Preliminary Examination of a Premature Failure in a Cold-Working Die for Sheet-Metal Cutting

D.Rigos[1], N.Stavridis[1], J.Sideris[1,2], C.Medrea[1]
[1]Department of Physics, Chemistry and Materials Technology, Technological Education Institute of Piraeus, 250 ,Thivon &P. Ralli Str.,12244, Aegaleo , Greece
[2] Stasinopouloi-Uddeholm, Steels Company S. A., 20 Athinon Str.,18540 Piraeus, Greece

ABSTRACT

The present work studies the premature failure of a cold-working die for sheet-metal cutting. The tool was made of AISI O1 steel and was produced for cutting metal sheets of up to 2 mm thick. The die failed during the manufacturing process, during the fine face-grinding. After the specific procedure, the cutting surface exhibited a uniform pattern of cracks, to an extend that lead to the rejection of the die. The paper refers to preliminary examination of the failed tool. Data concerning tool production, manufacture and maintenance were collected. The die was subjected to visual inspection, dimensional changes of the part were examined and non-destructive testing was used for the examination of the cracks. Chemical analysis was performed in order to identify the die's material. The paper presents conclusions on the type of failure and the possible reasons that led to it. The conclusions may be of interest in providing information on avoiding similar situations.

KEYWORDS: failure analysis, tool lifetime, cold working die, cutting tool.

1. Introduction

Mechanical failure of a machine or machine part is defined by Collins as any change in the size, shape, or material properties of a structure, machine, or machine part that renders it incapable of satisfactorily performing its intended function [1]. The performance of a tool, or the tool lifetime, depends on parameters such as tool design, material selection, tool manufacturing, heat treatments, production conditions and tool maintenance. Failures can be attributed to any one or a combination of these factors. Failure analysis searches for the causes of a die's premature destruction. The method is based on the elaboration of information collected during construction, processing and operation of the component, in order to determine the causes leading to its destruction [2]. Failure analysis of tool steels is a topic of great interest for today's industrial production and scientific research.

Tool steels are widely used for the manufacture of all types of products. Depending on the working conditions, tool steels are classified into tool steels for hot-working, tool steels for cold-working and high-speed tool steels. Cold-working tool steels are used under conditions where the working temperature does not exceed 200^{o}C [3]. Nowadays, a wide range of tools is manufactured by cold-working tool steels, with the cold-working dies possessing the first place.

Tool-systems for cold working can be denoted as extremely high stressed components. Dies undergo the greatest stress and are expected to exhibit specific, increased mechanical properties (good wear resistance and high toughness) [4]. In order to obtain the required mechanical properties, steels are usually alloyed. Die-makers usually suggest specific standardized materials, suitable for this application. The choice of an unsuitable material or an inappropriate chemical composition can lead to premature die failure; therefore chemical analysis is necessary for the identification of the material used.

In order to achieve high mechanical properties, the majority of dies are used after hardening and tempering. The steels for cold working dies can be divided into two basic groups, depending on the conditions of operation and treatment, the properties and the structural state [5]. The first one concerns steels hardened by quenching to achieve a martensitic microstructure, which bears retained austenite and has low impact toughness. The second group concerns steels that exhibit two-phase hardening, due to martensitic transformation during quenching and precipitation hardening during tempering. These steels have no retained austenite in their microstructure but must preserve high hardness after tempering. In any case, these steels should have good hardenability and tempering resistance [6]. The appropriate heat treatment processing of the die provides the required mechanical properties for the predicted tool life-time. In case of premature failure, the efficiency of the performed heat treatments is estimated via hardness testing and microstructural analysis.

Dies can also fail during machining. In this case, the reason of failure is the use of inappropriate processing conditions. The suitable processing conditions for each phase (i.e. rough & fine machining, grinding and polishing) are usually recommended by the steel producer in the technical datasheet accompanying the tool steel. In case of mistake, the die fails during the manufacturing process before performing any production service.

