Main damages on upper die in industrial hot forging

Glavne poškodbe na zgornjem orodju za vroče kovanje v industriji

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Abstract: An analysis of main damages on industrial hot-forging die, made of Dievar hot-working die steel is presented. Die was previously gas nitrided, sectioned and examined after its service life. The measurements of microhardness depth profiles and optical microscopy of nitrided layers were applied in analysis of wear, cracks and failures on the most loaded sections of tool. In order to prolong die service life some improvements were suggested.

Izvleček: V tem prispevku so prikazane glavne poškodbe na orodju za vroče kovanje, narejenem iz orodnega jekla Dievar. Orodje je bilo predhodno plinsko nitridirano ter preiskovano po izteku njegove trajnostne dobe. Za analizo poškodb, tj. obrabe, razpok, zlomov, na najbolj obremenjenih delih orodja, so bile uporabljene optična mikroskopija in meritve profila mikrotrdote. Za izboljšanje trajnostne dobe orodja so bile predlagane izboljšave.

Key words: hot forging, die, gas nitriding, damages
Kjučne besede: vroče kovanje, orodje, plinsko nitridiranje, poškodbe

Original scientific paper

INTRODUCTION

Hot-forging dies are during the process of hot forging subjected to a complex loading, i.e. to simultaneous thermal, mechanical, chemical and tribological loads. Various parts of hot-forging dies are subjected to mentioned loads that results in different types of damages, like erosive, abrasive and adhezive wear,[1–4] plastic deformation,[1, 8] thermal and mechanical cracking,[1, 7] gross cracking, etc.[1, 5, 6] Die life (service time) plays an important role in economy of hot forged products, thus goal of every technologist in practice is prolongation of die service life as much as possible on one hand and accurate prediction of die service time on the other hand.[1]

Damages and their propagation are also additionaly influenced by applied die steel, die shape, and applied technological processing parameters, i.e. schedule of forging sequences, way of manufacturing the die, operating forging parameters, used forging press, as well as forging stock properties, i.e. temperature, scaling, local adhesion between die and the workpiece, etc. Further, die steel should be produced in an appropriate way in order to achieve optimal microstructure, i.e. grain size as well as distribution, type, size and shape of carbides. Finally, manufacturing of die should be performed without negative influences on the die surface quality, and also shapes of die should be optimized with sequential forging steps in order to avoid areas of essentially higher loads in regard to other areas of die.[9,10]

In order to increase die service time, wear and fatigue resistance, the die surface is improved by coating, diffusion procesess like nitriding, etc.[11] During nitriding the die steels, two different types of microstructure are formed on the die surface, i.e. microstructure with "compound layer" on top of the surface and diffusion layer below, and in the second case diffusion layer alone. It is advisable for hot forging dies to produce nitrided microstructure without compound layer since it consists of brittle iron nitrides, i.e. ε phase (ε-$Fe_{2-3}N$), γ' phase (γ'-Fe_4N), or mixed phases (ε+γ'). At slightly higher contact pressures (about 20 MPa)[12, 13] compound layer usually spalls of the die surface at the very beginning of forging process and that usually essentially accelerates process of wear. In each application nitrided microstrucure as well as die design should correspond to actual loads that prevail on die in the selected forming process.

In order to elucidate doubtless relationships between occurrence of die damages, loads, properties of applied steel, die shape, etc. there are still not sufficient data on failures of industrial dies, especially on dies that were previously nitrided, coated or duplex treated. Thus more data on die damage analysis from industrial practice are needed. Analysis of main damages that occurred on a gas nitrided industrial die for hot forging that has failed have been presented in this paper with aim to prolong its service life.

Experimental

Description of hot-forging die and shape of forged product

The main damages of die (Figure 1) with two impressions for penultimate forging operation and two impressions for the last forging operation were analysed after its service life. However, analysis was predominately focused on the impression used for the last forging operation since it gave final shape and dimensions of the product (see Figure 2). This shape was achieved in five sequential forging operations. Upper and lower parts of die had similar design of impressions. Essential difference between the upper and the lower die was height of mandrels. With regard to reference,[1] it could be supposed that the die surface temperature was in the range of 600–700 °C and contact pressure exceeded the value of 1000 MPa. Lubricant that was used was water suspension of graphite.

