Original Article

Failure analysis of hot stamping die

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Abstract

The need to reduce weight combined with increased resistance of automotive safety parts leads to an increase in the application of the hot stamping process.. The hot stamping die behavior knowledge is of great importance to optimize the process. In this way, the present work proposes the analysis of the predominant wear mechanisms of an end-of-life hot stamping die. The initial part of a failure analysis was carried out, with visual and microscopic analysis, hardness and residual stress measurements, preserving the die. It was found that the predominant failure mechanisms in the hot stamping die were adhesive, impact and abrasive wear. Furthermore, the cracks found in the die are associated not only to wear, but also to mechanical stress. Finally, due to the characteristics of the application, overtempering may occur in the die and, consequently, a decrease in the wear resistance of the die in such regions.

Keywords: Hot stamping die; Failure analysis; Wear mechanisms.

1 Introduction

In the last 30 years, the use of hot stamping in the production of automotive parts has grown by more than 3,500%. This is due to the demand for parts with high mechanical resistance and lower weight, in order to provide greater safety and reduce carbon emissions [1]. In the hot stamping process, the steel tailored sheet (from here called blank) is heated (austenitized) to approximately 900 °C and then formed and simultaneously quenched to achieve the desired martensitic structure [2].

In the case of hot stamping for automotive parts, the most used material is the ultra-high strength steel (UHSS) 22MnB5, belonging to a group of materials that reaches martensitic structure directly after hot stamping. It is common to the sheet to have an AlSi coating to prevent oxidation and decarburization of the material during the austenitization process [1]. Another important information is that the main blank can be connected to a patched blank via spot welding [3]. The patchwork blank hot stamping forming technology can be used to obtain different thickness and shapes of the main blank and patchwork blank [3].

The die (tool) is subjected to mechanical and thermal stresses, causing failures of the same. The main failure mechanisms, according to literature [4], are adhesive wear, abrasive wear and fatigue. Tool wear can lead to a greater number of maintenances, in addition to worsening the dimensional tolerance of the part and affecting the heat transfer necessary to guarantee the properties of the part.

Adhesive wear is claimed to be the principal wear mechanism, with abrasive wear having a secondary role [4]. In addition, it is also known that the transfer of the material coating can lead to the adhesive wear "galling", which worsens the surface finish of the part [5]. Studies show that there is a direct relationship between adhesive wear resistance and material hardness [6]. Furthermore, it is known that, in forming processes which involve repetitive impact sliding, the tool can be submitted to impact wear and the die needs to have higher wear resistance [7]. It has been found, in different hot stamping process simulations, that the highest die temperatures reach from 150 °C up to 190 °C [8,9].

Because it is a relatively recent subject, the number of studies on wear in the hot stamping process is still relatively small. In this way, a correlation can be made between wear in the hot forging process and wear in hot stamping, since both processes involve plastic forming at high temperatures.

For hot forging, it was observed that it is also necessary to consider plastic deformation, in addition to wear mechanisms in areas where the tool is subject to high stresses. Furthermore, the "level" of wear is greatly affected by contact pressure and contact time [10]. It was also found that, although abrasive wear was considered the predominant mechanism, defects related to plastic deformation and thermal fatigue were more severe, probably because evidence of abrasive wear was easily removed, according to the author [11].

Still for the hot forging process, it is possible that under mechanical and thermal stress, the martensitic microstructure of the tool changes, possibly losing its mechanical properties [12]. In the macroscopic analysis, evidence of thermal fatigue cracks and abrasive wear was found [13].

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It is clear, therefore, the importance of studying the wear mechanisms to which hot stamping dies are subjected. In this way, the present work proposes the initial analysis of the predominant mechanisms of failure in an end-of-life die for hot stamping.

2 Methodology

For this work, an end-of-life hot stamping die from the automotive sector was studied, kindly provided by the company "*Benteler Automotive – Mercosur & South Africa*". The die material in question is WP7V, whose chemical composition is shown in Table 1.