Very often die failure occurs during operation. An extensive study on various cold working dies has revealed five main mechanical failure mechanisms; wear and tear [7], plastic deformation [8], fracture [9], chipping (fine fracture of the surface cutting edge) and galling (adhesion of particles of the material to be processed, onto the die surface) [10]. All these mechanisms take place when high pressure is exerted or when sliding, between the die surface and the surface of the material to be formed, occurs. The reasons of these failures could be unsuitable material selection or thermal processing, wrong handling during use, inadequate or improper maintenance, or a combination of them. In any case, failures are associated with losses for the manufacturer and therefore should be limited. The study of each failure provides information on the mistakes often made in practice, either due to the lack of knowledge, or due to inattention; helping, this way, especially the young engineers in the industry, to avoid them.

The present paper is part of an extensive failure analysis of a cold-working die, and presents the results of the preliminary examination.

2. Experimental Details

A tool was made of AISI O1 steel and was designed for cutting of metal sheets up to 2 mm thick. The die failed during the manufacturing process, at the fine face-grinding stage. Thus, the tool failed before performing any production service, although it was initially designed for 300,000 working cycles. The machine workshop refused to undertake any responsibility for the failure, implying that the selected material wasn’t suitable for the specific application.

The first step in conducting the failure analysis was to gain an on the whole understanding of the conditions under which the die was designed and processed. Recorded history was collected, with data concerning the material’s selection, manufacturing and final heat treatment.

The die was delivered for failure analysis after long-term storage. Extensive rust was present on the fine-ground surface. Rust was removed by grinding using Si-C papers, from P80 to P500 [11]. The die was inspected visually and was photographed in order to record its general features, the position of the cracks and their orientation. Photographs were taken in two stages. One set of photos was taken by an experienced photographer using a Nikon D3X D-SLR camera. A second set of photos was taken by the researchers using a Nikon Coolpix L3 camera without any artificial lighting. A photographic archive was created and the most representative photos will be presented.

The die was subjected to non-destructive testing, using penetrating liquids for the inspection and study of the cracks. Initially, in order to remove impurities such as dust and dirt, the surface was sprayed with a cleaning agent (MR 85), which was removed using a common cloth. Afterwards, the surface was sprayed with a penetrating agent (MR 68C), which was removed after five minutes using a clean cloth, slightly soaked in the MR 85 cleaning agent. During this phase, special attention was paid to avoid removing the penetrating agent from the crack. Finally, the surface was sprayed with a liquid that reveals cracks (MR 70), which was left to dry completely and then photographs of the area of interest were taken.

Hardness measurements, using the HRC method, were made in accordance with the ASTM standard [12]. An Alpha Duromatic hardness tester was used and hardness measurements were carried out on both sides of the die; i.e. the side that exhibited failure during the fine-grinding stage and the opposite side that wasn’t subjected to any final grinding.

Chemical analysis was carried out using an ARL optical spectrometer, in order to identify the material used for the tool. Representative samples were cut from the die, using an AGIECUT CLASSIC 2 (Serial Equipment: 500/Equipment list:C32.003) EDM with a RIVADOSSI TRAFILERIE-EDM WIRE (Type:01.AI) electrode. The samples were collected and prepared for preliminary examination.

The die was subjected to optical inspection and macroscopic observation using a Meiji Teckno (S/N: NTB-3A) stereoscope. The piece was lighted by a torch attached onto the stereoscope and photographs were taken using a Pixel Fox digital camera. The fracture surfaces of surrounding areas were also examined.

3. Results and Discussions

The tool consisted of two parts, the mould and the counter-die. The die was made of a sheet with square cross-section, from which a piece was cut in the desired dimensions. The piece was then machined to its final dimensions (260mmx210mmx28mm) and shape.

After machine processing, the piece was heat treated according to procedure No: P70738, for a final hardness of 58÷60 HRC. The following heat treatment cycle was followed: first preheating at 600^o C for 30 min, second preheating at 700^o C for 30 min., quenching at 830^o C for 40 min., martempering in a salt bath at 180^o C for 15min., first tempering in salt bath at 190^o C for 120min. and finally, second tempering at 180^o C for 120 min. The final hardness was between 58 and 60HRC.