Die life is determined by surface quality of forged product as well as by its shape and dimensions. In our case customer had special demands for forged product in respect of the quality of impression surface, and the shape and dimensions at the base of mandrels. These areas were considered as critical areas of the hot-forging die (see Figure 1). The die with higher mandrels failed after 45 766 forging strokes due to change of shape of forged product in the depression around high mandrels.

Initial billet made of C35E steel for forging the steering mechanism had diameter of $\varnothing$ = 32 mm and weight of 930 g, and was heated to temperature interval of 1230–1280 °C. Geometry of forged product is adapted for steering mechanism in car that is a relatively simple 3D-geometry (Figure 2).

Die material, applied methods

Dievar, a high performance chromium-molybdenum-vanadium alloyed hot-working die steel (see Table 1), developed by Uddeholm, was used in manufacturing industrial die; steel is characterized by excellent toughness, ductility in all the directions, good tempering resistance and high-temperature strength, excellent hardenability, and good dimensional stability throughout the heat treatment procedure, as well as during coating operations. Consequently, this die steel has a very good resist-

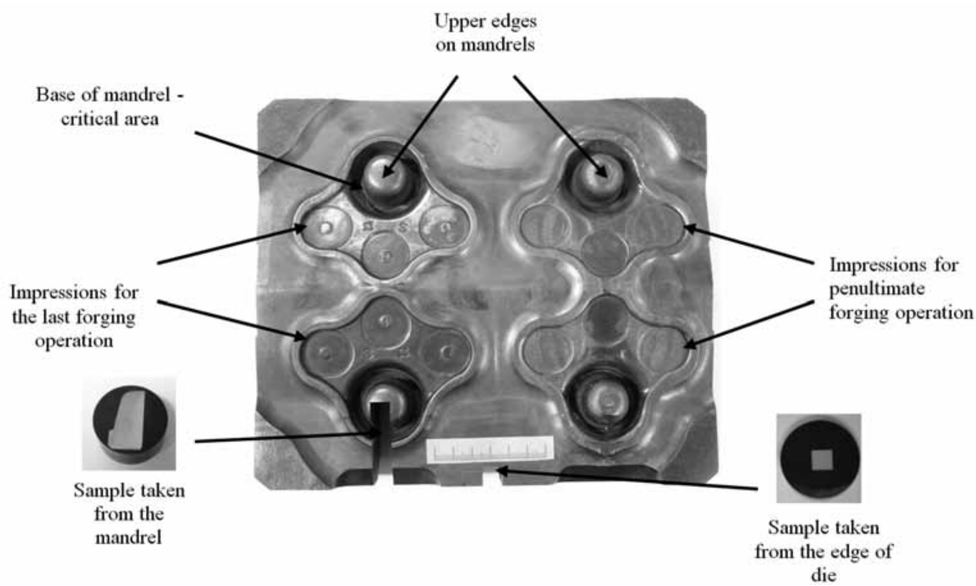

Figure 1. Upper die after 45 766 strokes; two impressions for penultimate forging operation and two impressions for the last forging operation with mandrels

Figure 2. Shape of steering mechanism after the last hot forging operation

ance to thermal fatigue, gross cracking, hot wear and plastic deformation. It is used for dies in die casting, hot forging, and hot extrusion.[14]

Die was gas nitrided and taken out of industrial process after its service time. Die was sectioned and examined with light microscopy (Olympus GX51) and by Vickers microhardness measurements (Leitz Miniload 2). Die surface was examinated using macro and micrograph techniques to reveal surface damages of nitrided layer. Additionally, metallographic examinations of samples taken from certain cross-sections were performed. Nital etchant for metallographic preparation of nitrided samples was used.

