in the industry for hot-work tool steels, and their effect on toughness and hardness. AISI H13 (DIN 1.2344) steel is widely used to make both hot and cold forming dies. Its popularity depends on its high hot hardness (resistance to thermal fatigue cracking) and high toughness. An exhaustive survey has been conducted to pool together information about mechanical properties of H13 steels, both from published literature and from tool steel manufacturers. A number of in-house experiments have also been conducted to supplement and corroborate the published data. Tool steel samples have been subjected to different heat treatment routines, and tested for relevant mechanical properties. Various graphs have been plotted to show the variation of mechanical properties, and the variation patterns have been analyzed.

2. Data collection and experimentation

Experimental data for H13 steels have been collected through a comprehensive search of published literature and from tool steel suppliers/manufacturers [2-10]. The data set covers values of K_{IC} , CVN , HRC , and σ_y of H13 samples that have been single-tempered and double-tempered at different tempering temperatures. Careful curve fitting and interpolation-extrapolation were employed to generate additional data points, thus yielding a comprehensive data matrix of H-13 properties.

More data has been generated in-house. Hardness testing and impact testing has been carried out on samples subjected to different tempering schedules. Standard Charpy impact specimens were made from H13 steel in collaboration with ALUPCO's die manufacturing plant, using EDM wire cutting and high speed machining. First stage of the experimental work consisted of single and double tempering of H13 samples, following the standard procedure [4-10] outlined below.

Annealing

To remove any preexisting anomalies of material properties, all samples were first subjected to a careful annealing cycle:

Preheating to 200°C; hold for 15 min. Slow (stepwise) heating to 850°C; room temperature → 200 → 400 → 600 → 850°C; hold for 15 min at each step. Hold for 2 hr at 850°C. Slow cooling; shutoff furnace and leave samples inside until cooled to 480°C. Brisk cooling; open furnace door, cool to room temperature.

Single Tempering

One set of samples followed the austenitizing → tempering → air cooling routine outlined below: Stepwise slow heating to austenitizing temperature (1050°C): room temp → 200 → 400 → 600 → 800 → 1050°C. Hold at 1050°C for half an hour (called soaking). Remove from furnace; air cool to 50-60°C. As soon as temperature reaches 50-60°C, place in furnace already steadied at required tempering temperature; hold for 2 hr. Remove from furnace; air cool to room temperature. Different sets of samples tempered at 425°C, 500°C, 550°C, and 600°C to match published data on single tempered samples.

Double Tempering

Another set of samples underwent the following austenitizing → tempering → oil quenching routine: Slowly heat to 1010°C; room temp → 200 → 400 → 600 → 800 → 1010°C. Soak (hold) for half hour at 1010°C. Remove from furnace; oil quench to about 50-60°C. Immediately place in furnace already steadied at required tempering temperature; hold for 2 hr. Remove from furnace; air cool to room temperature, at least one hr. Place in furnace steadied at the same tempering temperature as before; hold for 2 hr. Remove from furnace; air cool to room temperature. Different sets of samples tempered at 500°C, 550°C, 575°C, and 600°C to match published data on double tempered samples.

Hardness Testing

Oxide layers etc formed during heat treatment were removed by stage-wise grinding. Average HRC were determined by taking a number of hardness readings at different positions on the samples.

CVN Testing

Samples were carefully positioned in the holder of the Charpy impact tester, and the hammer was dropped. Impact energy reading from the dial was recorded for each case.

3. Results and discussion

As mentioned earlier, experimental data reported and analyzed in this paper are from in-house experiments and from published sources or tool steel manufacturers and suppliers. The nine different data sources are listed in Table-1. Being from various sources, the data sets do not cover the same temperature

Table 1.