After the heat treatments, the piece was returned to the machine workshop for the finishing process (i.e., fine grinding and polishing). The aim of the final grinding is to obtain the desired final dimensions of the die, whilst the aim of polishing is to improve the quality of the surface. According to the machinist, final grinding was carried out using a No 6 grinding wheel, in accordance with FEPA (60 grains/mm^2) and the cutting depth of each pass was 40µm ÷ 50µm. During the process, the surface of the piece was cooled using a common oil coolant. The piece failed during the final grinding of the face of the die, whereas the rest of the sides were not subjected to any final machining.

Figure 1 shows a general aspect of the die face. At each corner, there is a pair of holes, designed for the assembly via toggles. The diameter of the four external holes is 10mm (point I in Fig.1). The internal holes have a diameter of 9.5mm ending with a flash-off (point II in Fig.1). At the centre of the die, there are four openings 3.65mm in diameter. These openings end up to a vent (point III in Fig. 1) and were designed for cutting. A rectangular gap is observed on the upper right side of the die, with dimensions of 88.3mmx9.8mm, which was intended for cutting (point IV in Fig. 1). On the left of the cutting edges, the main G-shaped cutting section is located (point V in Fig. 1).

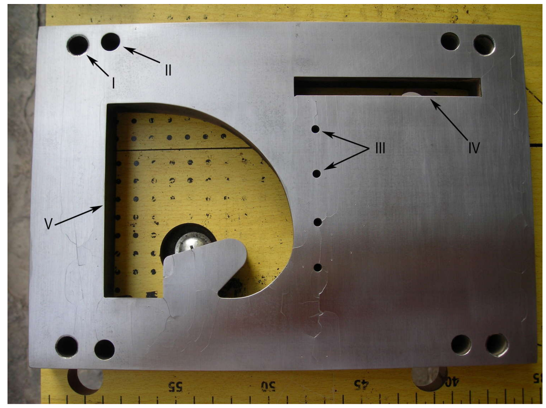

Fig. 1. *General aspect of the die face*

The surface that failed (die face) during final grinding presents a network of primary and secondary cracks. Inspection using penetrating liquids revealed the main cracks on the surface of the die (point I in Fig. 2), and the largest secondary cracks (point II in Fig. 2). The main cracks are gathered around the holes, the cutting gaps, the points with narrow radii and the edges of the die. All the wide cracks begin from the vents.

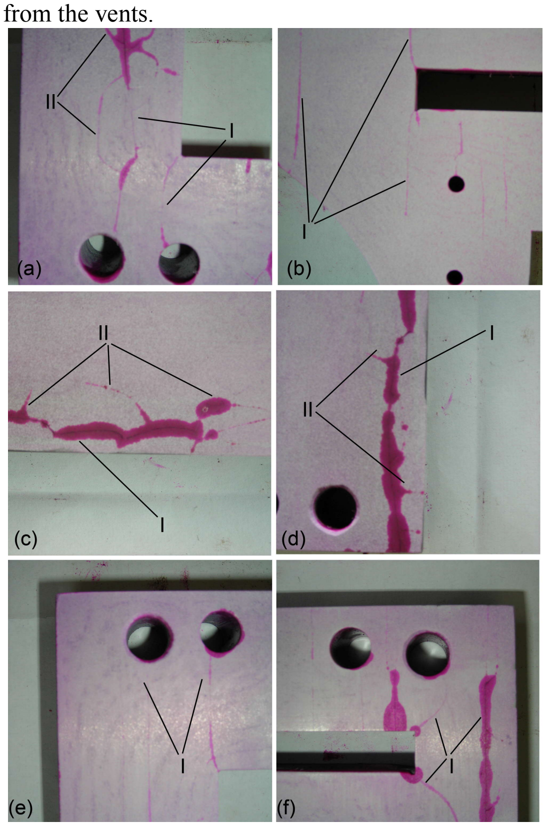

Fig. 2. *Inspection using penetrating liquids. Parts of the die (a) lower left corner, (b) inner side of cutting area, (c) internal of the complex cutting gap,(d) lower right side,(e) upper left corner,(f) upper right corner*

The crack initiation is more intense at points where the distance between vents is narrow. The development of secondary cracks occurs to an angle in relation to the main cracks. Inside the complex cutting profile, a subsurface crack initiates from a flash-off (point I in Fig.3a), propagates to the centre of the die passing through the radium (point II in Fig.3a,b), progresses as a loop (point III in Fig.3a,b), and ends up to another vent point (point IV in Fig.3a). At this point, the crack caused the material detachment.

