13th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2009, Hammamet, Tunisia, 16-21 October, 2009

EFFECT OF HEAT TREATMENT ON MECHANICAL PROPERTIES OF H13 STEEL

S.Z. Qamar, R.A. Siddiqui, T. Pervez
Box 33, Mechanical and Industrial Engineering Department, Sultan Qaboos University, Al-Khodh 123, Oman; email siddiqui@squ.edu.om

ABSTRACT
This paper reports results of in-house experimentation on heat treatment and mechanical testing 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, hardness and other mechanical properties is also analyzed. It was found that 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 nonlinearly manner against tempering temperature. Toughness shows a decreasing-increasing trend, while hardness exhibits an opposite increasing-decreasing pattern with increasing temper temperature. Optimum heat treatment strategy for commercial aluminum extrusion dies (H13 steel) appears to be tempering in the 525-550ºC temperature range, to get the best combination of high toughness and high hardness.
Keywords: Heat treatment, hot extrusion die, H13 tool steel, fracture toughness, impact energy, hardness

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 continual 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.
Since plane-strain fracture toughness (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 [2-10]. 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. EXPERIMENTAL WORK

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.

To remove any preexisting anomalies of material properties, all samples were first subjected to annealing at 850°C (2 hr). One set of samples was austenitized at 1050°C (soaking for half hour). After air cooling to 50-60°C, samples were immediately tempered 2 hr at different tempering temperatures (425°C, 500°C, 550°C, and 600°C). Another set of samples underwent double tempering: hardening to 1010°C (soaking for half hour); oil quenching to about 50-60°C; immediate tempering (2 hr + 2 hr) at 500°C, 550°C, 575°C, and 600°C.

Oxide layers etc formed during heat treatment were removed by stage-wise grinding. Average hardness values (*HRC*) were determined by taking a number of hardness readings at different positions on the samples. For 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 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: 980ºC, 1010º, and 1050ºC. Tempering temperatures well beyond 600ºC are not reported, as lower hardness values (at higher tempering temperatures) are not optimal for die steels.

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). Impact energy first decreases, and then increases as 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 1010ºC. 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).

Variation of Hardness (*HRC*)

As expected, hardness (Fig-2) exhibits a mirror trend to that of toughness: first increasing and then decreasing with increasing tempering temperature. *HRC* values for single-tempered samples (set-5) are generally higher than those of double-tempered ones (set-3), both air-cooled from 1010ºC. 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).

Comparison of Toughness and Hardness

As can be seen in Fig-3, with increase in 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 temper 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 temperatures. Looking at the combined graph it becomes quite clear why we do not find any properties reported for samples tempered beyond 625-650ºC. 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.

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 525ºC-550ºC temperature range.

Commercial aluminum extrusion is a hot-working process, typical working range being 425-525ºC. 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

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 525-550ºC range, to get the most favorable combination of high toughness and high hardness.

5. REFERENCES

[1] Arif AFM, Sheikh AK, Qamar SZ, al-Fuhaid KM "Modes of Die Failure and Tool Complexity in Hot Extrusion of Al-6063," *Journal of Materials Processing Technology*, 2003, **134** (3), p 318-328

[2] Timken Latrobe Steel "Data Sheet: H13 Tool Steel," 2007, http://www.timken.com

[3] International Mold Steel, Inc "Premium H13," 2007, http://www.moldsteel.com

[4] ASM International, ASM Metals Handbook, 10th edition: Volume 2: Properties and election: Nonferrous Alloys and Special Purpose Materials, American Society for Metals, Metals Park, Ohio, 1990

[5] Bryson B, Bryson WE, Heat Treatment, Selection, and Application of Tool Steels, 2nd edition, Hanser Gardner Publications, Cincinnati, 2005

[6] Thelning K-E, Steel and its Heat Treatment (2nd edition), Butterworths, London, 1984

[7] Roberts GA, Krauss G, Kennedy R, Tool Steels, 5th edition, American Society for Metals, Metals Park, Ohio, 1998

[8] ASM International, ASM Handbook Volume 4: Heat Treating, American Society for Metals, Metals Park, Ohio, 2006

[9] Wilson R, Metallurgy and Heat Treatment of Tool Steels, McGraw-Hill, London, 1976

[10] Szumera J, The Tool Steel Guide, Industrial Press, New York, 2003

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 1010ºC, single tempered (2 h) at tempering temperature	[4, 6]
Set-1	Air cooled from 1010ºC and double tempered (2 + 2 h) at tempering temperature	[2, 3]
Set-2	Oil quenched from 1010ºC and double tempered (2 + 2 h) at tempering temperature	[2, 3]
Set-3	Air cooled from 1010ºC and double tempered (2 + 2 h) at tempering temperature	[4]
Set-4	Air cooled from 980ºC and double tempered (2 + 2 h) at tempering temperature	[4]
Set-5	Set-5: Air cooled from 1010ºC and single tempered (2 h) at tempering temperature	[6]
Set-6	Set-6: Air cooled from 1010ºC 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

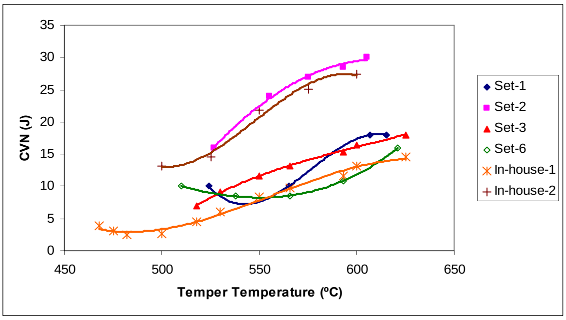

Figure 1. Variation of CVN for H13 samples, single and double tempered to different tempering temperatures; air and oil quenched

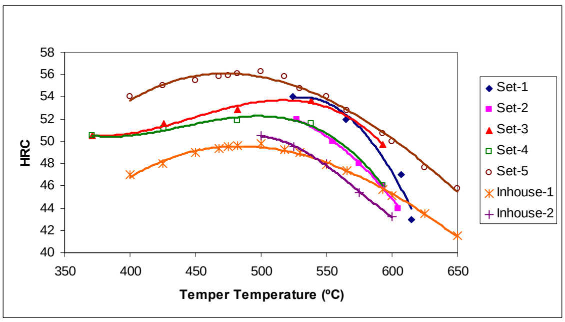

Figure 2. Variation of HRC for H13 samples, single and double tempered to different tempering temperatures; air and oil quenched

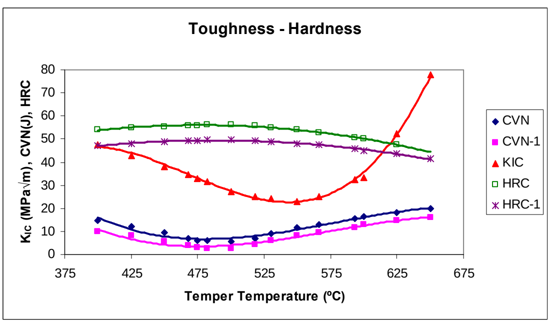

Figure 3. Variation of fracture toughness, impact energy, and hardness; H13 samples single tempered to different tempering temperatures