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Preliminary Failure Examination of a Plastic-Injection Mould Part

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ABSTRACT

The paper studies the failure of a mould-part for the hot-forming of plastics, by injection. The mould's component was manufactured from AISI H13 and was intended for the production of plastic cups for cylindrical aluminium cans, used for coffee packaging. The tool belongs to a system that produces simultaneously four pieces per cycle. It exhibited a single uniform through thickness crack, after five millions working-cycles, where the lifetime was expected to be ten millions cycles. The paper refers to the preliminary examination of the failed tool surfaces. Data concerning the manufacture, processing and operation of the part were collected and a complete photographic file was created. Non-destructive testing was performed, including hardness measurements, inspection with fluorescent penetrating fluids. Chemical analysis was carried out and the material used to make the tool was identified. The paper presents conclusions on the crack initiation and propagation and the main causes that led to the premature failure.

KEYWORDS: failure analysis, tool lifetime, hot working die, moulding tool

1. Introduction

Tool steels are an important class and are primarily used to make tools used in manufacturing processes as well as tools for machining metals, woods, and plastics. According to the final application the tool steels are divided in hot-work tool steels, cold-work tool steels, high-speed tool steels, shock-resistant tool steels, special-purpose tool steels and water-hardening tool steels [1].

Hot- work tool steels are used for applications in which process temperature is an important parameter for the machining of the tooling material. In consequence, they must be of a very high quality. Usually, they are alloyed and used after hardening and tempering, with or without surface-coating. Among the hot work tools, dies are the most critical components, due to their high manufacturing cost, very fine dimensional tolerances and high demands on repeated thermo-mechanical performance [2]. During the operation a die is subjected to cyclic temperature changes and to increased stress and deformations. In consequence, it must present specific mechanical properties, such as: high hardness and hardness stability at temperatures as high as 600°C, good hardenability, good temper resistance, high strength at elevated temperatures, good toughness and wear resistance [3]. The toolmakers provide a wide range of high grade steels that cover the specific requirements for a determinate time (the die's lifetime). AISI H13 is the most common steel used for hot working dies. It is chromium-molybdenum-vanadium-alloyed steel and by special processing techniques and close control, it can attain high purity and a very fine structure [4]. Since technologies evolve continuously and hot working tools are subjected to increased stresses the tools-failure continues to occur. Material failures can lead to many potentially disastrous consequences and every case mast be elucidated.

The objective of failure analysis is to identify and explain the causes leading to premature damage and also to determine and correct their root causes [5]. Dies present two main failures: fracture and deformation. Failure due to fracture are catastrophic and present more interest for researchers [6,7]. The fracture, prior to achievement of the minimum production, increases costs. Sudden and premature die destruction after installation interrupts production. The analysis of die failure plays an important role in the prediction and prevention of similar situations and gives the possibility to extend and enhance the life of the tool [8]. A few articles are available in literature presenting failure analysis based on a substantial number of samples of real die breakdowns. Arif studied 616 die failures involving 17 die profiles made of AISI H13 steel [9]. He concluded that the predominant failure mode was fracture, 43%, followed by wear, 26%, deflection, 19%, mixed mode, 45%, miscellaneous, 2%, and mandrel-related, 3%. The major fracture-type failure was due to tracking/breaking of the brush path, the main wear-related one was of the dimension change variety, and the foremost deflection failure was located at the bearing. Continuous improvement of die error correction and careful elaboration of materials used for their manufacture is continuously changing percentages.

This paper refers to preliminary examination of a hot working die that presented premature failure**.**

2. Experimental Details

A die was produced for hot-forming by injection. The die is part of a moulding machine that consists of four components, and produces simultaneously four pieces per cycle. One of the four components failed during the production operation. The paper presents results from the preliminary examination of the tool's damaged surfaces. In some cases, the results are relevant at this stage and permit to deliver immediately practical solutions to the problem associated with the respective failure mode.