Description of heat treatment routines of the test sample sets described in the study

Data Set	Description	Source
KIC, HRC, CVN	Air cooled from 1010°C, single tempered (2 h) at tempering temperature	[4, 6]
Set-1	Air cooled from 1010°C and double tempered (2 + 2 h) at tempering temperature	[2, 3]
Set-2	Oil quenched from 1010°C and double tempered (2 + 2 h) at tempering temperature	[2, 3]
Set-3	Air cooled from 1010°C and double tempered (2 + 2 h) at tempering temperature	[4]
Set-4	Air cooled from 980°C and double tempered (2 + 2 h) at tempering temperature	[4]
Set-5	Set-5: Air cooled from 1010°C and single tempered (2 h) at tempering temperature	[6]
Set-6	Set-6: Air cooled from 1010°C and double tempered (2 + 2 h) at tempering temperature	[7]
Inhouse-1	Air cooled from 1050°C and single tempered (2 h) at tempering temperature	In-house
Inhouse-2	Oil quenched from 1010°C and double tempered (2 + 2 h) at tempering temperature	In-house

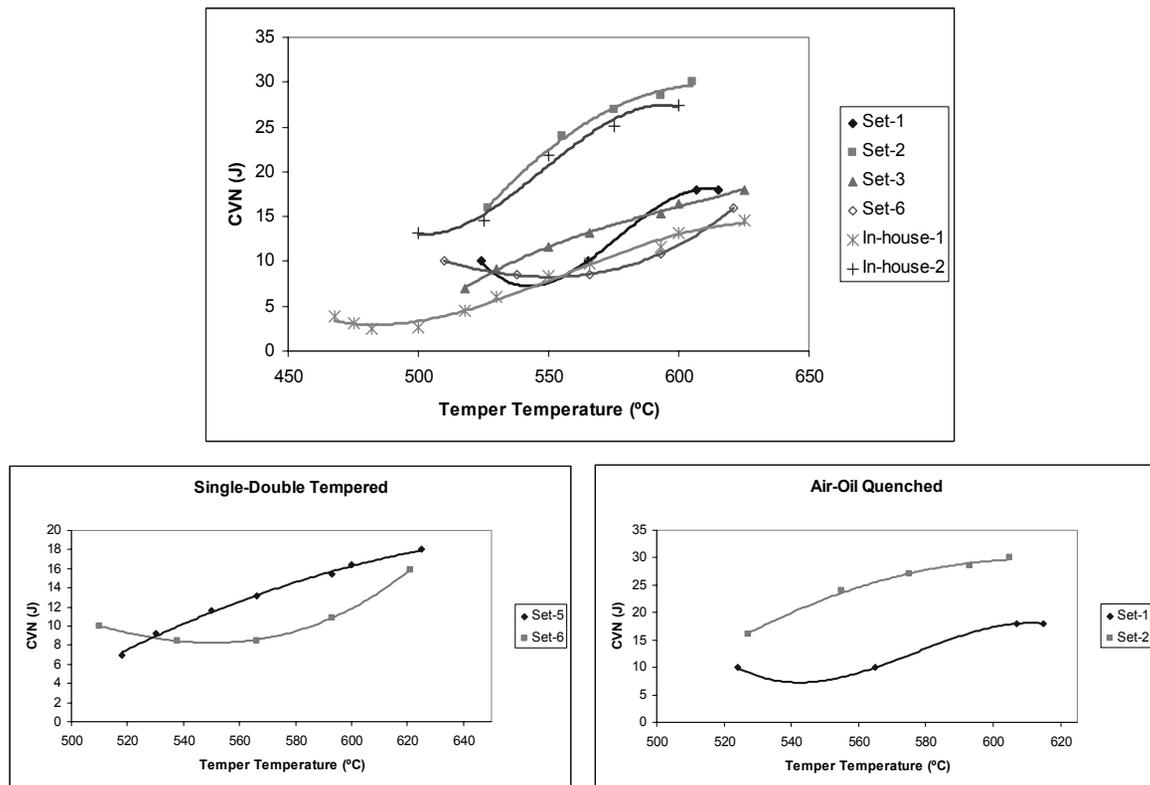


Fig. 1. Variation of CVN for H13 samples, single and double tempered to different tempering temperatures; air and oil quenched

