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Review Article

Effect of Heat Treatments on Fatigue Failure and Fracture Toughness of Various Tool Steels – A Review

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Abstract

In manufacturing industries, tools can be exposed to various loading condition like mechanical, tribological and environmental condition. So it is very important to enhance the material properties especially fatigue strength and fracture toughness, to increase the life of the tools and decreasing the production cost. Various heat treatments like hardening, tempering and cryogenic treatments are used to increase the wear resistance and the mechanical properties of the tool steels. This paper will present the state of the art review on the effect of the various heat treatments on fatigue strength and fracture toughness of the different tool steels. The different researchers used the experimental tests like thermal fatigue test, thermo-mechanical fatigue (TMF) test for calculation of fatigue strength and three-point bend tests for fracture toughness of the tool steels.

Keywords: *Tool steels, Heat Treatment, Fatigue Strength, Fracture Toughness, TMF cracking,austenitising, etc.*

1. Introduction

Fatigue Failure and the Fracture Toughness are the most important parameter to be considered in the industrial applications. In metal forming industrial applications, like stamping, rolling or die casting, the service life of the tool is limited due to their extreme working environment in terms of thermal and mechanical loadings which result from the close contact between the tools and the hot workpiece (1200 ºC for steel forging) or the molten metal (675 ºC for Al-alloy casting, 930 ºC for Cu-alloy casting). Under such working conditions, in generally the tools are damaged through wear and thermal fatigue cracking processes. The thermal fatigue damage process during hot die forming process, results basically in compressive and tensile stresses at the tolls surfaces that came from differential thermal expansion and /or contraction during sudden transient temperature changes D. Mellouli, N. Haddar, A. Köster, and H. Ferid, *et al*.

Die casting is a nearly like net-shaped process that has been used to produce the non-ferrous alloys (such as Al, Mg, and Zn based alloys) with high strength, close tolerance, complex geometrical shape, various surface finishing, and high production rate, A. Persson, S. Hogmark, and J. Bergström, *et al*. But, the high efficiency of this die casting technique must have a good performance of molds (like dies) to withstand in the served environmental conditions. The extreme temperature, wear, corrosion and the Thermo-Mechanical Fatigue (TMF) (induced by the cyclic thermal and mechanical loading during die casting cycles) are the major issues to the durability of molds. The external surface of molds would be gradually worn out by these attacks; giving rises to both the decrease the production quality of casting parts and also affects the failure of molds. Nowadays, hot work tool steels are mainly used as tooling materials for die casting because of their higher thermal and mechanical properties; however, their lower resistance to molten metal corrosion and TMF cracking are the main problems to be resolved in the die casting industry. Different surface treatments like heat treatments and coatings have been applied to tool steels for the purpose of increasing the resistance to wear and thermal corrosion; however, the TMF properties were significantly affected by the surface treatments. Since tooling accounts for a great part of the total production cost of the final outcome of die casting products, the materials used for the manufacturing of the tools with longer service life and high wear resistance are very effective in reducing the manufacturing cost in die casting industry A. Persson, S. Hogmark, and J. Bergström*, et al.*

2. Type of Heat Treatments

The use of heat treatments to improve mechanical properties of metals and various metal components is a very old art still used until today. Most of the developed processes apply heat treatments in a span/range

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of temperature higher/lower than room temperature. The first attempts to perform subzero treatments like cryogenic treatment were investigated at the beginning of the 20th century, but the actual investigation on cryogenic treatment (CT) was developed during the last decades of the century.

Various heat treatments include hardening, tempering, cryogenic treatment etc. of metals to improve their mechanical and physical properties, without changing its shape. Heat treatments can be called as a method for strengthening materials but can also be used to change some mechanical properties such as improving wear resistance, formability, machining, etc. Most common application is metallurgical research but heat treatment can also be used in manufacturing of aluminium, glass, steel and other. Heat treatment involves the use of heating or cooling, usually to extreme positive and negative temperatures to achieve the required result. Heat treatments are very important in the manufacturing processes that can not only help in manufacturing but can also improve the product, its characteristics, and its performance, in many ways D. Das, R. Sarkar, A. Kishore, and K. Kumar, etal.