For further investigation, hardness measurements were conducted on both sides of the die; i.e., on the surface where failure occurred during final grinding (face), and on the opposite surface, which was not subjected to any final machining (back face). Hardness measurements on the 'face' were carried out around the circumference, covering most of the core surface and the areas of narrow radius distance; avoiding the regions with cracks. Hardness measurements on the 'back face' were carried out at various distances from the surface to the centre of the piece.

The fine ground surface exhibited inhomogeneous hardness. The minimum value of 51 HRC was measured in the region between a guide opening and the rectangular cutting area; whereas all the other measuring points exhibited the maximum hardness value of 58 HRC. The hardness of the 'face' was lower than the required value, since the die was designed to have a hardness of 58÷60 HRC. Possible reasons for this hardness variation between the required and the actual value could be the use of a different material than the one suggested, the use of defective material, or an error during the heat treatments or the machine processing.

The 'back face' of the die, which was not machined after the heat treatments, had a uniform hardness within the desirable limits, i.e., from 59 to 60 HRC. Therefore, the heat treating stage is not responsible for the reduced hardness of the 'face' of the die.

Chemical analysis was carried out for the material identification and the assessment of its suitability for the specific application. The die was made of ASTM O1 steel (W. Nr 1.2510). The material was supplied by UDDEHOLM under the commercial name ARNE. The chemical composition of the material used, together with the nominal composition given by UDDEHOLM [6] and DIN specifications [13], are presented in Table 1. In fact, chemical analysis revealed that the die was made of ASTM O1 tool steel.

ARNE is a general purpose oil-hardening and versatile manganese-chromium-tungsten tool steel suitable for a wide range of cold-working applications

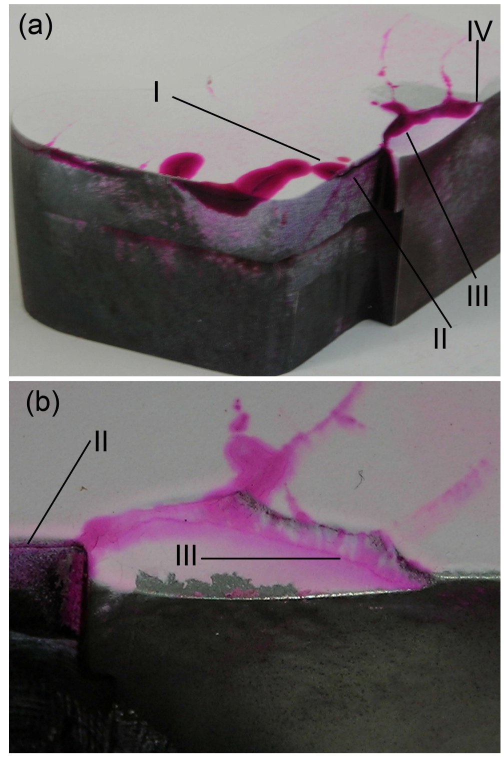

Fig. 3. *Fragments of the die from the interior of the complex cutting area, after inspection using penetrating liquids*

Table1. *Chemical analysis of the steel*

		Die composition	Arne Uddeholm composition	Standard DIN composition
Component %	C	0.950	0.95	0.90÷1.05
	Mn	1.030	1.10	1.00÷1.20
	Cr	0.566	0.60	0.50÷0.70
	W	0.600	0.60	0.50÷0.70
	V	0.060	0.10	0.05÷0.15

Its main characteristics include good machinability, good dimensional stability in hardening and a good combination of high surface hardness and toughness after hardening and tempering. The combination of these characteristics offers a steel suitable for the manufacturing of tools with increased life-time and low production cost. Consequently, the material selected for the construction of the die was the right one, and cannot be accountable for the failure.

