A case study of mechanical and thermal fatigue of press hardening dies

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Abstract. Press hardening provides ultra-high strength steel components, typically boron steels, of complex geometries. In the process, the steel sheet is heated in a furnace to the austenitization temperature, transferred to the press, then simultaneously formed at high temperature and cooled in the die. Life limiting factors for the press hardening dies are mechanical fatigue, thermal fatigue, and wear. In the present case study two die segments were selected where critical damages were mechanical and thermal fatigue, respectively. The dies were made of a H13 type premium hot-work tool steel with complex heated die technology, die design integrating an advanced cooling system, for pressing automotive frame parts. The first die failed due to mechanical loading with a crack initiated from the ejector pin area. The second die cracks initiated from an ejector pin hole, as well, due to thermal cycles causing alternating compressive and tensile stresses at the surface, which led to crack nucleation because of the accumulation of local plastic strain in the surface.

1. Introduction

During the last decades press hardening (also called hot stamping) has become increasingly popular in automotive industry. This is due to the advantageous features involved as optimized processing, allowing for tailored component properties with high and optimized mechanical performance with improved high strength and high toughness. In the press hardening process blanks are both hot formed and quenched in one step in a water-cooled tool to achieve high strength [1]. The final steel component will have a martensitic microstructure with improved mechanical properties, and it allows using lower thickness components and in the end lighter final products. Evidently, it reduces both the amount of steel required per vehicle body shell and the fuel consumption when the vehicle is in use. In addition, the higher strength of components significantly improves the energy absorption capacity and therefore the crash performance of structural components [2]. This point plays an important role in the production of car body components in the automotive industry.

However, the high temperature forming process entails demanding working conditions to the forming steel dies. The main damage mechanisms leading to die failure in hot forging processes are abrasive and adhesive wear, mechanical and thermomechanical fatigue, plastic deformation and oxidation [3]. According to the statistics provided by many authors, 70 % of forging dies are taken out of service due to wear, 25% due to mechanical fatigue, and only 3-5% of the forging dies failed due to thermal cracking and plastic deformation [4]. All of the mechanisms occur simultaneously from the very beginning of the
press hardening process, and they can be more or less intensive depending on factors as the design of the die, lack of hardness at elevated temperature, contact time, sliding distance, inadequate die material, work piece temperature and lubrication [3]. Moreover, high temperature processes involve changes in mechanical properties due to microstructural changes and thermal softening; surface chemical and morphological changes due to oxidation and diffusion; and deterioration of the surface and bulk material by adhesive/abrasive wear and thermal fatigue. Therefore, investigations on these processes are complex. The surface and near surface regions are points of attention since many of the initial damages occur there [5].

One of the most common materials used in press hardening is manganese–boron steels, as the 22MnB5 grade. The presence of boron in this steel helps to stabilize the austenite phase at elevated temperatures and limits the formation of ferrite and pearlite by promoting the formation of martensite during rapid quenching [6]. As a result, the martensitic microstructure provides the hardened final product with a high tensile strength up to 1500 MPa.

In the present case study the focus is on segments of damaged press hardening dies used for production of automotive cross member and side plates. The present effort is split into two sections for each die. First, macro-observations were performed to identify the different damages, then hardness measurements and micro-investigation was carried out by SEM for analyzing the occurred mechanisms. Finally, after detailed examination, mechanical and thermal fatigue were identified as the two main mechanisms of matrix damage.

2. Materials and methods
The press hardening dies were made of QRO 90 Supreme, a high performance chromium hot-work tool steel and specified to hold a hardness of 52 ± 1 HRC (~550 HV) for this application. The blank material was made of an uncoated boron steel, 22MnB5, with sheet thickness 5.9 mm. Subsequent to the press hardening process, it transformed to a martensitic microstructure with a hardness of about 500 HV from initial ferritic–perlite structure of the blank material with hardness of 170 HV.

The nominal chemical composition of both the dies and the sheet metal are displayed in Table 1.

|                        | C     | Cr | Mo  | Si   | Mn  | V    | Al | Ti | B  |
|------------------------|-------|----|-----|------|-----|------|----|----|----|
| QRO 90 Supreme         | 0.38  | 2.6| 2.25| 0.30 | 0.75| 0.9  |    |    |    |
| 22MnB5                 | 0.22  | 0.25| 0.20| 1.25 |     | 0.04 | 0.035|    | 0.003 |

The press hardening process involves several steps. First, the boron steel sheet is heated up in a furnace to its austenitization temperature (about 930 ºC). Then, it is transferred by means of a robot arm into the press. During transferring the temperature drops and the sheets are about 850 ºC when they are put in the press. In the next step, the sheets are simultaneously formed and quenched in a closed water-cooled die, and the contact time between the die and sheet metal is about 26 s. Finally, at about 220 ºC the pressed sheets are ejected from the dies. In order to maintain a controlled temperature history throughout the die an intricate cooling and heating, channel system is perforating the die.