The general purpose of heat treatment on tool steels is to get a homogeneous structure, consisting of a full matrix hardened and tempered, which contains systematically arranged primary and secondary carbides. Whether the required type of martensite is of lath or plate-type, which may depend on toughness or high resistance against abrasive wear is desired. If correct heat treatment at correct time and temperature is applied, the properties of a tool steel will get enhanced for higher life of that component.

3. Literature Review

Dhouha Mellouli *et al*. studied the effect of hardness on thermal fatigue damage of hot-working tool steel. Cracks originating from thermal effect in die casting are often caused by thermal fatigue loading, low material strength, surface stresses, and surface irregularities. In the process cycle, the alternate heating and cooling of the component lead to thermal fatigue. Mostly mechanical stress and thermal stress fluctuations initiate very fine cracks on the cavity surface that grow larger and finally lead to failure of the dies and tools. The hardness of the material or surface heat treatment can extend the life time of the various dies and tools. The main objective of this work is to reveal the effect of various heat treatments on thermal fatigue damage of AISI H13 tool steels. The results obtained shows that the thermal fatigue resistance is very much related to the initial material hardness.

Specimens were followed by two different heat treatment used to achieve tempered martensite microstructures with two hardness levels of 36 and 49 HRC values. The monotonic tensile test was carried out to get the mechanical properties of the H13 tool steel with different temperature with standard test specimen cross section of 5×2 mm^2 and 24 mm gauge length as shown in the Fig. 1.

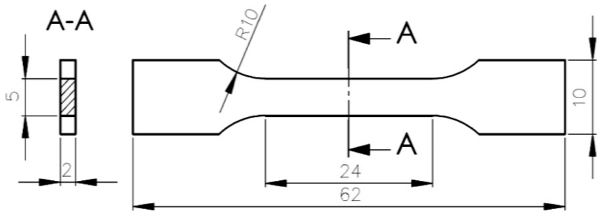


Fig. 1 Geometry of monotonic tensile specimen

The results obtained from the monotonic tensile test shows that, the mechanical properties are the function of the tensile strength (R_m), tensile yield strength ($R_{p0.2}$), and Young modulus decrease when the temperature of the steel increases as shown in Fig. 2. Also, at room temperature, the tensile yield strength of H13 steel having HRC value 49 is higher than that of having HRC value 36. But as the temperature increases of the test specimen, it is found that the tensile yield strength is similar for both HRC valued steel.

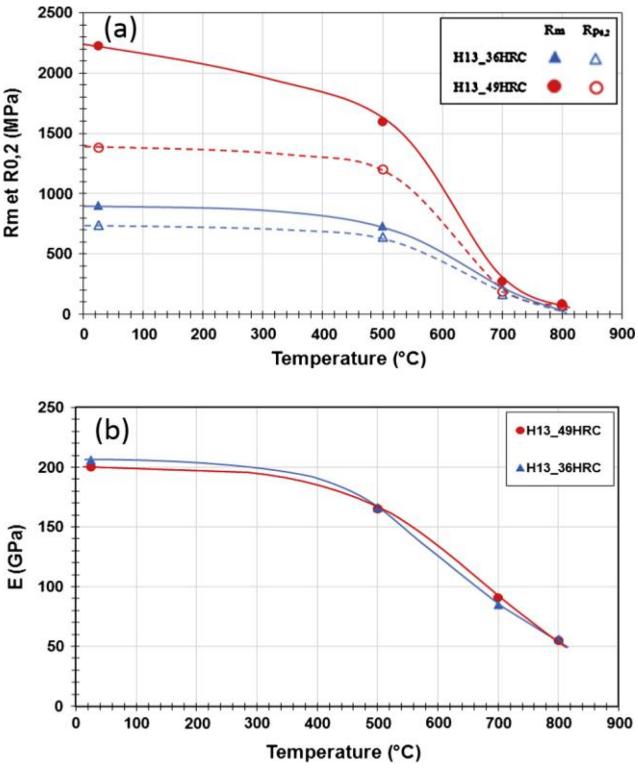


Fig. 2 Mechanical properties of H13_36 and H13_49 steel showing (a) tensile strength (R_m), tensile yield strength ($R_{p0.2}$) vs. temperature and (b) modulus of elasticity vs. temperature

Thermal Fatigue test carried out to get the evaluation of the damage of H13 tool steel as shown in Fig. 3. The results obtained from the test shows that the evaluation of the crack length is the function of the number of the cycle and the crack growth rate of H13 steel having hardness 36 HRC is more than that of H13 steel having hardness 49HRC.

