ABSTRACT

In warm and hot forging, the dies are subjected to high contact pressures and temperatures. The selection of the die material, hardness and coating is critical for increasing die life in precision forging. In addition to traditionally used hot work die steels, latest studies have also shown improvements in die life by use of ceramics and surface treatments including vapor depositions techniques. This paper reviews the latest state of technology on die materials and surface treatments used in hot and warm forging of steel. Finite Element Analysis (FEA) based methods have also been used to estimate abrasive wear and plastic deformation on forging dies. These estimations can help to evaluate the life of die materials and coatings as well as in estimating die costs for a given production run.

1 INTRODUCTION

The selection of the die materials is a very significant decision in the production of precise components by forging. Appropriate selection of die materials is imperative to get acceptable die life at reasonable cost. Die wear is mostly influenced by the hardness of the die material and other material properties such as toughness and ductility. Selection of proper die materials is very important for reducing the production costs and setting narrow tolerance for the forged part (1).

In hot forging, the mechanisms by which the dies fail are due to wear (adhesive and abrasive), plastic deformation and fatigue (mechanical and thermal). Of all the failure mechanisms present during a forging process, wear and mechanical fatigue is found to be the most common form of failure during forging.
In this review paper, some of the commercially available die materials were compared based on their hardness data available in material data sheets. These materials are used for hot and warm forging in mechanical presses. This paper also includes the results of a study by ERC/NSM, in which wear and plastic deformation on warm forging dies was successfully estimated by using Finite Element Analysis. Some of the studies on ceramic die materials present in literature were reviewed. Surface treatment techniques such as nitriding, weld overlays as well as ceramic coatings were also investigated.

2. DIE MATERIALS FOR FORGING OF STEEL

There are various tool steels which are used in forging. Although in hot and warm forging, mainly hot work die steels are used due to their ability to retain their hardness at elevated temperatures with sufficient strength and toughness to withstand the stresses that are imposed during forging. There have also been some successful applications of other materials such as ceramics, carbides and super alloys although their application is limited due to design and cost of manufacturing. The selection of die material grade and subsequent treatment affects the mode of failure and rate of tool failure.

2.1 Hot Work Die Steels

Hot working die steels used at temperatures between 310 °C and 650 °C contain additions of chromium, tungsten, vanadium and molybdenum to provide deep hardening characteristics and resistance to abrasion and thermal softening at high temperatures. Molybdenum increases resistance to thermal softening, vanadium improves wear and thermal fatigue characteristics. Tungsten alloy steels are not resistant to thermal shock and must not be cooled intermittently with water.

The selection of die steel largely depends on the temperature developed in the dies, the load applied and the mode of cooling of the dies. Most hot work tool steels are low carbon steels with medium or high alloying elements. The compositions of the AISI grade hot work tool steels are given in literature, for example. Chromium hot work steels are the most commonly used for forging applications. In general, chromium die steels retain their hardness upto 425 °C, tungsten hot work steels retain much of their hardness upto to 620°C. The properties of molybdenum based hot work steels is in between that of chromium based and tungsten based hot work die steels. Thermal and mechanical properties of various AISI standardized hot work tool steels is available in many books hence have not been listed here.

Apart from the AISI standardized die steels, many manufacturers have standardized materials which are either having the composition similar to the AISI standard or their variants based on the alloy contents and the heat treatment used. Some commercially available hot work die steels which are suitable for use in extrusion tooling for forging of engine valves are listed in Table 1. The compositions and the hardness ranges recommended by the manufacturer are also shown in the table.
Except DRM1 and DURO F1 die materials, all other materials were regular Chromium and Molybdenum based hot working die steels. These materials are suitable for the extrusion die inserts and other surrounding tooling such as the extrusion bushing and die holder. DRM1 and DURO F1 are matrix high speed steels (MHSS) which are suitable for extrusion punches. MHSS usually contain higher percentage of tungsten or molybdenum which provides high hardness to the dies. To understand the performance of the nine materials, the data obtained from the individual data sheets was compared.