Table 1. Chemical composition of applied die steel (Dievar) in mass fractions, *w*/%

C	Si	Mn	Cr	Mo	V
0.37	0.26	0.5	5.0	2.36	0.55

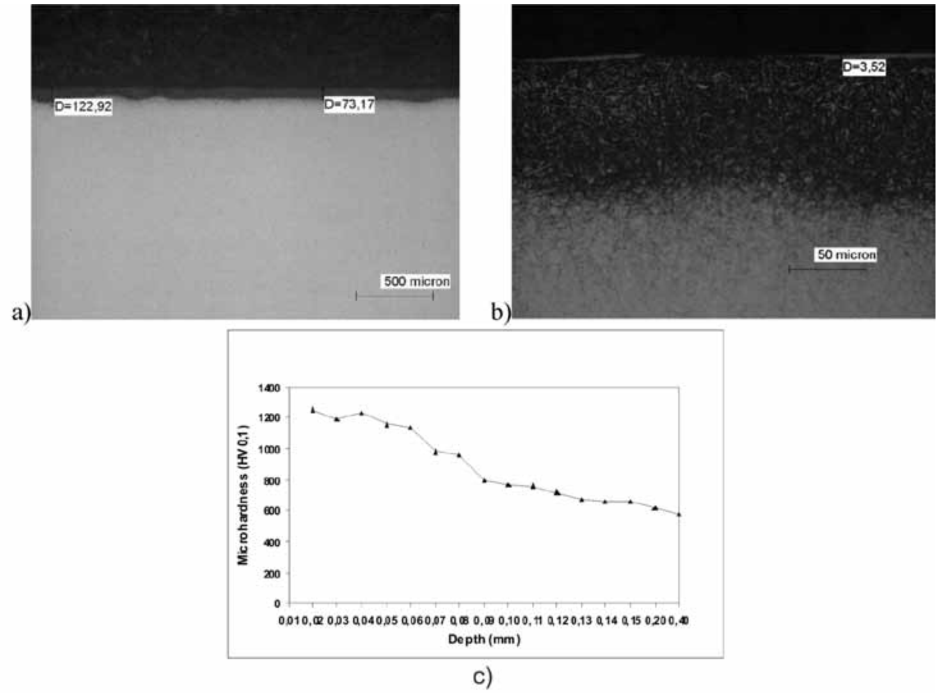

Figure 3. Microstructures and microhardness profile on cross-section of the die edge: nitrided diffusion layer with compound layer (a-b), microhardness profile (c)

Results and discussion

Initial nitrided microstructures

Diffusion layer can be well seen on cross-sections of the surface edge (Figure 3a). The depth of diffusion layer is not homogenous and it is thick from 73 μm to 122 μm (see Figure 3a). This nonhomogeneity could be atributed to unappropriate preparation of die surface before the nitriding process that resulted in different adsorption abilities of nitrogen into the die surface layer. Thickness of compound layer was in the range of about 0–3.5 μm (Figure 3b). Further, presence of nitrides was visible on grain boundaries. It was also remarked that microstructure was slightly overnitrided (nitrides on grain boundaries were in that area pependicular to diffusion front and parallel to die surface) that could result in premature spalling of die material from the die surface layer. Figure 3c gives microhardness profile; max. values were above $HV = 1200$.