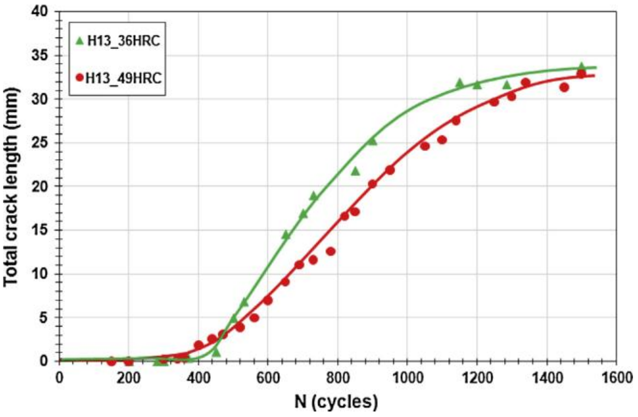


Fig. 3 Evolution of the total crack length vs. cycles for H13_36 and H13_49 specimens

It seems to be concluded that the H13 steel treated at 49 HRC is beneficial than that of treated at 36 HRC for an application like industrial Dies.

Anders Persson *et al*. described an experimental test machine for simulation of thermal fatigue. Also, simulation has done to study the thermal fatigue cracking of hot work tool steels. Most of the applications of this test were used for demonstration of hot work tool steel grades that are hardened and tempered to different heat conditions, and heat cycled between T_{min} 170 ºC and T_{max} 600–850 ºC.

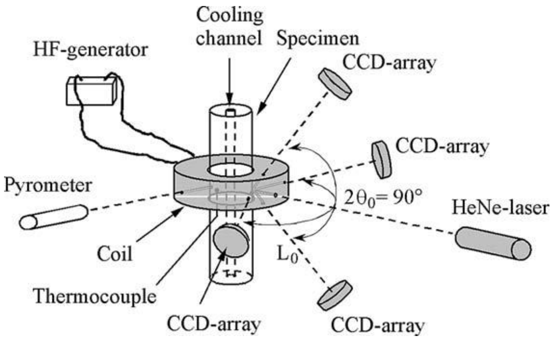


Fig. 4 Schematic of the experimental set-up used in the thermal fatigue test.

The test setup used for the simulation of the thermal fatigue test is as shown in Fig. 4. It consists of the continuous heating and internal cooling of a hollow cylindrical test rods. By using the non-contact laser speckle technique, the strain of the surface of the test specimen is continuously recorded while thermal loading and unloading. The test specimen used for this type of the test is hollow cylinder having 10mm diameter and 80mm in length with 3mm axial hole for the internal cooling. The induction unit will heat the approximately 20mm of the middle part of the test specimen. The internal cooling is used to cool down the internal part and the external argon gas cooling is used for the external cooling.

For the simulation purpose, two types of the material namely QRO 90 supreme and Hotvar were used as test specimens. QRO 90 specimen was treated with two different types of the heat treatment namely hardening including austenitizing for 30 min at 1030 ºC, followed by air quenching and tempering at 640 ºC to get the hardness of 430 HV_{30} and hardening as above followed by tempering at 625 ºC to a hardness of 510 HV_{30}, respectively. The Hotvar specimen were hardened at 1050 ºC including air quenching and tempering at 575 ºC to get the hardness value of 640 $HV_{30.}$

After Heat treatment, the specimens were tested for thermal fatigue test using the setup as shown in Fig. 4. In this technique during the thermal loading and unloading, the surface strain is continuously recorded using laser speckle technique by using change in the specimen dimensions, and this is represented as surface strain versus temperature. And any thermal damage is found by using scanning electron microscopy.

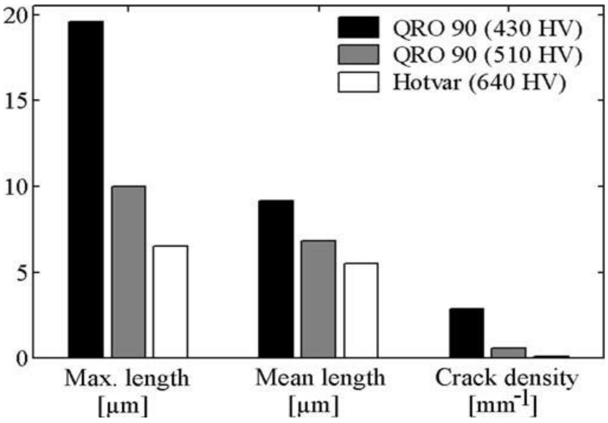


Fig. 5 Length and density of thermal fatigue cracks after 1000 cycles to 700 ºC in air

