FAILURE ASSESSMENT IN A H10 HOT DIE FORGING TOOL RELATED TO THERMAL FATIGUE

AMONDARAIN Zuriñe[1], MENDIA Leire[1], PEREZ Iñaki[1], LACHMANN Stefan[2]

[1]*TECNALIA Research and Innovation, Industry and Transport Division, C/Geldo 700, 48160 Derio (Bizkaia), Spain, EU,* zurine.amondarain@tecnalia.com

[2]*Schmiedewerke Gröditz GmbH, Riesaer Straße 1, 01609 Gröditz, Germany, EU,*

stefan.lachmann@stahl-groeditz.de

Abstract

A failure analysis has been performed to investigate the root cause for the rejection of the H10 (DIN 1.2365) hot work tool steel of the Hatebur forging machine. The punch is subjected to intensive thermal shocks, cyclically variable loads and high pressure at high temperatures. Although several surface defects are found related to different degradation phenomena, the higher thermal expansion occurred at the surface, compared with the inner part of the die, makes thermal fatigue the main failure responsible. In fact, thermal conductivity of an alloy will depend upon temperature and microstructure and therefore time and of course chemical composition. Damage analysis including dimensional control, surface analysis and metallographic analysis is completed by ThermoCalc and JMatPro calculations done for the standard 1.2365 tool steel. These are very useful tools to know in advance which are the stability ranges of the phases present (at equilibrium and non-equilibrium conditions), the elements in solid solution, the nature of the carbides, CCT curves and some other features for a better understanding of the failure analysis of the described system.

Keywords: failure, hot work tool steel, thermal fatigue, ThermoCalc, JMatPro

1. INTRODUCTION

Closed-die forging is a type of forging, where a billet with carefully controlled volume is deformed by a punch in order to fill a die cavity without any loss of material. Material flow over dies and punches causes a great thermal and mechanical interaction between dies and material. This interaction is the usual origin of die failures: abrasive die-wear, thermal fatigue, mechanical cracks and plastic deformation. Many of these phenomena often occur simultaneously and the correlations between them depend mainly on the design of the tools, the conditions in which they are forged and made, the heat treatment of the tool material and others.[1,2] Tooling life in hot forging operations is a main factor of production costs for long batches of forged parts. Forging temperature is usually around 1250°C and this results in die temperatures of about 300-400°C. As a result of cyclic forging operations, dies material fails. In this sense, failure mechanisms are the basis for establishing the steel requirements regarding mechanics, thermal stability and microstructure. For this reason minimizing the dies failure and increasing tooling life is a well-known challenge for forging process designers. Designing and manufacturing of hot forging dies and die materials selection are very important issues in the production of forged parts, because their cost represent around 15-20% of the parts final cost.[1]

The study case of the present work is the forging process of an automotive transmission part. This process is divided in four stages, being the final the most critical one, because dimensions must be obtained according to previously defined tolerances. The punch, which is made of DIN 1.2365/AISI H10 case hardened by nitriding, is used in the forging process and it is the most critical die due to its complex shape and the loads it has to support. The punches are rejected after the manufacture of 6000-7000 parts. In the present failure analysis two used punches (U1 and U2) and a new one (N1) are studied.

2. EXPERIMENTAL

2.1 Failure Analysis

To evaluate the importance of each failure mechanism a full analysis has been performed regarding a macroscopic inspection, dimensional control, surface analysis by scanning electron microscopy (SEM), metallographic analysis, mechanical and chemical characterisation. The used punches (U1 and U2) present different types of defects (Fig 1) on the working surfaces: surface roughness, cracks, marks related to the area of the gas outlet and a dark colouration on the whole surface due to oxidation. Areas with a polished appearance are also visible and this is coherent with the operation of wear mechanism related to the tool movement and the friction created between the tool and the part.

