Journal of Mechanical Engineering Research and Developments
ISSN: 1024-1752
CODEN: JERDFO
Vol. 44, No. 7, pp. 93-99
Published Year 2021

Investigate Thermal Fatigue Mechanism of Hot Work Die Steel

Ahmed Qays Abdullah

College of Engineering Al-Shirqat, Mechanical Engineering Department, Tikrit University, Iraq.

*Corresponding Author Email: hayder.murad@uowasit.edu.iq

ABSTRACT

The thermal fatigue (TF) performance of H13 hot work die steel is the main factor that affects the service life of the die. Brief detail of status and evaluation method of thermal fatigue performance of hot-work die steel are described. At the same time, the factors affecting TF performance and methods to improve TF performance are discussed. Experimentally analyzed the performance and the influence of microstructure evolution, crack initiation and propagation on TF. In addition, summarized the trend of TF research on hot work die steels is prospected.

KEYWORDS

hot work die steel, thermal fatigue, crack initiation, crack growth

INTRODUCTION

The mold industry is the leading industry of contemporary manufacturing, and its industrial level has become a standard to measure the level of a country's manufacturing industry [1-3]. The demand of modern industry has promoted the rapid development of the mold industry. With people's increasing attention to product quality, modern industry has put forward higher requirements for mold performance and service life. Hot work die steel is mainly used in the fields of metal hot forming, hot extrusion and pressure casting. The hot work mold is not only subjected to high temperature and heavy load impact during service, but also subjected to repeated cycles of heat and chill. The harsh service environment is likely to cause TF cracks to initiate and expand on the surface of the mold, thereby reducing the service life of the mold [3]. Thermal fatigue of hot work mold refers to the phenomenon that the free expansion or contraction of the material is restricted due to temperature changes, and thermal stress is generated in the material due to deformation and resistance, which leads to the phenomenon of cracking on the mold surface [4-5]. The surface state of the mold cavity directly affects the quality of the product, so the thermal fatigue performance has a very important impact on the service life of the hot work mold and the quality of the product.

A lot of research on the TF mechanism of hot work die steel, in order to understand the initiation and propagation of TF cracks. In [12] studied the influence of the crack network evolution mechanism on crack propagation, and concluded that there are stress concentration and stress shielding areas around the interacting cracks, which makes the cracks form a network and inhibits the initiation of cracks. In [13] proposed that during mold work, cracks would preferentially initiate at crack tips, grain boundaries, and stress concentrations. In [14] studied the TF properties of tool steels with hard coatings, and pointed out that adding hard coatings on the surface of tool steels can inhibit the initiation of TF cracks and delay the nucleation and propagation of cracks. In [15] introduced TF testing machine to conduct TF tests, and simulated the thermal cycle process by thermal-mechanical coupling finite element. The fatigue life of the compound layer and the sample with reduced compound layer thickness ratio is higher. It is also pointed out that due to the diffusion of nitrogen, it has a very high surface hardness, which increases the threshold of crack initiation at the surface.

Recently, many researches have also carried out in-depth research on the TF properties of hot work die steel. In [16-19] put forward a quantitative parameter for quantitative evaluation of TF performance, TF crack factor, in response to the problem that TF performance cannot be quantitatively evaluated, so that TF performance enters the stage of quantitative evaluation from qualitative evaluation. In [20] developed a new TF life prediction standard for the die-casting process through an improved general slope equation, and processed and tested the micro-H13 steel insert samples, and concluded that the model can predict the die-casting die TF life is an effective tool for predicting the life of hot working tool steels. In [21] improved the traditional fatigue prediction life model and established a cyclic softening model for fatigue life prediction. This model can be applied to the prediction of thermal-mechanical fatigue life, and a complete stress amplitude-cycle time curve can be obtained. Papers must be written in British English. Technical terms should be explained if they are highly specialized, in the session called "Glossary". Abbreviations should be explained at least upon first use.