The overview images of the two case study dies are presented in Figure 1 and Figure 2. Both of the dies considered as damaged after approximately 20000 number of press cycles. Cross member die with a mechanical fatigue fracture is displayed in the CAD-model in Figure 1a. The ejector-pin hole and the cooling channel are the main die features that influenced the fracture and both were designed with a 15mm margin from the die boundaries. The main crack of interest suffered from mechanical fatigue, Figure 1b, it originates from the ejector pin hole and grew to a length of 7 cm long on the die’s upper surface. Beneath the die surface cooling channels are running along the die.

The side-plate die suffered from thermal fatigue cracks around the ejector pin hole after 20000 press cycles. The ejector pin hole opens on the flat surface and there is a row of running cooling channels about 10 mm below and parallel to the surface as displayed in the CAD model in Figure 2a. Figure 2b shows the top view of the die surface. On the left part and around the ejector-pin hole the surface have
a roughened appearance. Various damages were found on the die, however the die failed due to the thermal fatigue cracks originating from the ejector pin hole (Figure 2c).

**Figure 1.** a) CAD model showing the design of the cross member die, and (b) overview of the main crack.

**Figure 2.** (a) CAD model showing the ejector pin hole and cooling channels, (b) overview of the side-plate die, and (c) thermal fatigue around the pin hole and plastic deformation damage on the die.

To identify failure mechanisms, detailed studies of the tool surface and polished cross-sections were performed by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) (JSM-7900F with X-MaxN EDX detector). Hardness measurements were carried out by macro- and microhardness Vickers indentations (Future Tech FM) using a load of 300 kg, 0.50 kg and 0.25 kg.

3. Results

3.1. Failure mechanisms in the press hardening die for automotive cross member

The main mechanical fatigue crack originates from the ejector pin hole growing in two opposite directions along the die, Figure 3a, initiated by the stress concentration of the pin hole and controlled by principal stresses along the blank sliding direction and perpendicular to the die length. The crack grows along the die and perpendicular to the die surface down to a depth of 1.5 mm. Here, it meets up with another crack following the die radius seemingly affected by the thermal stresses between the cooling channel and the curved die surface. The examination of the fractured surfaces, the die surface, cross-sections along and transverse to the die, and ejector pin hole and cooling channel, revealed different types of damage mechanisms that took place and lead to the degradation of the die and eventually its fracture. A grading of the main different damages is summarized, seen in Figure 3b, as: i) mechanical fatigue, ii) thermal fatigue, iii) blank - die surface press and oxidation damage, iv) internal creep damage, and v) cooling channel damage. Nevertheless, types i) and ii) are the two main damage mechanisms that led to the fatal failure of the die, and the mechanical and thermal fatigue evidence can be seen already by the naked eye on the fractured surface (Figure 3a).

SEM photos of the fractured surface imply that two different events took place, the mechanical and the thermal fatigue, even though coordinated by the press cycle. The fracture lines revealed that the
damage of the events meeting points was approximately 1.5 mm beneath the die’s blank surface, Figure 4a.

![Crack growth](image)

**Figure 3.** (a) Overview of the fractured surface (b) Grading of the different types of damages.

The assumption of the two mechanisms is being confirmed by the evidences of Figure 4b and 4c. Figure 4b, shows a cross-section transverse to the die length direction and perpendicular to the blank surface of the die. It seems that microcracks start from the upper surface and grow in a direction in accordance to a transverse stress responsible to the mechanical stress fracture. Concerning thermal stresses, thermal cracks were detected in a die curvature cross-section as viewed in Figure 4c.

![Cross-sections](image)

**Figure 4.** (a) Overview of the mechanical and thermal stress fractured surfaces meeting, (b) cracking due to mechanical loading in the die-blank surface contacts, (c) thermal crack in the die curvature cross-section.

Other secondary damage mechanisms than mechanical and thermal fatigue took place as well. SEM photos revealed phenomena of oxidation, especially beneath the blank-die surfaces (Figure 5a). Oxidation cavities were detected not only beneath the blank surface of the die, but in most cross-sections beneath examined surfaces; ejector-pin hole surfaces, the fractured surface and in some cases different from the cracked area.