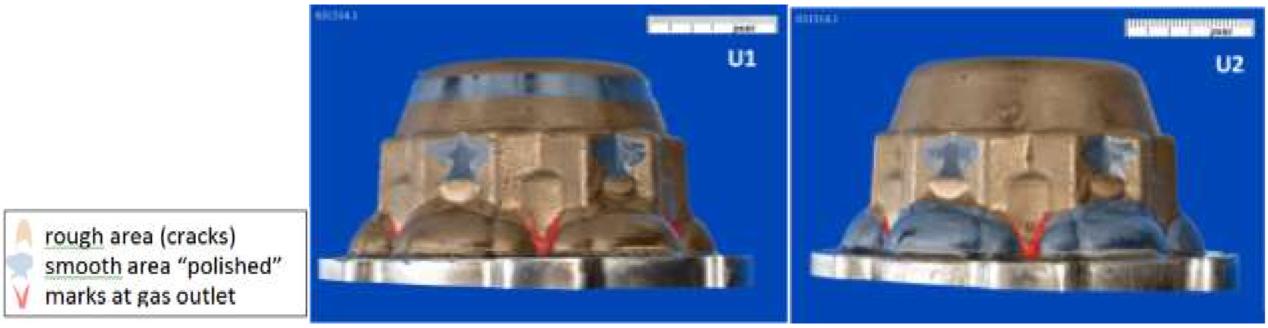

Fig 1. Defectology present in the working surfaces

Areas with a higher roughness have a crazed appearance and given the working conditions of the parts (temperature and stress cycles) the cracks that appear in these areas are related to thermal fatigue. In fact, SEM analysis reveals cracks of different sizes that form crack nets and they are not only longitudinal but also transversal. The finer crack nets are associated to areas with a polished surface which probably only affects the oxide layer while the areas with high roughness have coarser crack nets which suggest a greater length of the cracks (Fig 2).

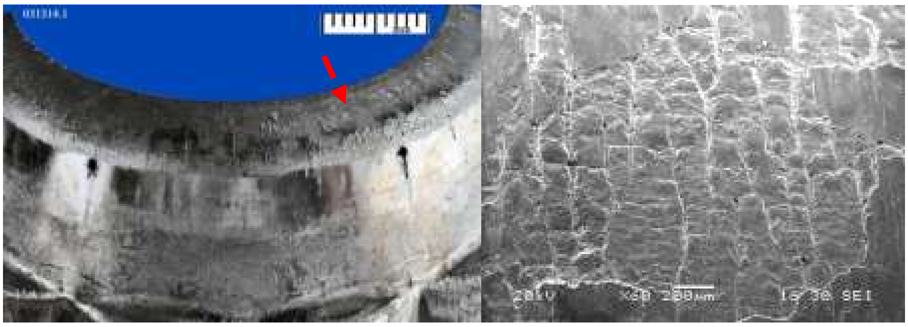

Fig 2. SEM micrograph of cracks net and oxides on ref. U1

The presence of cracks with different sizes points to the operation of a mechanism extended in time as it is the case of thermal fatigue. Moreover, the transversal analysis of some sections of the punches have revealed the presence of cracks in all of them. The triangular morphology of the cracks, their progression perpendicular to the surface and the presence of oxides inside them confirm the operation of a thermal fatigue or heat checking process (Fig 3). Due to the intensive thermal cyclic loads, produced by the alternate heating and cooling of the tool surfaces, the material is alternately tensioned and compressed whereby thermal stresses arise resulting in a network of cracks producing thermal fatigue. In fact, there is a greater thermal expansion at working surfaces than in the inner side of the die. This expansion difference causes plastic deformation at the surface which results in tensile stresses and cracking during cooling. In addition, the presence of cyclically variable mechanical loads lead to fatigue processes, which intensify as the network of cracks caused by thermal fatigue appears, resulting in macrocracks. Since the mechanisms of thermal fatigue and those of mechanical fatigue are mutually dependent, they are considered jointly as thermomechanical fatigue. This is a kind of wear in which a local loss of cohesion and the resulting material loss are caused by material fatigue due to the cyclic action of stresses (generated by high pressures, i.e. mechanical loads and temperature gradients) in the forging die surface layer [3,4,5].

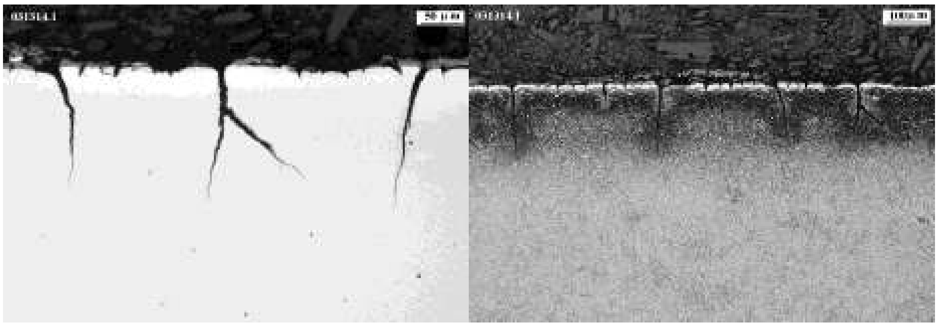

Fig 3. Light micrographs of ref.U1. Left image: presence of triangular cracks and oxides filling them. Right image: etch condition, presence of a nitrided layer