The studied die was used to hot stamping tailored patched blanks of 22MnB5 steel with AlSi coating.

The initial stages of a failure analysis were carried out, with the preservation of all evidence, namely: i) visual observation/analysis of failures, with photographic records; ii) microscopic record of the regions that presented failure; iii) liquid penetrant test; iv) hardness measurements; and v) measurements of residual stresses. The identification grid, with 221 points, for micrographic analyses, hardness and residual stress measurements is shown in Figure 1.

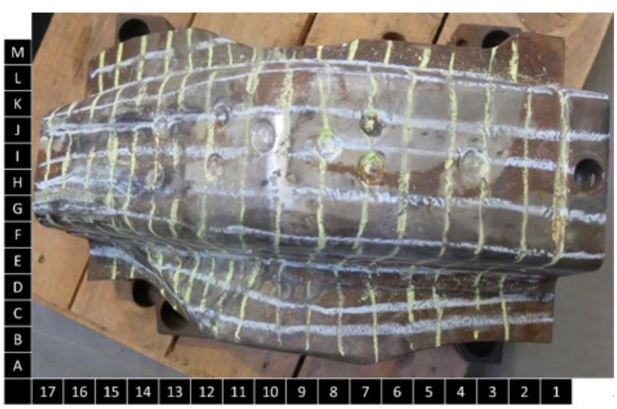


Figure 1. Mesh with the identification of the analyzed regions in the end-of-life die for hot stamping process.

3 Results

Visual analysis of the end-of-life die showed that in the top view, Figure 2a, there are regions on the surface with rounded marks in lower cavity (H10). Such regions correspond to the places where there is spot welding on the tailored blank, used for fixing the patch. It is also possible to observe the presence of three shades of gray in the die. A metallic gray (H10, H8), a darker one (close to H7) and a lighter one (I16). The lighter gray (I16) is attributed to welding regions, resulting from die maintenance. Oxidation, visibly observable, was not considered as a failure mechanism, being attributed to the storage mode of the die. Figure 2b shows apparently crushed regions (E7) and regions with material removal (F6).

With the liquid penetrant test, it was possible to observe the regions of the die with superficial cracks, Figure 3. It is possible to verify that the cracks are found, mainly, in the regions with greater mechanical stress and that cracks propagate over long distances. In addition, there is a tendency for the cracks to be close to the points of contact with the "spot weld" (of the blank), which leads to the hypothesis that these are crack initiation regions.

Figures 4 to 11 show representative photographs (left) and photomicrographs (right) of the wear regions. In position D2, Figure 4, grooves are observed, due to the contact of the blank material with the die, and cracks with a superficial appearance.

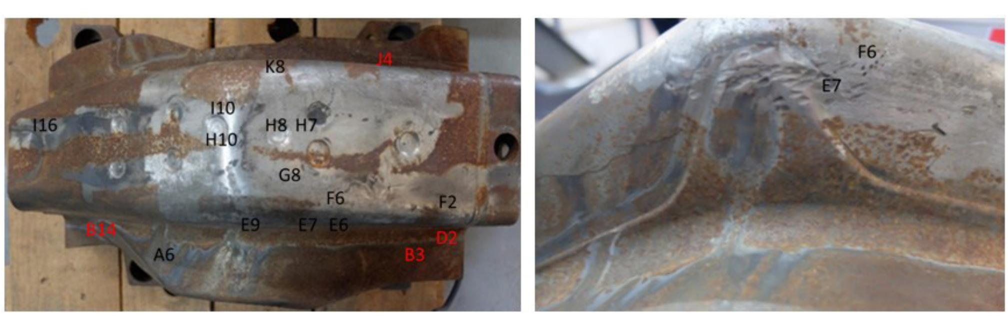
In position G8, Figure 5, unidirectional grooves can be observed, also resulting from the contact of the blank with the die.

In position F6, Figure 6, there is a crack, which appears to be very deep, in addition to a deep pullout.