BACKGROUND

Thermal fatigue crack propagation mechanism

Thermal fatigue crack (TFC) growth is usually divided into 4 stages: micro-crack form growth-small crack form growth-large crack form growth-and finally ring failure occurs. Generally, the first two stages are called crack initiation stage, and the third stage is called crack propagation stage. In [22] have shown that the initiation of TF cracks is the generation of vacancies under the interaction of dislocations during thermal cycling. Under the action of thermal stress and high temperature, these vacancies accumulate in the grain boundaries and are the first in the grain boundaries. Cracks are generated in it. Therefore, the initiation of TF cracks mainly depends on the change of the material's microstructure, the type and size of stress, and so on. TF crack growth is related to fatigue crack growth rate and stress intensity factor [23]. Some researchers believe that due to the sudden cooling and heating of the mold surface temperature, the surface temperature changes greatly, while the core temperature change is small, and the surface core temperature difference produces plastic deformation and cracks [22]. Some researchers have also obtained through computer simulations that TF cracks are generated under the action of thermal stress. Compressive stress is generated when heated, and tensile stress is generated when cooled, so that tensile strain and shear strain appear in the TF cycle loop [23].

Performance evaluation of thermal fatigue

A lot researchers have conducted research on the evaluation method of TF performance of hot work die steel, but there is still no set of accurate and universal evaluation specifications. Currently, the most widely used Uddeholm TF assessment method [24], this method divides the TF assessment method into two standards: reticulated cracks and main cracks. The reticular crack standard is mainly based on the comprehensive analysis and rating of the TF crack reticular integrity, density and crack size. It is divided into 10 grades. The higher the grade, the more severe the TF. The main crack evaluation standard is divided into 10 grades according to the size and number of the main cracks, the higher the grade, the more severe the TF [18]. The biggest advantage of Uddeholm method evaluation is that it is relatively intuitive, which can reflect the local width and overall width of the crack, but the disadvantage is that it is difficult to quantify, so that it is impossible to quantitatively evaluate TF.

In [24] used advanced image processing technology to analyze TF cracks based on the Uddeholm standard map, which could not be quantitatively evaluated, and proposed quantitative evaluation parameters for the first time, by defining the surface crack factor $Ds=A \cdot W/ L$ (where A is the surface crack area percentage; L is the total length of the surface crack; W is the width of the widest crack), the depth crack factor $Dd=P \cdot dmax/d5$ (where P is the percentage of the cross-sectional crack area; dmax is the deepest crack depth ; d5 is the average depth of the 5 main cracks) to obtain the total TF crack factor of the material $D=Ds\times Dd$. Thermal fatigue crack factor D is used as a quantitative parameter to quantitatively evaluate thermal fatigue performance, and a TF crack image analysis system has been developed. The system automatically evaluates the TF level by scanning the TF cracks and analyzing the TF crack images, and realizes computer automation and intelligent quantitative evaluation of the TF performance of hot work die steel [24]. This method can minimize the interference of human factors and can objectively assess the degree of TF crack. The evaluation flow chart of the analysis system for TF cracks is shown in Figure 1.

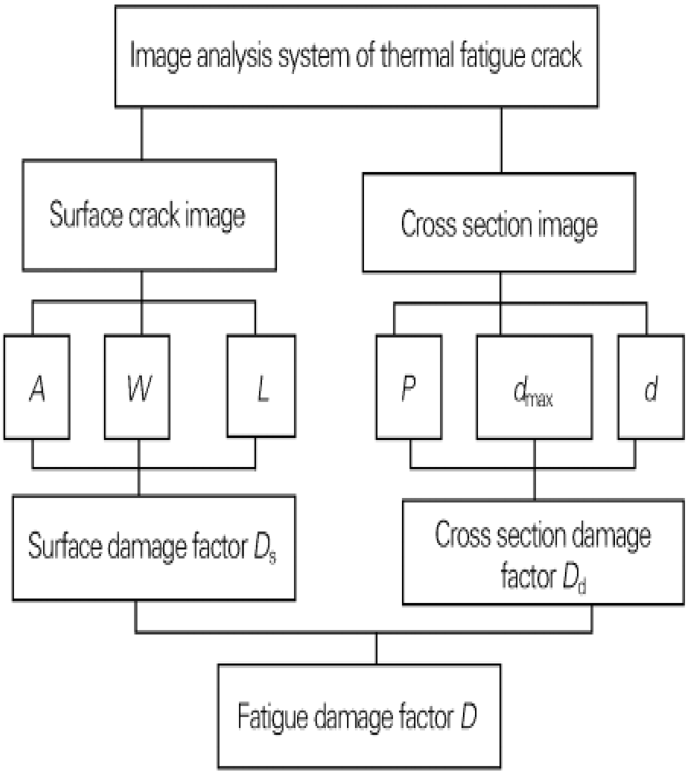

Figure 1. Flow chart of thermal fatigue crack analysis system [24]