The first step was to gain a good understanding of the conditions under which the part was operating [10]. Recorded history was collected, with data concerning the material's selection, manufacturing and final heat treatment.

The second step was to conduct a visual examination, cataloguing and recording at the same time the physical evidence. The visual examination gives to the investigator the opportunity to examine the damaged surfaces in detail and try to identify the mode of fracture initiation points and the direction of their propagation. Samples were examined, photographed and sketched taking particular care of identifying and recording any area of particular importance, such as cracks or surface defects. The failed parts were firstly examined and recorded before any surface cleaning was performed. In some cases substances such as dirt, paint and oil on the surface can be important clues, indicating the 'age' of the fractured surface and the environment in which the part was operating. Photographs were taken in delivery condition.

The third step was to decide on a course of action. There are several resources that an investigator can draw on, to determine the cause of failure. In this case, samples were collected and prepared for preliminary observation. Non-destructive testing was performed, including inspection with fluorescent penetrating fluids and hardness measurements. Rockwell C hardness measurements were made on the back side of the part, in accordance with the ASTM standard [11]. Visual examination was aided by using a stereoscope. Chemical analysis was also carried out and the material used to make the tool was identified.

The paper presents conclusions on the state of failure, the crack initiation and propagation, and the main causes that led to the premature damage of the die. The paper develops appropriate suggestions and remedial strategies.

3. Results and Discussion

A mould was intended for the production of plastic (PVC) cups for cylindrical aluminium cans, used for coffee packaging. The plastic cup is also marked, by mould-printing, with the logo of the customer company.

Prior to the failure, the mould performed two hundred million (200,000,000) working-cycle, producing eight hundred million (800,000,000) pieces (cups). Close inspection revealed extended fatigue marks on its surface.

The mould consists of four cavities. Four components (inserts) are installed in these cavities, for the product moulding. The forming components were made of Orvar Supreme tool steel (AISI premium H13), which was delivered by Uddeholm Company. The designed lifetime for the components was ten million (10,000,000) working-cycles. When a component is incapable of producing the accepted product quality, it is replaced by a new one.

The failure occurred in one of the four forming components, after five million (5,000,000) cycles, just in the middle of the predicted lifetime.

At normal working conditions, the plastic is injected into the mould components at a temperature between 170^{o} and 180^{o} C. The mould is cooled down with water at a temperature of 25^{o}-40^{o} C. The cooling water is provided by a bore and is rich in salts. The salt reduces significantly the cooling capacity.

The recorded history revealed that the following machining and heat treatments were applied for the manufacture of the mould's component:

-Machining was performed by the same company which used the final mould. Rough turning from a diameter of 65mm was made using cutting depth up to 0.5mm, prior to the final dimensions. The die-holes were made by milling.

-After machining, the piece was heat treated by a qualified company to a final hardness of 50-53 HRC. The following heat treatment cycle was followed: first preheating at 650^{o}C for 30 min, second preheating at 850^{o}C for 30 min, quenching at 1030^{o}C for 40 min., cooling in a martempering bath at 500^{o}C for 10 min and then freely in air down to 50^{o}C and then cleaning with hot water. Hardness after hardening was 53 HRC. First tempering at 550^{o}C for 2 hours and air cooling to room temperature, second tempering at 620^{o}C for 2 hours and air cooling to room temperature, and finally third tempering at 590^{o}C for 2 hours and air cooling.

The obtained final hardness was 48-50 HRC, i.e. lower than the expected value. This hardness reduction resulted from the decarbonisation of the surface (i.e. local loss of carbon) during the heat treatments. The obtained hardness was accepted considering that the surface layer would be removed at the final grinding stage, revealing the bulk material with required hardness.

-After the heat treatments, the piece was returned to the manufacturer for the finishing process. (i.e. fine grinding and polishing).

-Fine turning was carried out using a maximum cutting depth of 0.2mm.

-Electrical-discharge Machining (EDM) was performed for the engraving of the customer company logo and the machining of the hole for the plastic injection.

-Grinding and polishing were made manually.