Table 1. Chemical composition of WP7v steel

Carbon	Chromium	Molybdenum	Vanadium
C	**Cr**	**Mo**	**V**
0.5	7.8	1.5	1.5

Chemical composition taken from: Dörrenberg Edelstahl GmbH [14].



a. Upper View b. Lateral View

Figure 2. Photographic record of the naked eye analysis of the hot stamping die at the end-of-life.

a. Upper View b. Lateral View

Figure 3. Photographic record of the liquid penetrant analysis of the hot stamping die at the end-of-life.

Figure 4. Photograph (left) and photomicrograph (right) of the end-of-life die at position D2. Cracks can be clearly observed.

Figure 5. Photograph (left) and photomicrograph (right) of the end-of-life die at G8 position. Grooves in the material flow direction can be seen.

At position I16, Figure 7, grooves are observed, which seem to have a preferential direction, in addition to a material with a darker color.

At position I10, Figure 8, one can see the wear resulting from the spot weld, which has distinct layers, indicating an uneven and progressive deformation, in addition to a crack with a thin appearance.

In the case of position E7, Figure 9, again, there are pullouts and cracks, but these pullouts are less profound and occur more frequently and closer to each other. Moreover, in this case, the crack is quite deep and is in the middle of a pullout. An important observation here is the impact wear observed, evidenced by kneading.

At position E9, Figure 10, cracks with different propagation directions and different depths can be noticed.

Finally, in position F2, cracks and pullouts are observed again; however, in this case the pullout is in the middle of the crack.

Figure 6. Photograph (left) and photomicrograph (right) of the end-of-life die at position F6. Material pulled out, and cracks.

Figure 7. Photograph (left) and photomicrograph (right) of the end-of-life die at position I16. Grooves.

Figure 8. Photograph (left) and photomicrograph (right) of the end-of-life die at position I10, cracks.

The hardness map, Figure 12, shows that in the regions of greater mechanical stress on the die occurs a sharp drop in hardness values (darker regions of the map), with values reaching a minimum of 20 HRC. The regions of lower mechanical stress and, probably, with shorter contact time with the heated blank, presented higher hardness values, reaching a maximum of 59 HRC. It was assumed that the value of 59 HRC is the initial hardness value of the new die. According to the material data sheet [14], WP7v is a secondary hardenable steel that reaches 59 HRC (its hardness peak) if austenitized at 1070 °C, oil quenched, and tempered between 400 and 500 °C.

Figure 9. Photograph (left) and photomicrograph (right) of the end-of-life die at position E7. Kneading, evidence of impact wear, and cracks.

Figure 10. Photograph (left) and photomicrograph (right) of the end-of-life die at position E9, cracks.

Figure 11. Photograph (left) and photomicrograph (right) of the end-of-life die position F2, pulling out, cracks.

Residual stress correlated well with hardness, Figure 13. The higher the hardness, the more compressive is the residual stress. For very low hardness values (26 HRC), the residual stress is tensile. It was assumed that the die in its "new" condition presents compressive residual stresses on its surface.

4 Discussion

There are several cracks spread over the surface of the tool, which have great depth. There is a tendency for the cracks to be close to the deformation points of the "spot weld" and to the points of greatest mechanical stress,

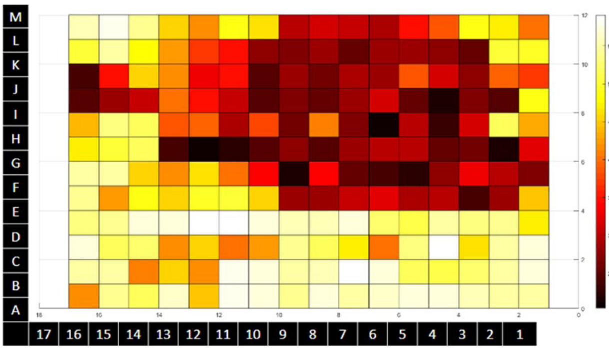


Figure 12. End-of-life hot stamping die HRC hardness map, the brighter the higher the hardness.