METHOD AND MEASUREMENT

Heat treatment process control

Laser cladding uses high-density laser beams to radiate the substrate and the coating material to melt the coating material and the substrate together. After rapid solidification, it forms a surface coating that is combined with the substrate at a low dilution rate to improve the corrosion resistance of the material, wear resistance, high temperature resistance and TF resistance. After laser cladding Ni-Cr-B-Si coating on the surface of H13 die steel, fine grains can be obtained, the hardness is high, the surface cladding layer is firmly bonded to the substrate, and the cladding layer is dense. There are no defects of cracks and pores. The expansion coefficient of Ni in the cladding layer is not much different from that of Fe, so that the thermal stress generated by the die steel during the cycle is small, which can avoid the phenomenon of fatigue life caused by the large difference between the cladding layer and the substrate's expansion coefficient. The Cr of the cladding layer can generate chromium oxide with oxygen, thereby inhibiting the oxidation of the matrix structure and improving the TF resistance of the die steel. The cladding Co-based alloy coating on the surface of H13 hot work die steel, and conducted the same cold-heat cycle comparison test on the Co-based alloy coating and ordinary H13 steel, and found that ordinary H13 steel has obvious TF.

Measurement

The thin-film electron diffraction and extraction replication methods used to study the carbides and microstructures of H13 hot work die steel after different times of TF cycles.

RESULT AND DISCUSSION

The selective laser surface melting conducted of chromium-nickel alloy on H13 steel, and found that laser alloying has relatively low crack density and low oxidation corrosion in the thermal cycle test, so it has good TF properties. The remelted and alloyed the laser surface of H13 steel, and the results showed that this method can repair a larger proportion of hot cracks, while strengthening the network to obtain ultra-fine structure and better TF performance, and inhibit the hot cracking extension. Figure 2, shows the cracks, and Fe, Co, Cr oxides on the surface of the Co-based coating, and no obvious cracks.

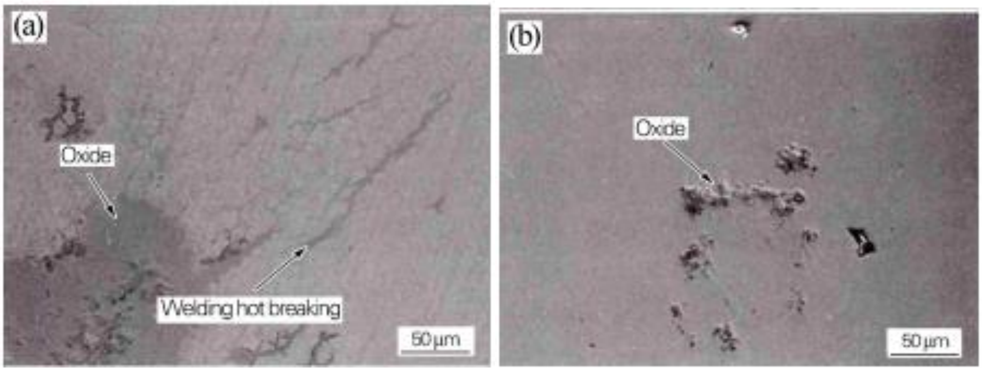

Figure 2. Surface morphology of H13 steel (a) and Co-based alloy coating (b) after 1000 thermal cycles