Damages on die surface

The main damages of the die on macro level are shown in Figure 4. The relatively sharp edges of the upper die impression around mandrels show wear usually combined with plastic deformation and spalling (see Figures 4c, 4e, 4f). On these edges high contact pressures as well as large sliding lengths between deformed material and die surface took place. These conditions led to higher heating and consequently to higher tempering of the die surface layer that favoured wear, spalling of fragments of nitrided layer and plastic deformation. Spalling of relative large fragments is seen on the upper edge of mandrels (Figures 4c, 4e) for penultimate forging impressions. Mentioned spalling of fragments was, next to higher contact pressures that prevailed on these surfaces, also consequence of presence of nitrides on grain boundaries of the diffusion layer (see Figure 3b) that decreased toughness of die steel. But spalling on mandrels took place only on one mandrel (Figure 4e) while on the other one only emphasized wear was observed (Figure 4b). Further, also spalling on top of mandrel (see Figure 4i) was detected. This occurrence of spalling could be atributed to thermal fatigue in combination with high contact pressure. On impression radii shown in Figures 4g and 4d1 plastic deformation was not observed but only furrows as consequence of abrasion were visible. Namely contact pressures on this surfaces were relatively lower since radius of mandrel was greater. The base of mandrels previously indicated as critical areas in the hot-forging die (see Figure 1) is also critical for service life of dies and the quality of forged products. In these areas, due to pressure of forged material on both depression surfaces and consequently due to bending load on bottom of die depression, stress concentrations took place. These repeating mechanical loads resulted in formation of cracks at the base of mandrel (see Figure 4h) that caused surface, geometry and shape inadequacies of forged products. For comparison, such damage was not observed on similar area of die impression for penultimate forging sequence (see Figure 4d2). This indicated that the last impression was subjected to comparatively higher bending loads, and that required changes of impression design at the mentioned five sequential forging steps. In Figures 4a and 4f abrasion wear close to outer area of die impression as consequence of higher sliding length was observed. For further explanation and analysis of surface damages the cross-sectional microstructures especially of critical areas, i.e. on top, on upper and bottom edge as well as in the middle area of mandrel, will be presented.