The result obtained from the test shows it will take <10^2-10^4 for heat cycles of 600-850 ºC to initiate and propagation of the first thermal crack. And after thermal cracking crack length and crack density decreases as an increase in the hardness value as shown in Fig. 5. But it also proves that after thermal cracking the hardness of all material will decrease as an increase in the thermal cycles for all conditions. It also seems that residual tensile stresses are slowly increases in the surface layer during the thermal cycling, but the residual shear stresses are not affected.

Debdulal Das *et al*. presented the influence of subzero treatments, like deep cryogenic treatment and shallow cryogenic treatment, cold treatment on fracture toughness of AISI D2 steel and have been compared with the general heat treatment. The Three-point bend test technique is used for the measurement of the fracture toughness. Also, the fracture surface was examined by using Scanning Electron Microscopy (SEM). Prior to the actual study, the literature survey was conducted for the analysis of the influence of subzero treatment on tool steel. Then test specimen of D2 tool steel was treated at different combination of the heat treatments including the conventional and subzero treatment. After the heat treatment the test specimens were examined by SEM.

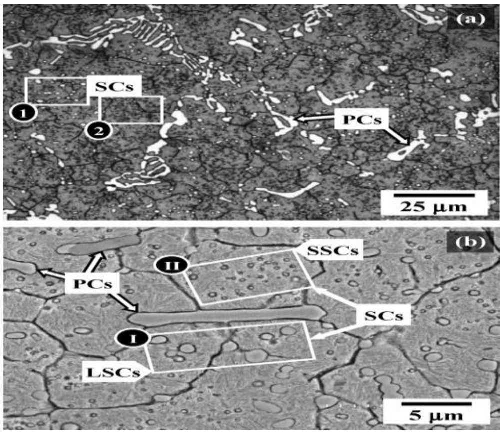


Fig. 6 Representative (a) optical and (b) SEM micr graphs of shallow cryogenically treated specimens

The result obtained from the microstructure shows the primary and secondary carbides on tempered martensite matrix. In this study, the primary carbides are the long elongated type and which is depends on the austenitization treatment. In the optical and the SEM micrographs the primary carbides are as small and tiny black patches whereas the secondary carbides as large as compared to primary one.

The results obtained from the Vickers Hardness test are as shown in the Fig. 7. And it shows that both macrohardness and microhardness increase with decreasing T_{LQ}

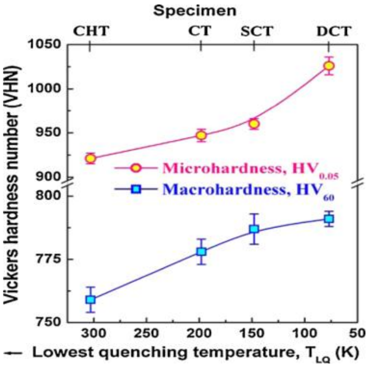


Fig. 7 Variations of Vickers macrohardness and microhardness with lowest quenching temperature

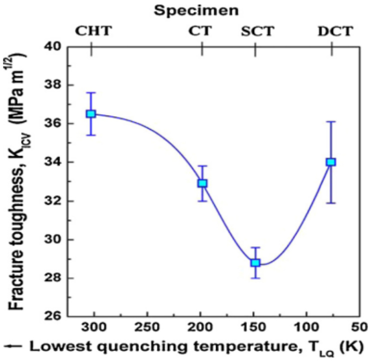


Fig. 8 Variation of fracture toughness with lowest quenching temperature (T_{LQ})

The result obtained from the three-point bend test is as shown in the Fig. 8. It shows that the subzero treatment will considerably affect the fracture toughness of the D2 tool steel. In general, we can say that the subzero treatment will reduce the fracture toughness of the D2 tool steel.

Johnny Sjöström, *et al*. used martensitic chromium hot-work tool steel grade with the Uddeholm designation DIEVAR for conduction of the thermal fatigue test. In this study, different heat treatment has been carried out on the specimen of the concern tool steel including hardening for 1120 to 1250 ºC followed by the various tempering cycles to get the 470 to 590 HV_{30} Hardness values. After giving the various combinations of the heat treatments the specimens were tested under the standard thermal fatigue testing setup as shown in the Fig. 4.