The area where the crack caused the material detachment was examined using a stereoscope (Fig. 4). A network of subsurface cracks is observed (point I in Fig. 4 a, b), which began from the surface of the 'face' near a vent (point II in Fig.4 a). The crack was located about 2mm under the surface, and caused the material detachment at a point with a change of radium (point II in Fig. 4 b).

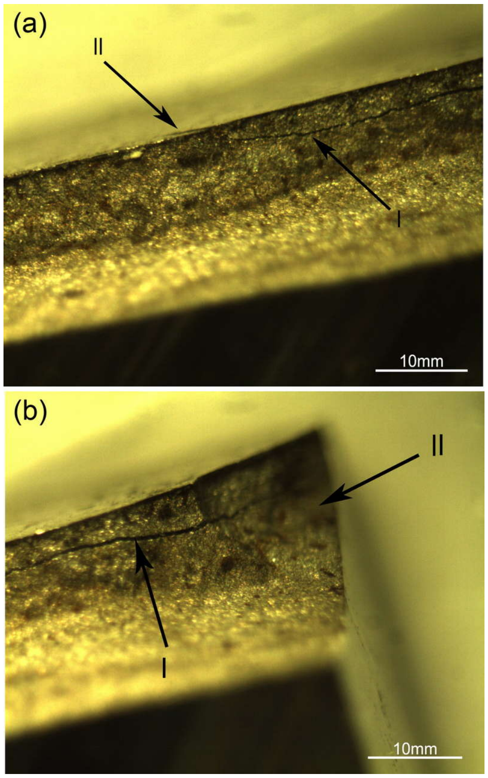

Fig. 4. *Area of the subsurface crack that caused material detachment (examined with stereoscope)*

Detachment occurred on a concave surface, since the complex geometry caused the development of diverse stresses in the specific area. As expected, the fracture surface is brittle, without showing any signs of previous plastic deformation, since the crack propagation is an extremely vigorous process.

3. Conclusions

The above examination of the die - failure led to the following conclusions:

The die intended for the production of profiles was designed with a rather complicated and asymmetrical geometry. Assuming that the shape and the dimensions of the die are correct, construction errors were identified. The die has a central cutting configuration with irregular radium that also presents fracture chips. At these points there is a stress concentration that facilitates the crack propagation. However, these dimensional irregularities are not sufficient to cause the destruction of this component.

The material selected for the manufacture of the die (i.e. ASTM O1 steel) is considered one of the most suitable steels for cold working tools. Chemical analysis confirmed the composition and quality of the material; indicating that it was not responsible for the failure.

As far as the heat treating is concerned, the required final hardness after hardening and tempering was designed to be 58÷60 HRC. Hardness measurements made immediately after the completion of the heat treatments confirm that the designer's requirements were fulfilled, and the selected heat treatment cycle was not responsible for the failure.

Hardness measurements revealed that a lower hardness was observed only on the surface of the die which was subjected to the final fine-grinding. This indicates that the final machining caused the hardness variation on the failed surface.

Preliminary examination showed that failure was caused by the final grinding and therefore the machine-workshop should be responsible for the die destruction

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Examinarea distrugerii unei matrițe destinată decupării la rece a tablelor

Rezumat

În lucrare se studiază distrugerea prematură a unei matrițe destinată decupării la rece a tablelor. Scula este realizată din oțel AISI O1 şi este destinată decupării tablelor cu grosimea de până la 2 mm. Matrița se distruge în timpul procesului de fabricație, prin uzarea feței de finisare. Muchia tăietoare prezintă o rețea uniformă de fisuri, a căror extindere duce la distrugerea matriței.

Lucrarea se referă la examinarea preliminară a sculei distruse.

S-au colectat date referitoare la fabricarea şi întreținerea matriței. Matrița a fost inspectată vizual, s-au făcut analize nedistructive pentru examinarea fisurilor. Au fost realizate analize chimice pentru identificarea tipului de material al matriței. Concluziile pot fi interesante în furnizarea de informații pentru evitarea unor situații similare de distrugere a matrițelor.