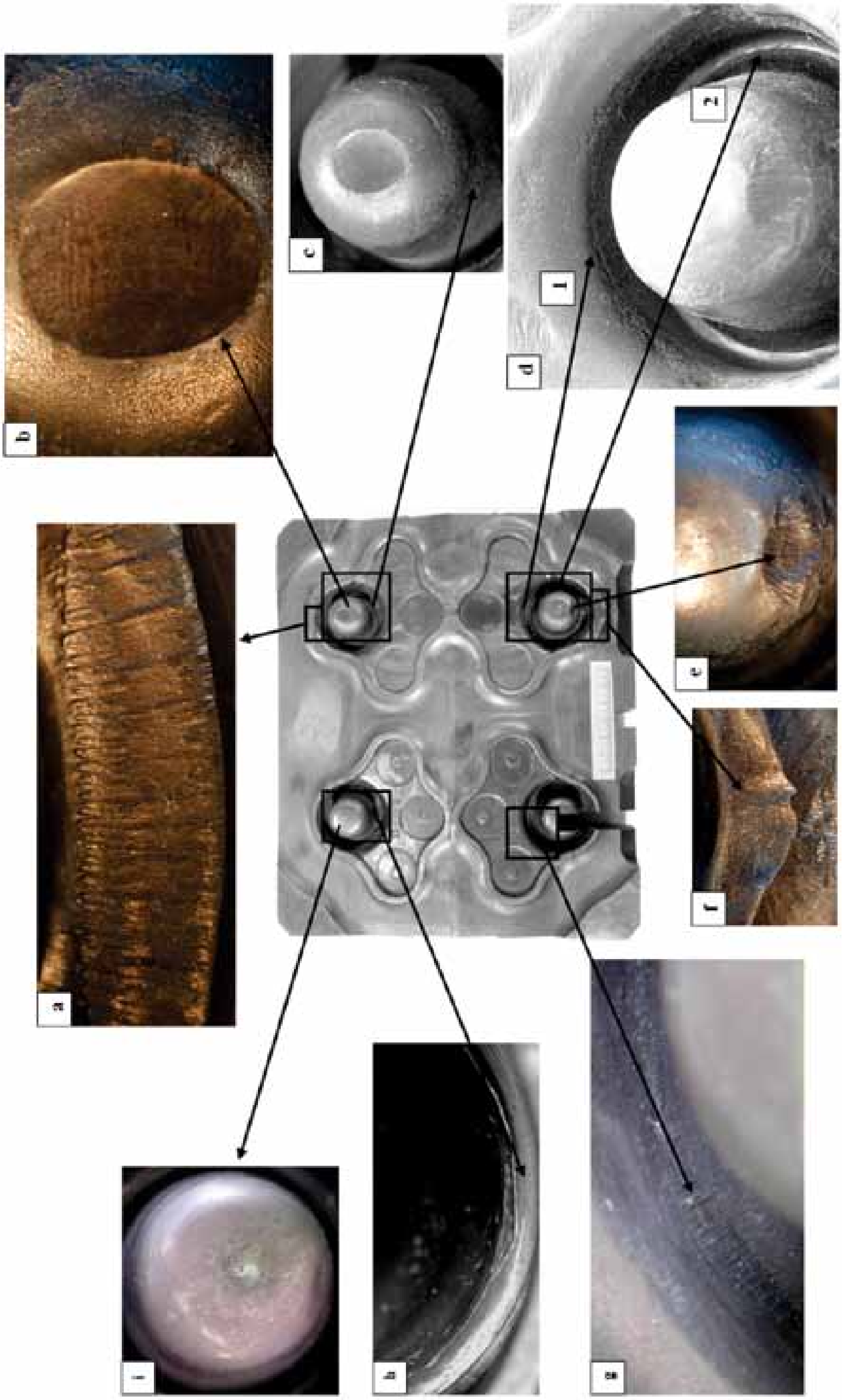

Figure 4. Damages of the die after 45 766 strokes; plastic deformation (a, f), mechanical deformation (b, c, d, e, g), spalling (d, e), cracks (d, h), wear (i).

Damages on mandrel cross-sections

Cross-sections of mandrel for the last forging operation revealed compound layer on the mandrel top (Figure 5) and in its middle area (Figure 7), while compound layer on the upper (Figure 6) and the bottom edge (Figure 8) was removed during the forging process; furthermore, formation of cracks in the diffusion layer was observed (see Figures 5 and 6). Removal of compound layer could be atributed to higher contact pressures and sliding lengths that preavailed in these areas and they led first to its cracking and then

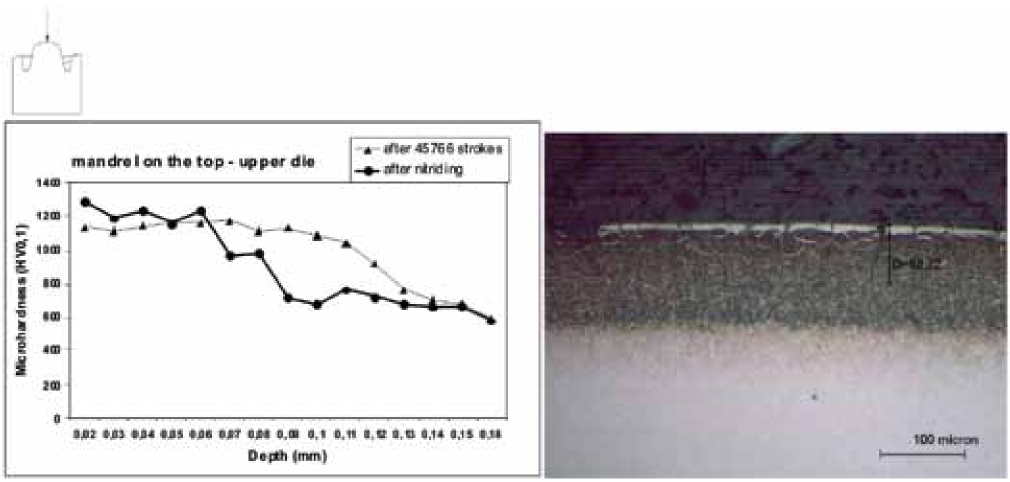

Figure 5. Hardness profile and cross-sectional microstructure on the top of mandrel