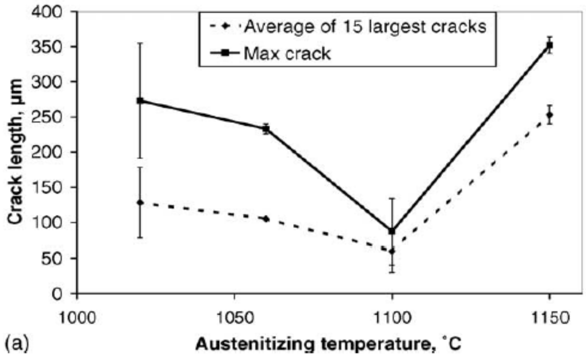


Fig. 9 Dievar at four different austenitizing conditions

Results obtained from the thermal fatigue test are as shown in the Fig. 9. It will give clear idea about the behavior of the DIEVAR for different austenitizing temperature. It was observed from the result that the toughness increased with the increasing hardening temperature up to there was no any grain growth.

R. Ebara *et. al*. investigated the effect of the thermal stress on the crack behavior and the propagation of the two types of the tool steels i.e. SKD62 which are Surface treated to get HRC values of 43.5 and 46.

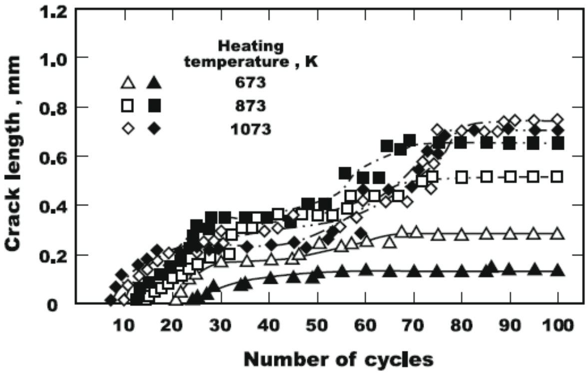


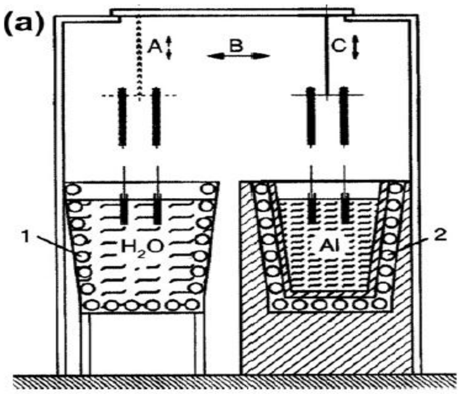
Fig. 10 Thermal fatigue crack propagation curves

The effect of testing temperature, hardness, and stress concentration factor of the specimen on fatigue strength is studied. It shows that as the hardness of the specimen increases the tensile stress decreases and as the stress concentration factor decreases the fatigue strength of the material is increased. Also it was found that as the axial stress of the specimen decreases the number of cycles required for the failure of the specimen increases.

The thermal fatigue test of SKD 62 tool steel was done on the laboratory-made thermal fatigue testing machine. In this apparatus, the water is used as the cooling medium whereas the LPG and Oxygen used for the heating purpose. This test was conducted for three different temperatures like 673 K, 873 K and 1073 K. The results obtained from this test are as shown in the Fig. 10. From the test it is observed that the number of thermal fatigue cycle required for crack initiation was 61, 36 and 22 for 673 K, 873 K and 1073 K test temperature respectively.

D. Klobcˇar *et al.* used H13 hot works die steel for the investigation of the effect of the different heat treatment on the thermal fatigue life of the specimen. Some specimens of H13 tool steel edge was cladded by maraging steel. For the simulation of the thermal fatigue test the new test apparatus called immersion test was developed. The test specimens were heat treated for two different groups of the hardening and tempering combinations. In first treatment the hardening is done at 1030 °C followed by the double tempering at 600 °C and 570 °C respectively in vacuum environment. Second group is heat treated in atmospheric conditions, includes hardening at 1000 °C followed by tempering at 530 °C.