Internal cavitation with microvoid formation related to creep-fatigue mechanisms was observed at grain boundaries as is displayed in Figure 5b. The microcavities were found not only at samples directly associated to the main crack, but also at samples cut from the bulk of the die. Noteworthy was not the size of the cavities, but the extent of the phenomenon. Although, these types of creep induced cavities are small in size, they are high in their number and the number getting higher closer to the hot surfaces.

Last but not least, corrosion pits were found beneath the surfaces along the cooling channels, combined with cracks at their end (Figure 5c). The small cracks propagated in the channel perpendicular direction, a feature that may be attributed to preload stresses due to clamping of the die segments.

Macro- and microhardness values of the die along the depth of the ejector-pin hole, as well as close to the main crack path change to the depth of 1mm, in a cross-sectioned fracture sample are shown in Figure 6. In general, it seems that the hardness is being maintained during the press hardening and there is no significant softening effect taking place.
3.2. Failure mechanisms in the press hardening die for automotive side-plates

Observations revealed that the tool had several radial cracks initiating from the ejector pin hole, Figure 2c. Some of the cracks were relatively straight beneath the surface, and some were branched, Figure 7a and Figure 7b. Crack sizes along the die surface and ejector pin hole surface were measured displaying a maximum length of 8.8 mm and maximum depth of 4.5 mm, Figure 7c. There is an almost linear relation between crack depth (a) and length (c), with a/c = 0.41 indicating a semi-elliptical surface crack in the die as is visualized in Figure 7d.

In higher magnifications, Figure 8, SEM observations revealed networks of cracks in the surface oxide typical of thermal fatigue cracking. These networks were observed along the cracks, Figure 8a, on the tool surface away from the cracks, Figure 8b, and close to the die surface on the polished cross-section of the die. EDS results confirmed the presence of oxides rich in Cr in the crack networks.

Furthermore, oxide layers were observed inside the thermal fatigue cracks on the polished cross-section of the die, Figure 9. The EDS results confirmed the presence of oxide layers enriched in Ca in the cracks, and water leakage from the cooling channels may be a probable reason for the presence of Ca.

Figure 5. (a) Oxidation cavities beneath the surfaces, (b) grain boundary cavitation, and (c) pit at the cooling channel surface.

Figure 6. Microhardness measurements along the ejector-pin hole, 1 and 15 mm along the height of fractured surfaces´ cross section.
Figure 7. (a, b) Measured thermal fatigue cracks originated from the ejector pin hole, (c) crack depth, a, and length, c, of cracks initiated from the ejector pin hole.

Figure 8. Oxide layer (a) along the cracks on the surface of the die (b) on the tool surface (c) near the die surface on a polished cross-section of the die.

Microhardness measurements were performed along the thickness of the die perpendicular to the surface in different locations including along the ejector pin hole and along two different cracks (1 and 2) up to the depth of 12 mm, Figure 10. For the cracks, the indents where recorded at polished cross sections (Figure 10) and at a distance corresponding to about 3 times the intent width. Measurements along the ejector pin hole were performed at a distance of 0.15 mm from hole.

Figure 9. Oxide layers inside the cracks on a polished cross-section of the die. EDS result confirms the presence of Ca.
The microhardness values increase along the ejector pin hole when reaching the depth of about 10 mm from the surface. Moreover, considering the measured hardness values in the first 2 mm depth from the surface, a small reduction can be observed below the surface. The maximum difference in the measured hardness is about 90 HV in crack 1.

**Figure 10.** Microhardness measurements along the ejector pin hole and two different cracks using a load of 50 g. The diagram is magnified in the range of 0-2 mm.

Some evidence of plastic deformation was also observed on the surface of the die, **Figure 2b and c** and **Figure 11.** SEM images of the chemically etched part revealed three different zones near the surface comprising 1) a deformation zone, 2) a transition zone, and 3) the tempered martensitic base material zone, **Figure 11a.** The hardness values of these regions were measured as 634.8±12.3 HV, 584.4±8 HV, and 574.2±14.2 HV, respectively. Viewed in higher magnification the top layer displays a deformed microstructure, **Figure 11b.** Additionally, EDS results showed the same chemical composition in all the three regions; therefore, the possibility of adhesive wear occurrence from the sheet metal was rejected.