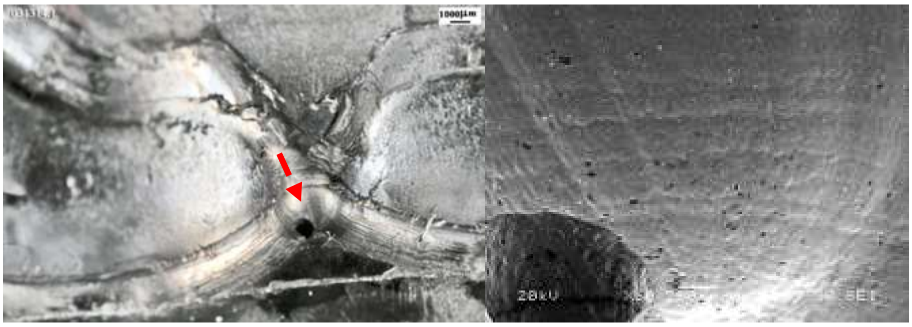

Fig 4. SEM micrograph. Presence of marks attributed to an erosion process

Some other defects are found in the area close to the small holes that serve as gas outlet (gas channels). Due to the morphology of the marks and cavities analysed by SEM (Fig 4), it is confirmed that these surface defects correspond to an erosion failure mechanism. In order to evaluate the level of wear and the presence of plastic deformations a dimensional control has revealed no significant change dimensions after use which concludes a minimum effect of a wear mechanism and plastic deformation. However, at microscopic scale the punches surfaces present patterns characteristic of the operation of this mechanism: plucked away material, plastic deformation of asperities and marks aligned with the relative movement. The nitridation layer depth of the punches is approximately 0.16 mm and has a diffusion layer with a similar thickness along almost all the surface. This fact confirms the minimum effect of the wear mechanism. However, there are some areas where the white compound layer is eliminated and the hardness is reduced.

2.2 ThermoCalc and JMatPro calculations

Phase evolution analysis as a function of temperature is done by ThermoCalc and JMatPro for standard 1.2365 steel grade. The calculations done by ThermoCalc assume equilibrium. The phase combinations at a given temperature in a given alloy have the lowest energy possible and have had sufficient time to attain that state. However, in real tool steels processing often there is insufficient time for the alloying elements to completely partition themselves between the various phases by solid state diffusion. Thereby, equilibrium calculations represent the phases which are at the beginning and at the end of the process. Martensite, which is the main microstructure of the H10 tool steel after the corresponding thermal treatment, is a non-equilibrium phase that is predicted by JMatPro. During the austenite-martensite diffusionless transformation, the carbon and the alloying elements are directly incorporated and inherited into the martensite. The temperature range where austenite and martensite coexist is important for a correct heat treatment design. In this sense, Ms is directly affected by the presence of alloying elements, in fact, they lower the Ms temperature. Below this temperature martensite coexists with austenite and it increases with decreasing temperature. Afterwards, when martensite is tempered, the supersaturation of carbon is relieved by carbides precipitation. At tempering temperatures where alloy elements are able to diffuse, alloy carbides precipitate. When introducing strong-carbide forming elements new phases can be introduced and may dramatically change phase equilibrium in tool steels. The simulations performed by ThermoCalc and JMatPro will help understanding all the aforementioned facts. The chemical composition of the material (U1) is in accordance with the specifications for a 1.2365 steel grade according to UNE-EN ISO 4957 (Table 1).

Table 1 Chemical composition of ref. U1, A_3 and $M_{23}C_6$ and M_6C precipitation temperatures

REF	Chemical Composition									A_3(ºC) ThermoCalc	A_3 (ºC) (1K/s) JMatPro	T(ºC) $M_{23}C_6$	T(ºC) M_6C
	C%	S%	Si%	Mn%	P%	Cr%	Mo%	V%	N%				
U1	0.31	<0.01	0.32	0.3	0.016	2.9	2.7	0.4	0.0077	863	866	797	629

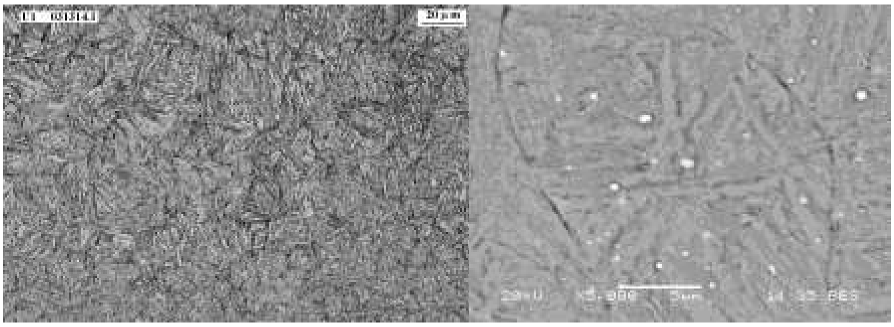

Fig 5 Left image: light micrograph of a longitudinal sample ref.U1: martensitic and bainitic microstructure. Right image: presence of carbides