The immersion test is conducted for thermal fatigue test; setup used for the test and required test specimen is as shown in the Fig. 11. It will give the controlled atmosphere for the thermal testing. In this test, first of all, the test specimen is immersed in water based lubricant for 3 second at 32 °C which will prevent sticking of the aluminium on the test specimen, after the test specimens were kept in air for 4 seconds followed by immersion in the molten alluminium alloy at 700 °C for 6.4 seconds. Then the specimens were cooled down in water based lubricant bath. In the concerned test cyclic thermal loading is achieved by moving the test specimen from air medium to the molten alloy medium while the internal cooling is done by using the water supply at 20 °C.



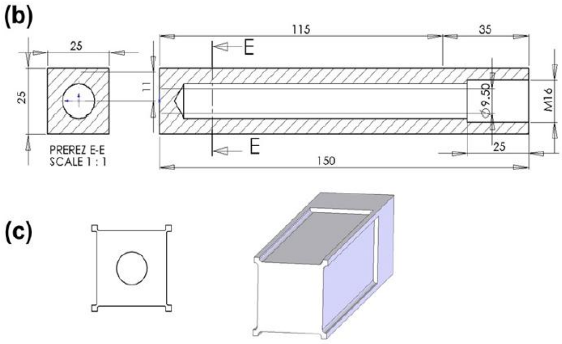


Fig. 11 a) Immersion test Setup
b) Schematic of classic thermal fatigue test specimen, and (c) cross section of optimal test specimen.

The results obtained from the Immersion test are as shown in Fig. 12. It shows that the longest crack is obtained at 1.2344 HTA which has low density, for other samples crack length was much shorter.

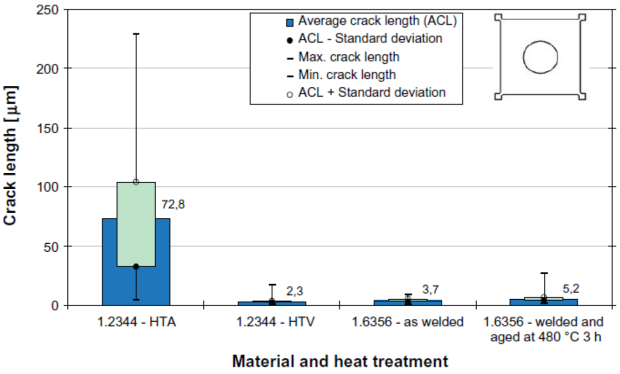


Fig.12 Edge Crack length.

Dhouha Mellouli *et al.* performed the thermal fatigue failure analysis of two types of the materials, namely, die steel and H13 tool steel. For the surface and fracture surface analysis the experimental techniques like Scanning Electron Microscopy, Light Optical Microscopy (LOM) and Energy Dispersive X-ray Spectroscopy (EDS) was used. For measurement of the mechanical properties, the monotonic uniaxial tensile test and Charpy impact tests were used.

Fig. 13 Typical macroscopic surface damage

As shown in Fig. 13, when we observe any type of the die surface under a microscope it shows that the surface damage is critical at the edges or at the sharp corners of the dies.

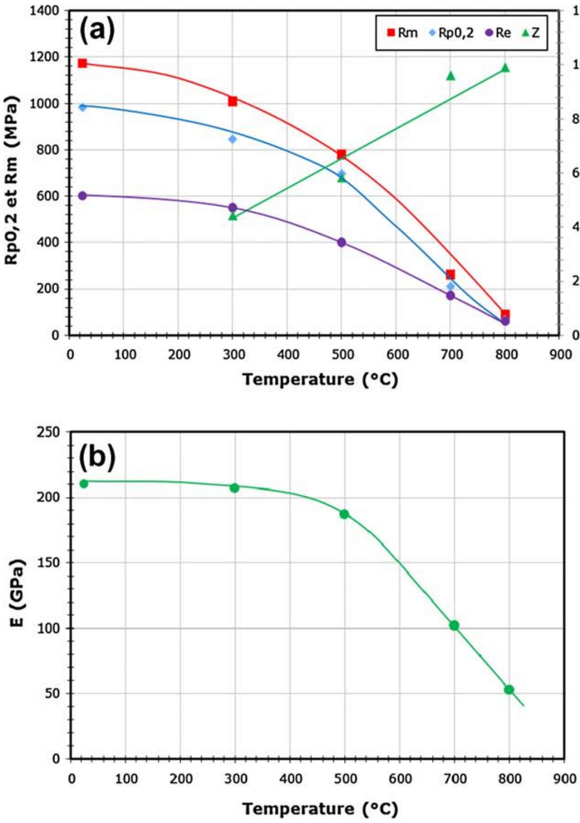


Fig.14 Mechanical properties of mold steel showing (a) tensile strength (Rm), tensile yield strength (Rp0.2), hold yield strength (Re), reduction of area at tensile fracture (Z) versus temperature and (b) modulus of elasticity versus temperature.