ranges. As H13 steel does not represent a fixed composition, but a range of component percentages (0.37-0.42% carbon, 0.3-0.5% manganese, 0.9-1.2% silicon, 5.0-5.5% chromium, 1.2-1.5% molybdenum, 0.9-1.1% vanadium, less than 0.03% phosphorus and sulphur), samples from different sources may have slightly differing properties even for the same heat treatment routines. However, the variation trend should generally be the same. Also, because of the slight compositional differences, experimenters have taken different hardening/austenitizing temperatures: 980°C, 1010°, and 1050°C. Tempering temperatures well beyond 600°C are not reported, as lower hardness values (at higher tempering temperatures) are not optimal for die steels.

3.1. Variation of impact energy (CVN)

Figure-1 shows the variation of fracture toughness (Charpy impact energy *CVN*) against various types of tempering (single tempering, double tempering, oil quenching, and air quenching). It can be seen that that all the samples exhibit similar variation trend. However, there is an offset from one curve to the other possibly due to slight variations in H13 composition, austenitizing temperature, and air/oil quenching. Variation is not linear and not unidirectional but a decreasing-increasing type. If curve fitting is attempted, 3rd degree polynomial fit would generally be the closest. Impact energy first decreases, and then increases as

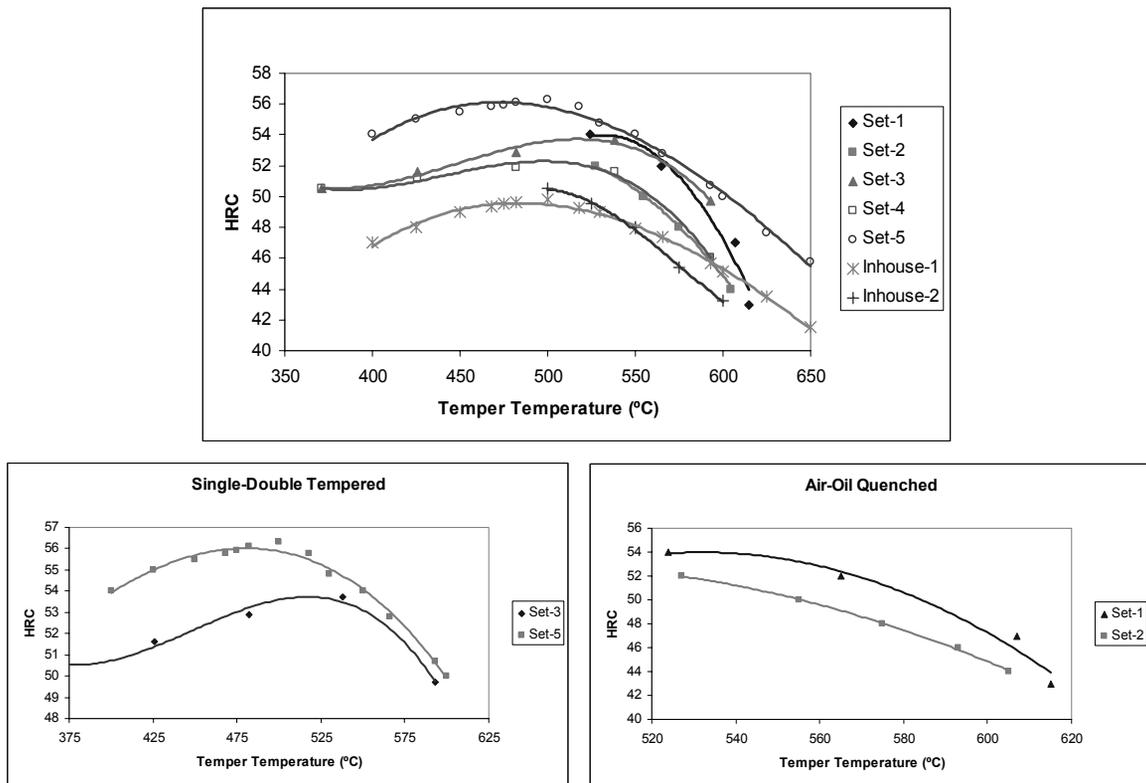


Fig. 2. Variation of *HRC* for H13 samples, single and double tempered to different tempering temperatures; air and oil quenched