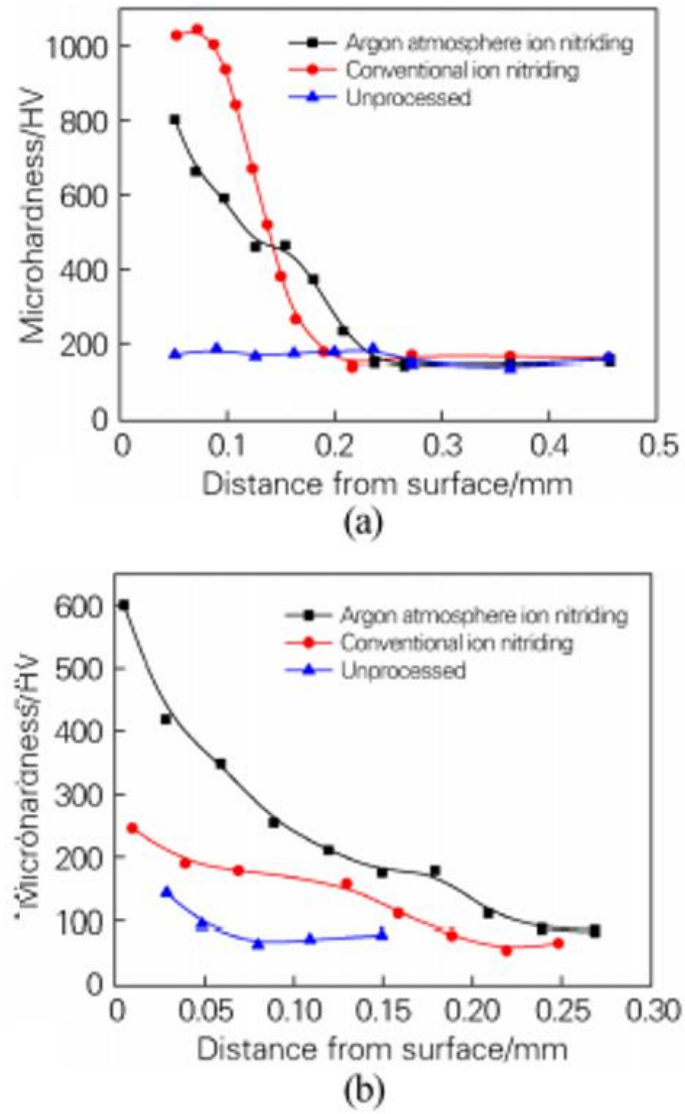

Figure 3. Hardness gradient of H13 hot work die steel without thermal fatigue cycle (a) and after 3000 thermal fatigue cycle (b) [18]

Figure 3 shows that the surface hardness was improved and the TF performance is improved by alleviating the hardness gradient of the seepage layer. Figure 4, shows the change of thermal stress along the radial distance when H13 hot work die steel is heated and cooled. The distribution chart shows that compressive stress produces compressive strain when heating, and tensile stress produces tensile strain when cooling, resulting in uneven thermal stress distribution. During thermal cycling, columnar cracks will be generated on the surface due to thermal stress and propagate in the axial direction. As the number of cycle's increases, the columnar cracks gradually coarsen and produce network branches, which eventually form TF cracks [23]. Therefore, the propagation direction of TF cracks on the surface of hot work die steel is controlled by thermal stress [13].

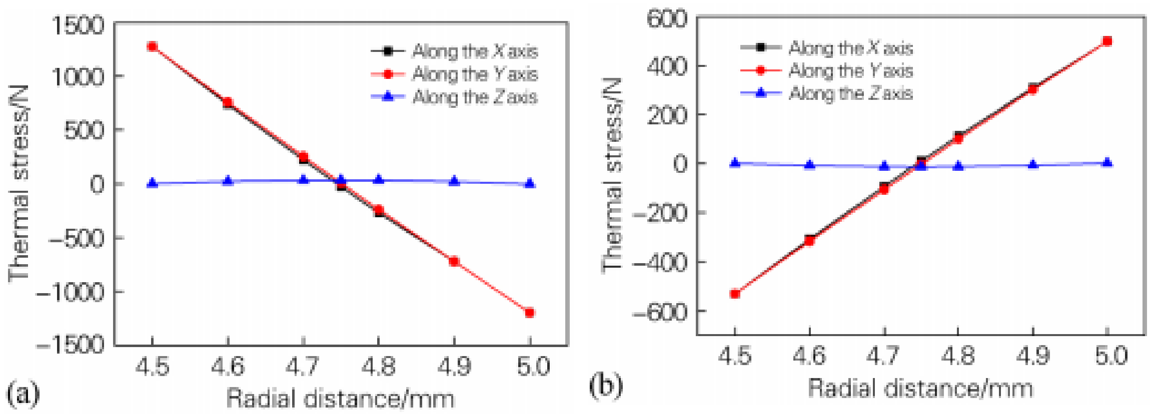

Figure 4. Thermal stress along radial distance of the H13 hot work die steel during TF cycle (a) during heating; (b) during cooling.