Fig. 14 shows, the evaluation of the various mechanical properties using the experimental technique like a monotonic uniaxial tensile test. It will show that the tensile strength (R_m), tensile yield strength ($R_{p0.2}$) and Young modulus decrease when the test specimen temperature increases. But, the area at tensile fracture increases as the temperature increases. In general, we can say that, the thermal fatigue was the first symptoms of the failure of the dies.

M. Pérez *et al*. investigated the use of the thermal treatment including cryogenic treatment to enhance the fracture toughness of the H13 hot works die steels. Nowadays the cryogenic treatment is widely used for the enhancing the various mechanical properties of the metals including various types of the tool steels. H13 is generally used hot works tool steel for applications like forging dies. The test specimens of the H13 tool steel was heat treated for the different combination of the tempering and the cryogenic conditions.

The results obtained from the test shows that there were not any remarkable changes in the tensile properties of the material takes place. But it shows that as the fracture toughness of the cryogenically treated specimen is higher than that of conventional heat treated one. Fig. 15 and Fig. 16 will give us the microstructural changes after conventional heat treatment and cryogenic treatment.

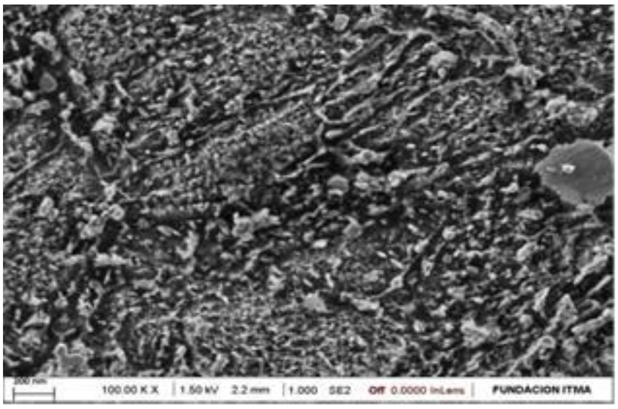


Fig. 15 H13 steel microstructure under 100000x for conventional heat treatment

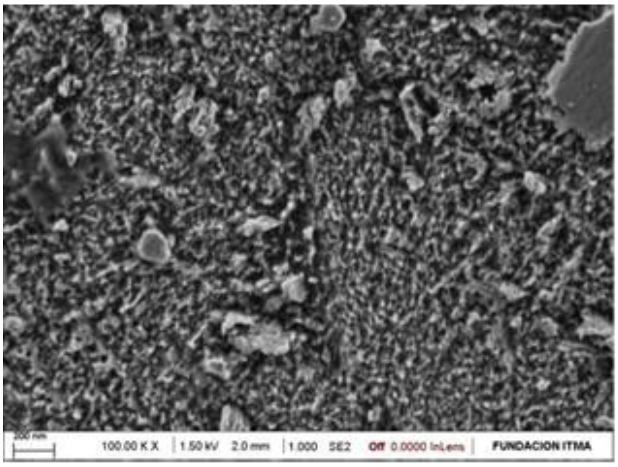


Fig.16 H13 steel microstructure under 100000x for cryogenic treatment

Conclusions

There is a wide use of the different types of tool steel for the manufacturing of the dies, tools, automotive components and other metal parts. So it is very important to study the various failures takes place in such types of the tool steels and the methods that are implemented to get rid of such types of problems. The tools and dies used in the industrial application in the metal forming industry usually fail due to the thermal fatigue failure. It is observed that the fatigue crack is the first indication of the failure of the dies.

It is found that the cryogenic treatment will give better results in terms of the fracture toughness and fatigue strength for many types of the tool steels. But the tensile properties of the tool steels are not much affected by the use of the cryogenic treatment. The thermal fatigue found to be strongly dependent on the test temperature.

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