The metallographic analysis reveals that the microstructure of the new punch corresponds to a quenched and tempered material (3 times) that has a martensitic and bainitic structure with finely dispersed carbides. When examining the microstructure of the used punches no visible evolution due to thermal cycling is found, the matrix remains being martensitic and bainitic as shown in Fig 5. EDS analysis of the carbides reveals that they are formed mainly by molybdenum carbides, with presence of chrome and vanadium.

The calculations done for 1.2365 standard grade by ThermoCalc show that Ac3 is approximately 860ºC, and that the main carbides are $M_{23}C_6$ ones, but also M_6C carbides are present being mainly M=Mo. Although Cr is the main element in the $M_{23}C_6$ carbide type, which is known to have high coarsening kinetics [6], it is remarkable that a considerable wt% of Cr still remains in solid solution. On summary, the actual chemical composition of the punches is prone to high coarsening kinetics carbides precipitation, having high contents of Cr in solid solution, low contents of M_6C carbides precipitation, which have good stability for secondary hardening and low coarsening kinetics. It is known that the tempering resistance of hot work tool steels is improved if the amount of carbides for precipitation by secondary hardening is high and it is also dependent on another important feature such as the stability of the carbides. This stability depends itself on carbides precipitates size and distribution, and on their resistance to coarsening and coalescence. Studies have shown that Cr rich carbides such as M_7C_3 and $M_{23}C_6$ can easily coalesce and coarsen while increasing molybdenum content generates more stable carbides.[6] Besides, CCT curves reveal that the steel grade is prone to martensite formation as shown in Fig 6, but a little presence of bainite microstructure is also found, which agrees with the JMatPro calculations. On austenising temperature secondary carbides decompose, thereby releasing alloying elements, which are substitutionally dissolved and carbon is interstitially dissolved in the austenite lattice. During cooling, these substitutionally dissolved carbide forming elements improve the hardenability, reducing the rates of the diffusion controlled pearlite and bainite formations.

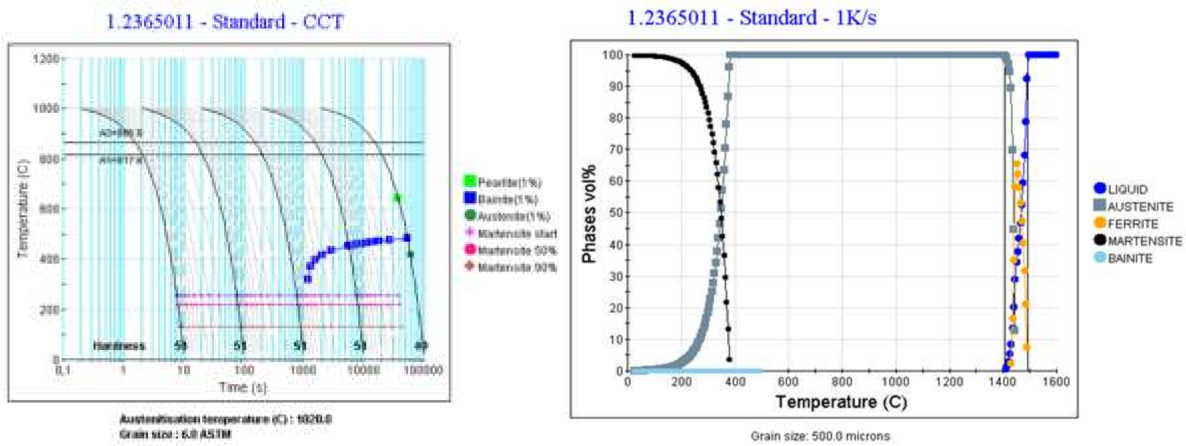

Fig 6 CCT-diagrams and phase stability diagram of 1.2365 (JMatPro Calculations)

If during quenching, besides martensite, also bainite and pearlite are obtained, toughness and tempering resistance might be reduced. Further triple tempering has the purpose of (i) to transform retained austenite, if present (ii) changing the martensitic structure towards quasi-equilibrium where carbides are formed and (iii) stress relieving introduced by quenching and as a result proper toughness and ductility is obtained. As said before, martensite plays an important role in the evolution of tool steel microstructure by presenting a supersaturated matrix structure for carbide precipitation and secondary hardening.