Table 1: Composition of materials considered suitable for extrusion tooling

<table>
<thead>
<tr>
<th>Make</th>
<th>Material</th>
<th>Composition</th>
<th>Recommended Initial hardness range (HRC)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C  Si  Mn  Cr  Mo  V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bohler</td>
<td>W360</td>
<td>0.5  0.2  0.25  4.5  3</td>
<td>0.55  52-57</td>
<td>Recommended for hot valve extrusion.</td>
</tr>
<tr>
<td></td>
<td>W302</td>
<td>0.39  1.1  0.4  5.2  1.4</td>
<td>0.95  52-56 in oil or salt bath 50-54 in air</td>
<td>Same as AISI H13</td>
</tr>
<tr>
<td></td>
<td>W303</td>
<td>0.38  0.4  0.4  5.0  2.8</td>
<td>0.55  52-56 in oil or salt bath 50-54 in air</td>
<td>Also recommended by Patricia Miller (Bohler)</td>
</tr>
<tr>
<td>Uddeholm</td>
<td>QRO 90</td>
<td>0.38  0.3  0.75  2.6  2.25</td>
<td>0.9  48-50</td>
<td>Used by Eaton-Torino for Extrusion die and bushing and Coining die.</td>
</tr>
<tr>
<td></td>
<td>Supreme</td>
<td>0.55  1.0  0.75  2.6  2.25</td>
<td>0.85  54-58</td>
<td>Used for wear resistance at high temperatures</td>
</tr>
<tr>
<td></td>
<td>HOTVAR</td>
<td>NA  NA  NA  NA  Cr-Mn-V type</td>
<td>44-46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DIEVAR</td>
<td>NA  NA  NA  NA</td>
<td>44-46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ORVAR</td>
<td>0.39  1.0  0.4  5.2  1.4</td>
<td>0.9  44-50</td>
<td>Premium H13</td>
</tr>
<tr>
<td></td>
<td>Supreme</td>
<td>0.39  1.0  0.4  5.2  1.4</td>
<td>0.9  44-50</td>
<td>Premium H13</td>
</tr>
<tr>
<td>Daido</td>
<td>DRM1</td>
<td>0.6  NA  NA  4.2</td>
<td>Weq = 2Mo+Mw/5</td>
<td>1.5  58 max</td>
</tr>
<tr>
<td>Nachi</td>
<td>DURO F1</td>
<td>NA  NA  NA  NA  NA</td>
<td>54-60</td>
<td>Also Matrix HSS type</td>
</tr>
</tbody>
</table>

All materials except DRM1 and DURO F1 are Chromium Molybdenum based die steels  NA= Not Available

The most important criteria for selection of die steel material for forging are its resistance to wear, plastic deformation and fatigue (mechanical and thermal). To provide resistance to wear and plastic deformation, the dies hardness should be as high as possible. But the dies should also have adequate toughness as the dies are subjected to changes in pressures and temperatures. Hot work die steels are usually subjected to a heat treatment cycle prior to use (Figure 1). After hardening (by quenching) they are also usually tempered (once or multiple times) to provide enough toughness. Tempering temperature is the temperature at which the dies are held after hardening. As the tempering temperature is increased, the hardness achieved after tempering decreases. So, the toughness required for the dies sets the limit of maximum hardness that the dies can be used.
The tempering curves for the nine die materials are given in Figure 2. The tempering temperature also defines the working temperature range for the dies. During forging, if the temperature on the dies exceeds the tempering temperature, the dies soften and lose their hardness quickly.

Figure 1: Heat treatment cycle of hot work tool steels (4).

After the dies are tempered the “initial” room temperature hardness can be determined. During forging, as the die surface is subjected to high temperature, the hardness of the die decreases. Even if the initial hardness for a material is high, if the hardness drops drown as the temperature is increased then the dies are not good. Die materials are considered to be better if they are able to retain their hardness at elevated temperature i.e. they should have better hot hardness properties. The variation of hot hardness of the nine materials is as shown in Figure 3. As the temperature in the hot forging tooling is above 500°C it is imperative for the die materials to retain their hardness prior to dropping down. Moreover, materials which have steep decrease in hardness are considered to be unsuitable compared to the dies which have moderate hardness and gentle reducing hot hardness curves.