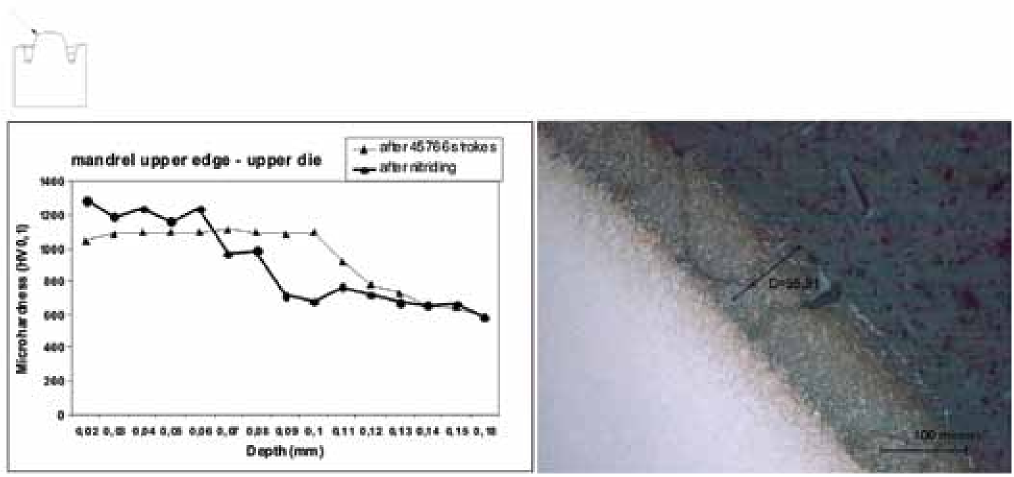

Figure 6. Hardness profile and cross-sectional microstructure on the upper edge of mandrel

to its spalling; compound layer is namely very brittle in comparison to the diffusion layer. Moreover, as mentioned above, nitrides were present on grain boundaries of nitrided microstructure that decreased toughness and accelerated spalling of fragments.

As already mentioned, cracks were also found in the diffusion layer on the upper edge having lengths of about 96 µm (Figure 6) and on the top of the mandrel with lengths of about 69 µm (Figure 5). Compound layer on the top of the mandrel also exhibited cracking as consequence

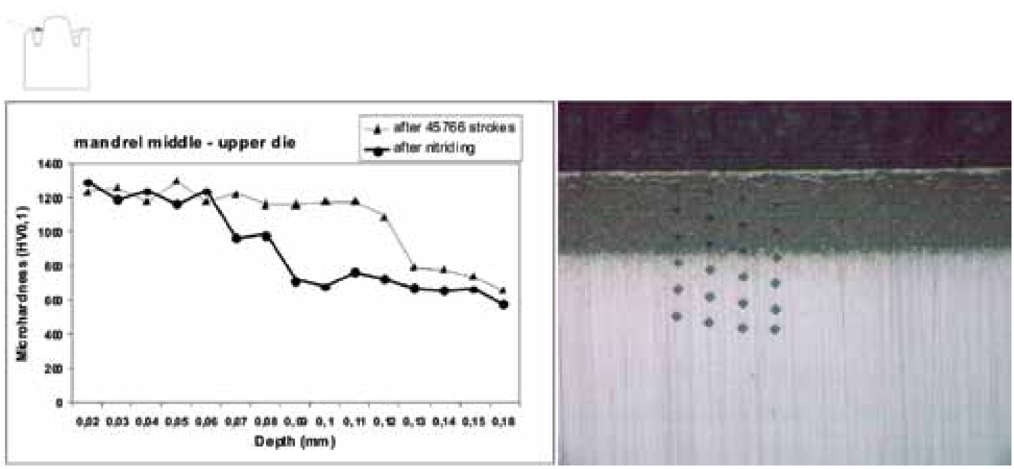

Figure 7. Hardness profile and cross-sectional microstructure in the middle part of mandrel