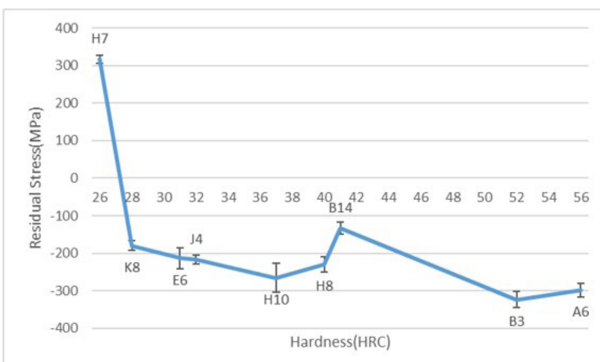


Figure 13. Graph of residual stress (MPa) X hardness (HRC).

which leads to the hypothesis that these are crack initiation regions. No evidence was found in the literature regarding the negative effect of spot welding on the die. However, Abachi et al. [10] showed that the onset of cracks is related to the pressure and contact time of the blank with the die, and Summerville et al. [11] found that cracks are related to plastic deformation, which can be observed in this process. Although thermal fatigue is an important cause of hot forging dies, it was not observed in the hot stamping die analyzed.

This tendency is reinforced by the results obtained in the residual stress. Among the 9 points measured, the only one with tensile stress was the point corresponding to the deformation region resulting from spot welding of the 22MnB5 plate (H7). This means that, probably, this region was a crack initiation region, confirming the previous hypothesis.

The main types of wear observed were: sliding wear, adhesive wear [4-6], abrasive wear [4,13], and impact wear [7]. In the literature, few references were found dealing with the failure analysis of this type of tool. However, citations of predominant wear modes were found, which were analyzed in laboratory tests, making it difficult in some cases to compare the mechanisms found in the present study with the literature.

Sliding wear occurred due to the flow of blank material into the die, leaving deformation marks, Figure 8, in the form of macro grooves (wear tracks). Sliding wear has delamination as one of the micro mechanisms, which may have been the origin of cracks and material tearing.

Adhesive wear (sometimes used to address sliding wear) has been observed. The galling mechanism can be seen in Figure 7, due to the repeated flow of material (sliding) in that region. In Figure 6, the material pulling out is observed, attributed to die/blank adhesion.

Most of the observed wear mechanisms, if analyzed separately, may suggest abrasive wear. Additionally, the type of wear observed in Figure 9 was attributed to impact wear. In this region there is contact of the patch, which is in high salience, with the die. It can also be seen that this mechanism seems to have a preferential direction. Thus, with time, the repeated contact between the patch and the die can cause the dents and cracks observed in the region.

It was observed that in regions with greater wear and greater stress in the die, the measured hardness values were lower. Thus, it can be induced that the regions of greatest wear are regions in which the material overtempers due to high holding time at high temperatures (up to 190 °C [8,9,13]) and this leads to lower hardness. Modifications in the martensitic matrix during hot work were observed by Barrau et al. [12]. It is known that higher hardness values are related to greater wear resistance [6], therefore, regions with a drop in hardness during the process will be more prone to wear.

Furthermore, a relationship between higher hardness values and higher compressive residual stresses can be observed. This corroborates the hypothesis of overtempering of the tool surface, meaning that due to high temperatures found in the process there may be a change in the microstructure of the material [8,9,12], leading to lower hardness values and higher values of residual stress.

This failure analysis is not conclusive, considering that only the initial stages were carried out, with preservation of the die. The next step is to cut the die to analyze in detail the surface and subsurface wear mechanisms.

5 Conclusion

The predominant failure mechanisms in the analyzed hot stamping die were adhesive wear, impact wear, and abrasive wear. In addition, cracks are associated not only with wear, but also with mechanical stresses imposed. Finally, due to the characteristics of the process parameters, overtempering may occur in the die and, consequently, a decrease in the wear resistance of the die in these regions.

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