Initial visual inspection of the tool revealed a cylindrical complex shape with several changes in diameter. In the centre of the moulding surface (the face), the company logo was engraved (Fig.1a). The surface appears polished but exhibits some small round corrosion marks close to the surface edge (point I on Fig.1a).

In the centre of the part, there is a hole, through which the plastic is injected into the mould for the production of the piece by pressing. Around the hole, the steel exhibits a colour alteration as if it has been burned (point I on Fig.1). This indicates that the material has been locally subjected to a significant temperature increase. After stopping the moulding machine operation, an amount of molten plastic remains in the injection hole. This plastic should be cleaned immediately; otherwise it solidifies and blocks the injection hole. Obviously the operator does not clean the part instantly and in order to remove the plastic from the injection hole, he uses a turbo gas to re-melt it. The blaze induces significant temperature increment at the specific area and thus, the steel is locally burned. As a result, the strength of the component is reduced around the plastic injection area.

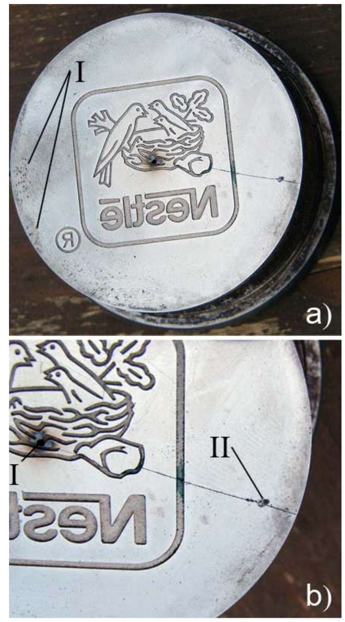

Fig.1. *Tool's face (pressing surface) :(a) General aspect; (b) Detail*

The examined mould-part exhibited a single crack on the surface that was visible to the naked eye, and expanded from the injection hole towards the edge. The crack path led to partial material detachment (point II on Fig. 1b).

The 'back face' of the tool has three holes; a big one in the centre and two smaller close to the edge (Fig. 2a).

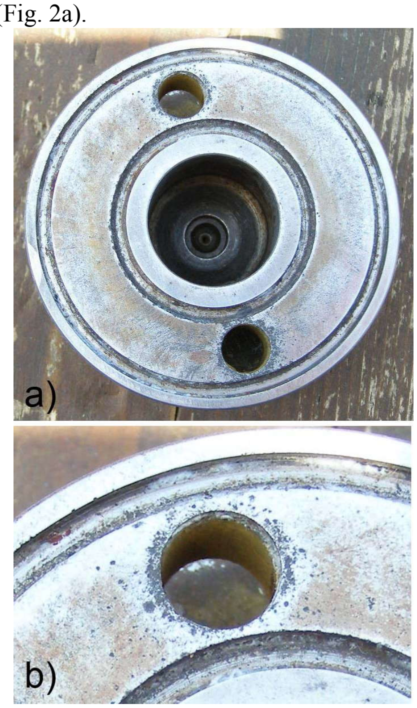

Fig. 2. *Tool's back face: (a) General aspect (b) Detail*

Through the central hole, the molten plastic is injected, whereas through the other two small holes the cooling mean (water) is circulated. Between one of the small holes and the injection hole, a crack was observed, propagating vertically from one end to the other. The part has also two round grooves; a shallow and a deep one. These grooves separate the cooling area from the injection area. Insulation is ensured by O-ring washers. Around the cooling holes and the grooves, significant corrosion marks were observed (Fig. 2b).