tempering temperature increases. Some data sets exhibit only increasing behavior may be because tempering was not done at lower temperatures. *CVN* values for single-tempered samples (set-5) are generally higher than those of double-tempered ones (set-6), both air-cooled from 1010°C. However, the impact energy is almost the same at low and high tempering temperatures. As for quenching, oil-quenched samples (set-2) exhibit higher *CVN* values compared with air-cooled ones (set-1). At lower tempering temperatures, the values are somewhat close, but not at higher temperatures.

3.2. Variation of hardness (*HRC*)

As with impact energy, variation trend for hardness (*HRC*) is the same for different samples, curves being slightly offset from each other. Hardness variation against tempering temperature (Fig-2) also shows a nonlinear pattern, the closest curve-fitting being a 3rd degree polynomial. However, as expected, hardness exhibits a mirror trend to that of toughness: first increasing and then decreasing with increasing tempering temperature. Probable reason for some data sets exhibiting only decreasing behavior may be that tests were not carried out at lower tempering temperatures. Once again, *HRC* values for single-tempered samples (set-5) are generally higher than those of double-tempered ones (set-3), both air-cooled from 1010°C. However, the curves almost converge for higher tempering temperatures. Showing an opposite behavior to that of toughness, hardness

values for air-cooled samples (set-1) are generally higher than those for oil-quenched ones (set-2), though the curves get quite close to each other in the low and high tempering regions.

3.3. Comparison of toughness and hardness

To compare the variation patterns of toughness and hardness against each other, K_{IC} , *CVN*, and *HRC* values of only single tempered samples are plotted against tempering temperature in Fig-3. As mentioned earlier, K_{IC} testing is difficult, time-consuming and costly. That is why only one set of K_{IC} values [4] could be traced even after a very thorough search of published literature and steel manufacturers. On the other hand, Charpy impact energy is a relatively easy, quick and accurate test, and can be used as an alternate indicator of material toughness. For corroboration of published data, experiments were conducted to determine *CVN* and *HRC* values of H13 samples after single tempering to various temperatures (data set identified as inhouse-1).

As we increase the tempering temperature, plain-strain fracture toughness (K_{IC}) of H13 steel first decreases to a minimum value and then increases. The other toughness pointer, Charpy impact energy (*CVN*), displays a similar trend of an initial decrease followed by an increase with increasing tempering temperature. The variation pattern for hardness (*HRC*), as expected, is almost a reverse mirror image of toughness, at first increasing and then decreasing with higher tempering