Very in line with the microstructure evolution and the failure analysis results, it is known that there is a direct relation between the phases and the thermal conductivity of the steel grade. Without changing composition, a large number of different compositions can be achieved, having different constituents of different compositions and distributions.[7] Since there is a large effect on thermal conductivity by any disturbance of the periodicity of the lattice, the temperature and thermal history of steels can be expected to greatly influence conductivity, thus thermal conductivity of an alloy will depend upon temperature and microstructure (therefore time). Alloying elements promote lattice distortions and cause disturbances as it happens in the case of metals where electrons provide additional contribution to the thermal conductivity. The thermal conductivity of steel alloys diverge as temperature is decreased, pure iron having the highest thermal conductivity and followed by carbon steels, alloy steels and then by high alloy steels. High alloy steels have lower thermal conductivities at normal ambient temperatures than at higher temperatures [8]. Miettinen [9] has developed special algorithms and has shown that there is a direct relation between thermal conductivity value and some elements at a temperature region, which concludes that there is a direct relation between chemical composition of the steel grade and the thermophysical value but the effect of cooling on resulting microstructures and the presence of special types of carbides must also be considered.

CONCLUSIONS

Punches do not present any significant deterioration by wear nor by plastic deformation, as it has been proved by the dimensional control and, in the case of wear, by the thickness of the nitrided layer. Deterioration of the punches is caused by the formation of cracks originated by thermal fatigue evidenced by the presence of multiple cracks perpendicular to the surface. Both oxidation and thermal stresses are coherent with the operating conditions of the punches: high temperatures and thermal cycles. The fatigue mechanism is leaded by the differences in thermal expansion between the die surface and its interior. Thermal conductivity controls the magnitude of the temperature gradients that occur in components during manufacture and use and depends on the constituents of the matrix which may affect negatively this value. The microstructure of the material, with a martensitic and bainitic matrix, is consistent with a quenching and tempering heat treatment.

High alloyed steels are prone to low thermal conductivities, and it is known that this property depends on lattice distortion. It turns out from ThermoCalc and JMatPro calculations that some factors are known to distort the martensitic (and bainitic) lattice: the presence of some elements in solid solution (as it is the case of Cr) and $M_{23}C_6$ Cr carbides, which have high coarsening kinetics and may also affect tempering resistance. M_6C carbides are also present, which are rich in Mo and good for secondary hardening. On summary, heat checking resistance, probably the main factor limiting the life of the punches, can be improved by actuating on: top operating temperature, cooling rate and die lubricant, thermal cycle and die material. In the latter, the evolution of the constituents due to alloying elements and thermal treatment are important factors that are known to affect the thermal conductivity and the thermal fatigue resistance of the hot work tool steel.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union's Research Programme of the Research Fund for Coal and Steel (RFCS) under the grant agreements of TOOLSTEEL (RFSR-CT-2014-00033)

REFERENCES

[1] ALTAN T. Cold and Hot Forging Fundamentals and Application. ASM International, Ohio, 2000.

[2] GRONOSTAJSKI Z., HAWRYLUK M. The main aspects of precision forging. Archives of Civil and Mechanical Engineering, Vol. 8, No. 2, 2008, pp.39-55

[3] KIM T.H, KIM B.M., CHOI J.C. Prediction of die wear in the wiredrawing process. Journal of Materials Processing Technology, Vol. 65, No 1-3, pp.11-17, 1997.

[4] PELLIZARI M., MOLINARI A., STRAFFELINI G. Thermal fatigue resistance of plasma duplex-treated tool steel. Surface and Coatings Technology, Vol. 142-144, pp.1109-1115, 2001.

[5] PERSSON A., HOGMARK S., BERGSTRÖM J. Thermal fatigue cracking of surface engineered hot work tool steels. Surface and Coatings Technology, 191, pp. 216, 2005.

[6] PICKERING F.B. The properties of tool steels for mould and die applications. In Tool materials for molds and dies. Proceedings of an international conference,1987, pp.1-32.

[7] VALLS I. High thermal diffusivity and high wear resistance tool steel. Patent EP 2 476 772 (A1) 2012.

[8] POWELL R.W., HICKMAN M.J. Thermal conductivity of a 0.8% carbon steel. Journal of the Iron and Steel Institute 154, 1946, pp.112-116.

[9] MIETTINEN J. Calculation of Solidification-Related Thermophysical Properties for Steels, Metallurgical and Materials Transactions B, Vol 28B, 1997, pp.281-297.