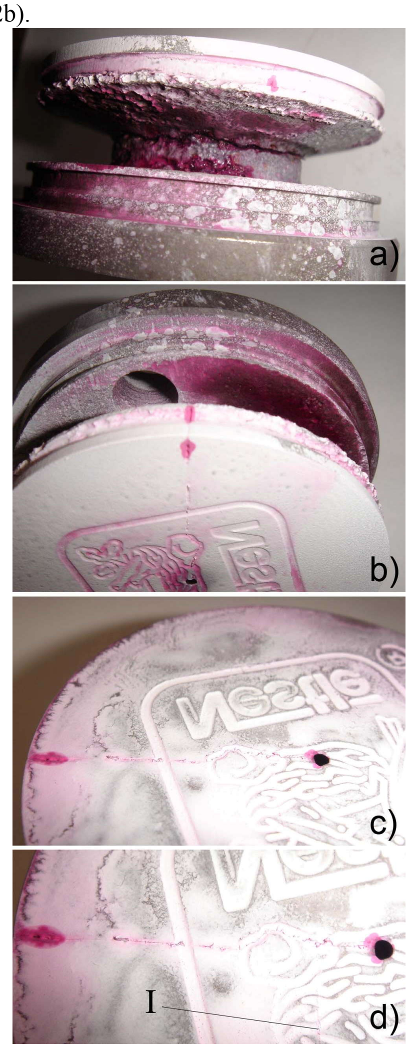

Fig. 3. *Tool's side view (a) General aspect (b) Detail*

The side view of the component shows considerable cross-sectional changes (Fig. 3a). Two grooves have been made for the proper positioning of the component onto the mould. A small hole has been drilled on the larger diameter, for mounting purposes.

The component has smaller diameter in the centre to allow water circulation during operation for cooling. The circumference of this cooling area shows extended material damage from corrosion; while in the corrosion-free regions the surface has high roughness. In the centre of the piece and around the circumference of the cylindrical surface a wide crack has been developed (Fig. 3b).

Inspection with penetrating fluids allows the exposure of cracks that are not visible to the naked eye, as well as their propagation path (Fig.4). Red penetrating fluid was intentionally selected to facilitate the observation. The crack follows the course surface presenting the lowest resistance (i.e. the points of maximum surface roughness).

The tool exhibits a main crack that appeared on the cylindrical surface of the cooling area (Fig 4,a). This crack grows towards the engraved mould surface (Fig 4,b), and then propagates from the edge of the piece through the stamp grooves, to end up at the central hole (Fig 4,c,d).

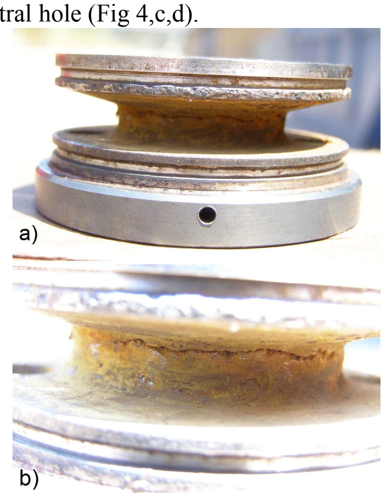

Fig. 4 *Inspection of tool using penetrating liquids: (a) Side view, (b) Side view detail, (c) Engraved mould surface, (d) Mould surface detail*

A secondary crack develops from the main crack and almost vertically to it; and extends to the mould area (point I on Fig 4,d). During the rapid crack propagation, from the internal cooling surface towards the central hole, the crack passes through the mould surface. At this point, the engraved stamp acts as an obstacle for the crack growth; whereas from the other side it acts as a preferential path of a high residual stress density. As a result, secondary cracks have been developed. Stereoscopic examination of the tool surface revealed these secondary cracks and their growth direction (point I on Fig.5). The selected magnification allowed the identification of the small fractured zone. The face of the die also presented a few areas of material loss (point II on Fig.5). This can be attributed to the fact that the face surface is strained - due to the engraving process – and therefore the crack initiation caused the material detachment.

Hardness measurements were carried out at corrosion-free points of the back side of the tool (i.e. the injection area). Figure 6 presents the hardness indentation topography. The following hardness values were obtained: (1) 49,6HRC, (2) 49,6HRC, (3) 50,5HRC, (4) 50HRC and (5) 49,5HRC. The tool presents a uniform hardness of 50HRC; i.e. the expected value after the heat treatment cycle. This indicates that the decarbonised layer was indeed very narrow and was removed during the final machining of the component. Therefore, since the designer's requirements were fulfilled, the selected heat treatment cycle can not be responsible for the failure.