**Figure 11.** SEM images of the chemically etched part: (a) plastic deformation in surface layer of die comprising three different zones of 1) deformation zone, 2) transition zone, and 3) tempered martensitic zone, and b) the deformed microstructure of region 1 in higher magnification.

4. Discussion

The examination of the cross member die of this case study, revealed different kind of damages due to the press hardening process. Except the mechanical and thermal fatigue, which were the two main failure mechanisms, oxidation, corrosion and creep mechanisms took place due to the high stresses, the temperature and the environment.

**Figure 3a** and **Figure 4a, b,** revealed that the existence of high stresses led to the formation of long and straight to the depth cracks in this complicated die design. Furthermore, the characteristic fatigue feature of radial lines in the fractured surface starting from the upper blank surface to the depth confirmed the fact that mechanical fatigue was one of the damages that contributed to the final fracture of the die. The pattern and the direction of the fracture surface markings imply that the initiation points are at the ejector-pin hole, even though it was difficult to detect the exact initiation points due to the
oxidized surface. From the ejector-pin hole the fatigue crack propagated at either side of the hole along the die segment. The main reason for the mechanical fatigue damage to happen in such an extent and type is believed to be the combination of the die’s design and the high stresses. In general, the design of the press hardening dies is always a case of discussion and constitutes one of the crucial factors that should be taken into account for a long die life [2]. In first case, the design of the die is challenging with the ejector-pin hole acting as a stress concentrator located close to the die segment curvature and side surface, raising the stress in this area.

Regarding the thermal fatigue damage, it seems that not only the temperature but the duration of the process and the heat transport from the blank through the die are critical factors. The design of the die seems to be critical in this case also, since the surfaces from where the heat can be transferred (cooling channel and outer surface of the die) are close to each other and accordingly a high thermal gradient is being created and repeated after each cycle. The curved crack around the cooling channel following the die segment curvature is a reflection of the thermal stress formation. Thus, the above phenomena led to the subsurface thermal fatigue and formation of thermal cracks in the die Figure 4c.

In addition, oxidation cavities located below the blank surfaces is one more damage mechanism that may become critical. The oxide layer that forms at elevated temperatures experiences a mechanical strain, which can result from one or a combination of the following mechanisms: 1) strain from the applied mechanical loading in the material, 2) mismatch in thermal expansion coefficients among the different stoichiometries of the material and the oxide or 3) viscous sliding of the oxide segments on the metal substrate [7]. On the die surface oxide pits and abrasive wear scratches were observed, and as viewed on the cross-sections internal oxidation was present, Figure 5a.

Furthermore, the combination of load with high temperature leads to the formation of creep microcavities. Even though thermal cycles are present, it can be considered that the temperature of the die remains high enough during the whole process since the production line works quick and the contact time is approximately 26 s. The die, except of the repeated mechanical load, experiences a constant loading due to die segment clamping as it is bolted to two other identical dies. Thus, the creep criteria temperature and stress may be fulfilled for microvoid creep damage to occur, Figure 5b. The microvoid and microcrack formation takes place through grain boundary sliding and carbides can concentrate the tensile stress at the interface at which the carbide and the matrix meet. Finally, the voids are getting bigger in size and as a result they meet each other around grains, forming microcracks. Although, these types of fatigue-induced cavities are small in size, they are also high in their number of density [8], which leads to degradation of the die.

Last but not least, pitting corrosion occurring in the cooling channels with cracks extending at the end of these pits was observed, Figure 5c. The existence of corrosion pits can be attributed to either a water leak or to the die cleaning process that is applied from time to time. The presence of Ca to the fractured surface implies that water is a part in the damage scenario.

The fact that the hardness was maintained, despite the extended damage that led to the cracking of the die, can be attributed both to the temper resistance of the material, but also acts like a validation that the combination of the design with stress and high temperature can result in low life; and also, demonstrates the importance and the challenge of a good and proper design for press hardening applications.