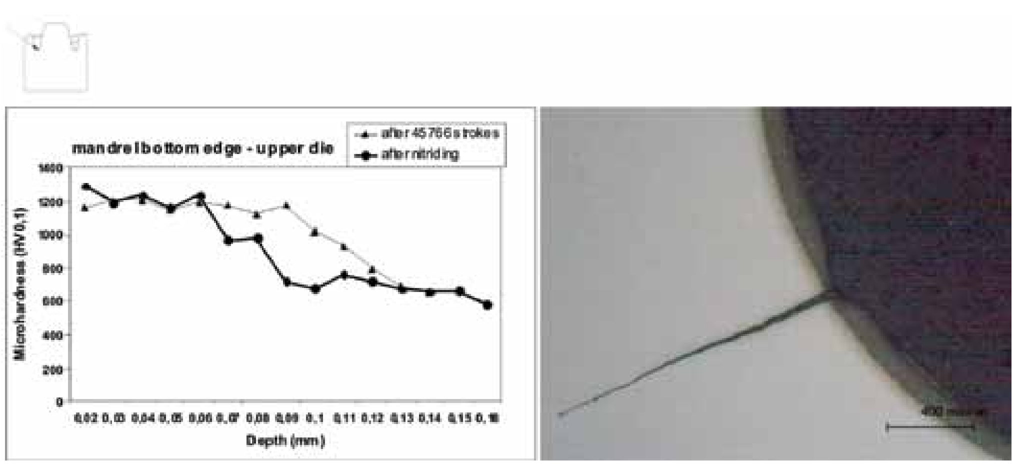

Figure 8. Hardness profile and cross-sectional microstructure on the bottom edge of mandrel.

of thermal fatigue and presence of higher contact pressures (compare Figure 5 with Figure 4i). Relative sliding between the die surface and the deformed material was reduced in these areas thus suface material was removed by spalling. Effective nitriding depths on all the cross-sections were in range of about 150–160 μm. Microhardness measurements showed the highest drop of hardness values from $HV_{0.1}$ = 1292 on the edge of die after the nitriding process, to $HV_{0.1}$ = 1044 (see Figure 6) on the upper edge of the high mandrel after die failure.

Furthermore, crack with length of about 1.5 mm at the base of mandrel was detected (Figure 8, compared with Figure 4h). In this figure also more intensive spalling of diffusion layer on the surface at the beginning of crack was observed. In fact, this surface damage limited die life since the surface quality and shape of forging did not fulfil demands of customer.

In Figures 5–8, increase of microhardness values was found at the depths of about 60 μm and less. This could be atributed to diffusion of nitrogen from the die surface layer into interior or eventual increase of carbon content since lubricant based on graphite was used for lubrication and cooling of die impressions.

Conclusions

In the presented work occurrence of damages of hot-forging die, made of Dievar, hot-working die steel that was used for hot forging of steering mechanism has been analyzed. Gas nitrided die was sectioned and examined after its service time, i.e. after 45 766 strokes using light microscopy and Vickers microhardness measurements. The essential conclusions are:

- Nitrided microstructure on cross-sections revealed presence of compound layer and nitrides on grain boundaries. Non-homogenous depth of diffusion layer that resulted in different adsorption abilities of nitrogen was observed and could be atributed to improper surface preparation prior to nitriding. In order to improve surface activation proper surface preparation prior to nitriding should be performed too.
- Proper selection of nitriding parameters is needed in order to avoid formation of nitrides on grain boundaries.
- Metallographical examination revealed that three main types of damages could be seen on die surfaces, i.e. cracks as consequence of mechanical and thermal fatigue, spalling of nitrided layer as consequence of thermal fatigue and mechanical loads, and furrows as consequence of abrasion.

- Mechanical fatique cracking occurred at the base of mandrels and it was decisive mechanism that was influencing die service life. Crack with length of about 1.5 mm was observed on the bottom edge of mandrel. This damage could be avoided by reducing the pressure of deformed material on die surface in the depression, i.e. by optimizing deformation sequences (steps) in forging.

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