Figure 5, it can be seen that the creep in the early stage of crack growth makes the crack growth rate high, so the creep plays a leading role in the early stage of crack growth, and the crack growth caused by stress relaxation and TF plays a leading role in the later stage. The temperature-displacement coupling method used to simulate the change of the instantaneous temperature field at the crack tip, and found that the crack tip position and the crack propagation maximum heating point are consistent. There is a power function relationship between the crack tip temperature rise signal and the crack growth rate and the range of the stress intensity factor in the crack tip, which can quickly predict the TF life.

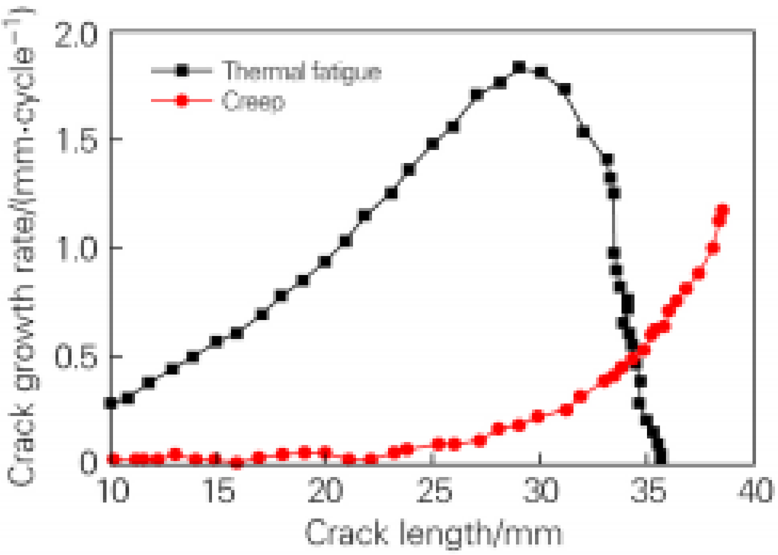

Figure 5. Crack growth rate of H13 steel under creep and thermal fatigue

CONCLUSION

The thermal fatigue performance of hot work die steel is the main factor that affects the service life of the die. Although scholars have conducted a lot of research on the initiation and propagation of TFC, the evaluation of thermal fatigue performance and measures to improve thermal fatigue performance, the following: 1) Research on the prediction of thermal fatigue life of materials, especially the use of computer technology to simulate the coupling of stress field and temperature field is relatively lacking. 2) The evaluation of thermal fatigue performance has developed from qualitative to quantitative, but there is no complete and systematic evaluation standard, so the evaluation standard of thermal fatigue performance needs to be further improved. 3) The thermal fatigue performance of die steel mainly depends on the internal structure. The growth theory of the second phase carbide in die steel and the law of influence on thermal fatigue performance need further research and improvement. 4) The use of innovative heat treatment processes and surface treatment methods can effectively improve the thermal fatigue properties of materials.

ACKNOWLEDGEMENTS

The authors would like to be obliged to Tikrit University for providing laboratory facilities and financial support

REFERENCES

[1] Z. Xiaoping, H. Xinbin, and J. Feng, “Thermal fatigue property of a new type hot-work die steel”, Heat Treatment of Metals, Vol. 36, No. 1, Pp. 107-109, 2011.

[2] X. Shuyang, Z. Pengpeng, and W. Xiaochun, “Effect of hardness on thermal fatigue of H13 hot work die steel”, Heat Treatment of Metals, Vol. 41, No. 8, Pp. 18-23, 2016.