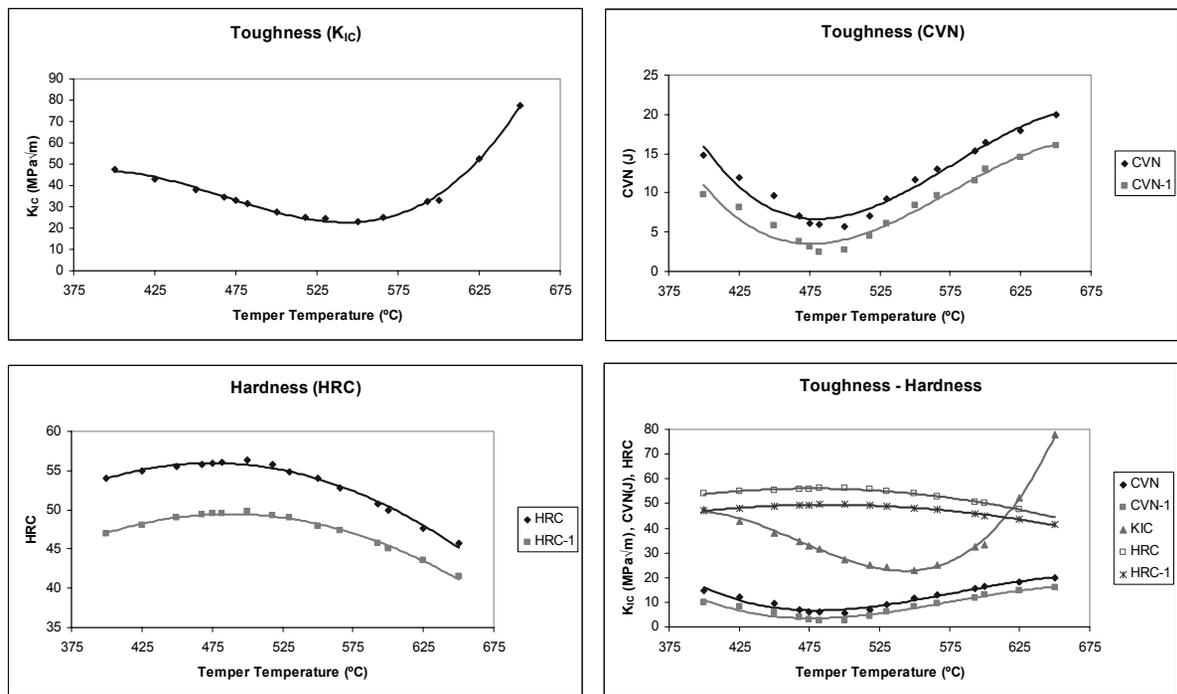


Fig. 3. Variation of fracture toughness, impact energy, and hardness; H13 samples single tempered to different tempering temperatures

temperatures. Looking at the combined graph it becomes quite clear why we do not find any properties reported for samples tempered beyond 625-650°C. Hardness of these tool steels continuously decreases as we increase the tempering temperature, and as hardness is an important requirement, tempering to higher temperatures would be counter-productive.

3.4. Optimum heat treatment

As was mentioned earlier, hot work tool and die steels (such as H13) have two contradictory material property requirements. Fracture being the dominant die failure mechanism in hot metal working, high fracture toughness is obviously needed. On the other hand, wear of the die land (die bearing surface) and going out of shape of the die profile are the other leading contributors to die failure, both requiring high hardness (especially in the bearing area). For optimum die performance therefore, high toughness is required together with high hardness. Looking at the combined graph in Fig-3, it is evident that maximum toughness (whether indicated by K_{IC} or by CVN) can be achieved at the highest tempering temperature. However, hardness decreases for higher temper temperatures. An optimal tempering range, to get both good toughness and high hardness is therefore around the 525°C-550°C temperature range.

Commercial aluminum extrusion is a hot-working process, typical working range being 425-525°C. It is a well-known fact that toughness of metals increases with temperature. At the operating temperatures just mentioned, toughness of the die

material is thus appreciably higher than the room-temperature value, which is good for fracture resistance. On the other hand, it is also an established fact that hardness of metals decreases at high operating temperatures, so we get a reduced value of die hardness during hot extrusion. When deciding on an optimum heat treatment strategy for die steels, high hardness therefore takes precedence over high toughness. That is why the optimum tempering range is closer to the highest hardness region than to the highest toughness region.

4. Conclusions

Toughness and hardness values for H13 tool steel have been collected from published literature and tool steel manufacturers for samples subjected to tempering at various temperatures. In-house heat treatment and mechanical testing has also been carried out on specially fabricated H13 samples, to augment and substantiate the published data. The data matrix has been completed by careful interpolation-extrapolation. It has been found that both toughness (K_{IC} and CVN) and hardness (HRC) vary nonlinearly against tempering temperature. However, toughness first decreases and then increases, while hardness first increases and then decreases, with increasing temper temperature. Optimum tempering temperature for H13 die steel used in commercial extrusion appears to be in the 525-550°C range, to get the most favorable combination of high toughness and high hardness.

Acknowledgements

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