Fig.5. *Tool's face examined with stereoscope*

Chemical analysis was carried out for material identification and assessment of its suitability for the specific application. The tool was made of AISI premium H13 (W.Nr. 1.2344). The steel was supplied by Uddeholm Company under the commercial name Orvar Supreme [12]. Orvar Supreme is a chromium-molybdenum-vanadium-alloyed tool steel suitable for hot-working applications. Its main characteristics include high level of resistance to thermal shock and thermal fatigue, good high-temperature strength, excellent toughness and ductility in all directions, good machinability and polishability, excellent through-hardening properties, good dimensional stability during hardening. The combination of these characteristics offers steel suitable for the manufacturing of tools. Consequently, the material selected was the right one, and cannot be accountable for the failure.

The chemical composition of the material used and the nominal composition given by Uddeholm Company and by Standard Specifications [13] are presented in Table 1. In fact, chemical analysis revealed that the die was made of AISI premium H13 tool steel (Orvar Supreme) and the material delivered was the right one.

Fig. 6. *The hardness measurement points*

Table1. *Chemical analysis of the steel*

Steel / Composition		Tool's composition	Orvar Supreme Uddeholm composition	Standard DIN composition
Component [%]	C	0.337	0.39	0.35-0.42
	Si	0.851	1.10	0.80-1.20
	Mn	0.405	0.40	0.25-0.50
	Cr	5.194	5.20	4.80-5.50
	Mo	1.195	1.40	1.20-1.50
	V	0.790	0.90	0.90-1.10

4. Conclusions

The preliminary examination of the mould-component led to the following conclusions:

The material selected for the manufacture of the die (i.e., AISI premium H13 steel) Is considered one of the most suitable steels for hot working moulds. Chemical analysis confirmed the composition and quality of the material; indicating that it was not responsible for the failure.

The required final hardness after quenching and tempering was designed to be 50÷53 HRC. Hardness measurements made immediately after the heat treatments revealed slightly lower hardness, resulting from a decarbonised layer on the tool surface. This layer was proved to be very narrow and was removed completely during the final machining (fine-grinding). The bulk material exhibited the required hardness, i.e. 50 HRC. Consequently, the applied heat treatment cycle was not responsible for the failure.

The failure was caused by a main crack which initiated at the internal surface of the cooling area of the component. This crack propagated towards the mould-surface and ended at the injection-hole point. Generally, cracks' preferential paths are areas which exhibit reduced strength (i.e., EDM engraved stamp, sharp edges, fine geometrical configurations such as the plastic injection hole). The following factors are responsible for the crack development and the failure of the mould-component:

- The internal cooling surface of the component did not have the appropriate radii. In fact, when a tool has considerable cross-sectional changes (i.e. diameter variation), these should be accompanied with suitable radii formation during machining. The role of the radius is to eliminate the local stress concentration. In the present case, it is not yet clarified whether this error comes from the designing or the manufacturing stage.
- The cooling area of the component exhibited poor quality of the surface, with increased roughness. The smoother the surface, the better the flow and circulation of the cooling performance. In the opposite situation, surface irregularities can convert the regular liquid flow to turbulence. During this type of flow, the cooling agent (i.e., water) may remain stable for a period of time (i.e., poor circulation). As a result, the cooling of the component is insufficient and the local temperature increment causes material expansion. In case of regular water flow, the same area is cooled down rapidly and contracts. Obviously, during operation the component was subjected to continuous expansion and contraction cycles that caused extensive material strain (because of the thermal shocks) and led to the crack initiation.
- The quality of the cooling agent also plays an important role. The water used in the specific application was rich in salts, causing considerable material corrosion. Corrosion increases the surface roughness, hinders the regular water flow, intensifies the thermal shocks and removes material from the particular area, reducing locally the strength.