[3] X. Pengcheng, C. Yunbo, and G. Xueyuan, “Research status and development trends of thermal fatigue property of hot die steels”, Heat Treatmenti of Metals, Vol. 33, No. 12, Pp. 1-6, 2008.

[6] W. Yaoli, S. Kexing, and Z. Yanmin, “A review on thermal fatigue behavior of hot working die steel”, Transactions of Materials and Heat Treatment, Vol. 39, No. 4, Pp. 1-13, 2018.

[7] S.S. Manson, “Fatigue: A complex subject—Some simple approximations”, Experimental Mechanics, Vol. 5, No. 4, Pp. 193-226, 1965.

[8] R. Monig, R.R. Keller and C.A. Volkert, “Thermal fatigue testing of thin metal films”, Review of Scientific Instruments, Vol. 75, No. 11, Pp. 4997-5004, 2004.

[9] A. Srivastava, V. Joshi and R. Shivpuri, “Computer modeling and prediction of thermal fatigue cracking in die-casting tooling”, Wear, Vol. 256, No. 1 /2, Pp. 38-43, 2004.

[10] D.A. Spera “What is Thermal Fatigue? [M]”. ASTM International, 1976.

[11] A. Persson, S. Hogmark and M.J. Bergstr, “Thermal fatigue cracking of surface engineered hot work tool steels”, Surface and Coatings Technology, Vol. 191, No. 2 /3, Pp. 216-227, 2005.

[12] M. Kamaya and S. Taheri, “A study on the evolution of crack networks under thermal fatigue loading”, Nuclear Engineering and Design, Vol. 238, No. 9, Pp. 2147-2154, 2008.

[13] H. Sehitoglu, “Thermomechanical Fatigue Behavior of Materials[M]”, ASTM International, 1993.

[14] C.M.D. Starling and J.R.T. Branco, “Thermal fatigue of hot work tool steel with hard coatings”, Thin Solid Films, Vol. 308, Pp. 436-442, 1997.

[15] D. Kundalkar, M. Mavalankar, and A. Tewari, “Effect of gas nitriding on the thermal fatigue behavior of martensitic chromium hot-work tool steel”, Materials Science and Engineering A, Vol. 651, Pp. 391-398, 2016.

[16] X. Luoping, W. Xiaochun, and S. Guangjie, “Effect of the tempering temperature on thermal fatigue behavior of 4Cr5MoSiV1 and 8407 steels”, Journal of Materials Engineering, No. 2, Pp. 3-7, 2001.

[17] P. Wenyi, W. Xiaochun, and M. Yong'an, “Study on thermal fatigue behavior of boriding layer of H13 steel”, Heat Treatment of Metals, Vol. 32, No. 12, Pp. 67-70, 2007.

[18] Y. Zeng, P.P. Zuo, and X.C. Wu, “Effects of mechanical strain amplitude on the isothermal fatigue behavior of H13”, International Journal of Minerals, Metallurgy, and Materials, Vol. 24, No. 9, Pp. 1004- 1009, 2017.

[19] Z. Xueyou, Z. Pengpeng, and H. Xijuan, “Effect of nitrogen content on thermal fatigue property of hot work die steel 4Cr5Mo2V”, Heat Treatment of Metals, Vol. 42, No. 1, Pp. 9-14, 2017.

[20] X. Xiao, W. Xiaochun, and S. Guangjie, “Thermal fatigue behavior in transversal and longitudinal directions in 8407 steel and 4Cr5MoSiV1 steel”, Journal of Shanghai University: Natural Science Edition, Vol. 7, No. 3, Pp. 261-266, 2001.

[21] W. Xiaochun, and X. Luoping, “Computer-alded evaluation for hot fatigue crack of model steel”, Shanghai Metals, Vol. 23, No. 6, Pp. 1-5, 2001.

[23] Y. Lu, K. Ripplinger, and X. Huang, “A new fatigue life model for thermally-induced cracking in H13 steel dies for die casting”, Journal of Materials Processing Technology, Vol. 271, Pp. 444-454, 2019.

[24] S. Cho, S. Park, G. Cha, and T. Oh, “Development of image processing for crack detection on concrete structures through terrestrial laser scanning associated with the octree structure”, Applied Sciences, Vol. 8, Pp. 2373, 2018.