The side-plate die main damage comprised cracks initiated from around the ejector pin hole, Figure 2c. A limited number of cracks were present with a high total length, as local stress relief along each thermal crack may postpone the crack growth of adjacent cracks as larger ones propagate [9]. In addition, the appearance of the cracks may be strongly determined by the maximum temperature during each thermal cycle. In a study on QRO 90 steel samples subjected to thermal fatigue results revealed that the crack path was relatively straight in the thermal cycling up to 700 °C, whereas branched cracks in addition to the single cracks were present after cycling to 850 °C [10]. These results are in agreement with our observation in which the die was subjected to the blank sheet at temperature of 850 °C, and the produced cracks were both single and branched cracks.
The observed cracks initiating from the ejector-pin hole (Figure 7) with even distribution of radial cracks around the hole and a network crack pattern in the microscale are typical of thermal fatigue cracks. Thermal fatigue is one of the first damage mechanisms in die-casting, forging and press hardening dies. In press hardening, generally, there are two steps. In the first step, which is heating stage (closing and pressing), the thermal expansion of the surface layer is constrained by the cooler sublayers, and a compressive stress field develops at the surface. Next, during die opening and cooling the contraction of the surface is hindered by the heated the sublayers, and a tensile stress state appears at the surface. Under this condition the die material is subjected to a significant damage through a process of non-isothermal low cycle fatigue (LCF) [11]. Therefore, alternating compressive and tensile stresses at the surface of the tools that arises from differential thermal expansion/contraction during sudden transient temperature changes may lead to thermal fatigue damage in hot forming operations [12]. Additionally, even higher temperature gradients are produced at slim and sharp corners like the ejector-pin hole, which results in higher stresses and strains. Hence, low-cycle fatigue gradually accelerates thermal fatigue cracking of these regions [9], [10].

Some oxidized crack networks appeared along the main cracks on and right below the die surface, and oxide layers were, as observed on the polished cross-section, inside the deep cracks of the die. Although the oxidized surface crack networks, Figure 8, were rich in Cr and observed in many different regions, they seem to be not as harmful as oxide layers rich in Ca inside the cracks, Figure 9. The presence of oxides in the cracks may lead to an increase in compressive stresses and plastic yield during the heating phase of the thermal cycle, and during the cooling phase the tensile stresses are further increased and thus amplifies the continued crack growth [12]. The negative impacts of the oxide layers are due to their low thermal expansion, bigger volume and brittleness [13]. Moreover, the grain boundaries along the crack are oxidized easily and form brittle oxidized grain boundary zones subsequently adding paths of thermal fatigue crack propagation [11].

Microhardness measurement along the ejector-pin hole and the two cracks showed some variation in hardness, as shown in Figure 10. A lower hardness at the die surface of the ejector-pin hole compared to 10 mm below the surface, and a slight drop in hardness closer than 2 mm to the die surface along the two cracks indicates a slight softening close to the die surface. Generally, tool steel temper resistance to softening is one of the important factors in thermal fatigue crack resistance [14], however as the hardness reduction was slight in this die, its effect on the thermal fatigue damage may be little.

Figure 2c and Figure 11 displays plastic deformation the die surface and parallel subsurface cracks, confirmed by the observed deformed microstructure and the higher hardness values in the deformed layer, Figure 11. Calculations based on the heat transfer from the blank to the die interior revealed that the temperature on the surface of the die may reach about 500°C. At this temperature the yield strength of the material is reduced to about 880 MPa, (Table 2), and mechanical and thermal stresses generated may exceed the yield point and plastic deformation is likely to occur. Moreover, shrinkage of the sheet metal in contact with the die during the 26 s long cooling step may cause high shear stresses on the surface of the die, and could be an important driving force for the occurrence of plastic deformation.

| Temperature (°C) | 200  | 300  | 400  | 500  | 600  | 700  |
|------------------|------|------|------|------|------|------|
| Yield strength (MPa) | 1200 | 1100 | 1000 | 880  | 640  | 340  |

5. Conclusions
The failure case study on two press hardening dies for production of cross member and side-plate components analysed several die damage mechanisms. However, the most severe and life limiting failure mechanism in the study were mechanical fatigue and thermal fatigue. The mechanical fatigue is a results from loads during pressing and thermal fatigue depends on the thermal gradients occurring during pressing, thus both are related to the press hardening cycle. The press hardening components are
made of thick boron steel sheets, thus with a large heat transfer into the die during press hardening. Therefore other elevated temperature dependant damages were found, e.g. oxidation, creep and corrosion, but mainly related to the time at high temperature. The case study is summarized by the following conclusions.

- Both the mechanical fatigue and thermal fatigue damages in both dies are related to ejector pin holes, and cooling channels, indicating a potential for design improvements.
- Other secondary phenomena, such as oxidation, creep and corrosion, degrades the quality of the die and at the end it may contribute with critical life limiting damages.
- Abrasive wear and oxidation pits may be observed on the die surface, but also severe plastic deformation on the side-plate die occurred during press hardening as a result of shear between the plate and die in combination with reduced die surface yield strength at the high temperatures.

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