In addition, improper maintenance of the moulding machine was noticed. As mentioned earlier, between the operation shifts (i.e., when the machine stops completely), the remaining amount of the injected plastic was removed from the injection hole using a blaze. The local temperature augmentation caused material burning, as demonstrated by the colour variation on the surface of the component. Inappropriate regular maintenance cannot be considered as the main reason of the specific failure, but has been proved to reduce the effective tool lifetime.

Bibliography

1.. **Tool Steel Facts:**" *Uddeholm High performance Tool Steel*", Uddeholm Company, Belgium, pp.9, 2009.

2. **Valberg, H.:** *" Extrusion welding in aluminium extrusion",* Int. Z. of Materials and Product Technology, Vol.17, Nr.7, pp.497-556, 2002.

3. **Pradip, K.S.:** *"Aluminium Extrusion Technology",* ASM International Handbook, Ed. by Metals Park, Ohio, pp3-24, 2000.

4. **Tool Steel Facts:**" *Hot work tool steel, Bohler W 302*",Bohler Company, Austria, pp.3-11, 2002.

5. **I. Canale, C. F., Mesquita, R. A., Totten, G. E.:** *"Failure Analysis of Heat Treated Steel Component"*, ASM International, Ed. by Material Park, Ohio, USA, pp.311-350, 2008.

6. **Tseronis, D., Sideris, J.F., Medrea, C., Chicinas, I.:"** *Microscopic examination of the fracture surfaces of an H 13 hot extrusion die due to failure at the initial usage stage",* Key Engineering Materials,Vol.367, pp.177-184, 2008.

7. **Pradip, K.S.:** *"Aluminium Extrusion Technology",* ASM International Handbook, Ed. by Metals Park, Ohio, pp3-24, 2000.

8. **DAS, A. K.**: *"Metallurgy of Failure Analysis - Types and Characteristics",* edited by Mc Grow-Hill Companies, New York, pp.67-75, 1997.

9. **Arif, A.F.M., Sheikh, A.K., Qamar, S.Z.:** " *A study of die failure mechanism in aluminium extrusion",* Journal of Materials Processing Technology, Elsevier, 134, (2003), 318-328.

10. **Davidson, T.:** *"An Introduction to Failure Analysis for Metallurgical Engineers",* TMS Outstanding Student Paper Contest Winner- Undergraduate Division, 1999.

11. **ASTM E-18-03:** *"Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials" (*editionally revised in June 2004).

12. **Tool Steel Facts:** *" Manual Orvar Supreme",* Uddeholm Company, Belgium, pp.3, 2000.

13. **Wegst, C. W.:** *"Nachschlagewerk Stahlschlüssel",* Verlag Stahlschlsüsel Wegst GmbH &Co, Marbach, Germany, pp.169, 2004.

Examinarea anterioară ruperii a unui reper injectat din plastic

Rezumat

În această lucrare se studiază ruperea unui reper turnat realizat prin injectare. Componenta turnata a fost realizată din AISI H13 şi intră în componenţa cutiilor de aluminiu utilizate pentru ambalarea cafelei. Scula face parte dintr-un sistem care produce simultan patru repere la fiecare ciclu. Aceasta prezintă o fisura printr-un material de grosime uniformă, după cinci milioane de cicluri de lucru, în timp ce durata de viață aşteptată este de zece milioane de cicluri. Lucrarea analizează examinarea suprafeței sculei, anterioară ruperii. Au fost colectate date privind fabricarea, procesarea şi operațiile efectuate asupra reperului şi a fost creat un fişier de imagini complet. Au fost realizate teste nedistructive, inclusiv măsurarea durității şi controlul cu lichide penetrante fluorescente.

Au fost realizate analize chimice pentru identificarea materialului sculei.

În lucrare sunt prezentate concluzii privind inițierea şi propagarea ruperii şi principalele cauze care conduc la distrugerea prematură a sculei.