It can be observed form the tempering curves that DURO F1 and DRM1 can be tempered to a higher hardness compared to other die materials. The hot hardness curves show that during forging, W360 and DRM1 are more likely to retain their hardness (at temperatures above 550°C) compared to other materials.
Figure 2: Comparison of tempering curves

Figure 3: Comparison of hot hardness curves
Although ability to be hardened and retain hardness, there are also other important factors that affect die life. Tool steels are usually manufactured by secondary refining (remelting) processes (or refined) to get the right composition and remove impurities. Impurities and inclusions can nucleate cracks when subjected to stresses. Tool steels produced under protective atmosphere such as Vacuum Arc Remelting (VAR) produce cleaner steels with better structural homogeneity compared to Electro Slag Remelting (ESR) processes. Tool steels produced by VMR are observed to have superior toughness compared to ESR. [Patricia Miller BU Corp]. Apart from mechanically induced stresses due to forging pressure, the hot forging dies are subjected to thermal stresses especially near surface of the dies where they are in contact with the work piece. These thermally induced stresses initiate cracks on the dies due to heat checking which can propagate and cause die fracture. Thermal stresses are proportional to the thermal expansion coefficient, elastic modulus and inversely proportional to the thermal conductivity of the material. [Patricia Miller BU Corp].

A number of researchers have attempted to use finite element simulation to predict die wear in metal forming and machining operations. The basic concept is to determine process variables (such as temperatures, stress, and sliding distances) using finite element simulation. Then a wear prediction equation or a set of equations is derived in terms of these process parameters. Considerable research has been done on die wear in forging by adopting Archard’s wear model (5). Painter analyzed abrasive and adhesive die wear during the hot extrusion process considering hot hardness of materials (6). Kang suggested a modified wear model to express the room temperature hardness of the die by function of temperature and operating time, tempering parameter, considering thermal softening of die in elevated temperature forging processes (7). Behrens suggested an advanced model in order to assess the influence of sliding velocity on the wear in relation to the influence of the contact normal pressure between workpiece and tool (8). Kim suggested estimating service life of hot forging dies determined by plastic deformation, by applying a function with respect to tempering parameter. The hardness holding time (or total forging time at elevated temperatures) of the die was calculated using an equivalent temperature and forging cycle time (9) (10).

In a research study for the Forging Industry Educational and Research Foundation (FIERF) in cooperation with Hirschvogel Inc., Columbus, OH, the ERC/NSM was able to estimate the wear and plastic deformation on dies using Finite Element Analysis for a steel pinion shaft. The pinion forging process consists of three stages namely, forward extrusion, upsetting and coining. This study was primarily focused on the first forward extrusion stage. The schematic of extrusion tooling and extrusion insert is as shown in Figure 4. The extrusion die insert is made of tool steel (various materials were tested, but DURO-F1 is presented in this paper).
Figure 4: Schematic of Extrusion tooling and Extrusion Insert detail (Courtesy Hirschvogel, Inc)

From CMM measurements of used dies, it was concluded that the extrusion inserts undergo both wear and plastic deformation during forging. The measured die surface profile, obtained after failure, includes the effects of both plastic deformation and abrasive wear. The equation used to predict the wear profile, assuming abrasive wear, does not include the effect of the plastic deformation on the die surface. The methodology used for the prediction of abrasive wear is shown in Figure 5, and outlined below (11):

- Conduct finite element analysis of the steady state temperature distribution of the dies, using multiple operations using DEFORM-2D, a commercial FE software package.
- Estimate the plastic deformation from the results of the steady state temperature distribution of the dies.
- Extract the wear profile from the measured die surface profile (obtained by CMM) by separating the plastic deformation from abrasive wear.
- Determine the abrasive wear parameters, in order to predict abrasive wear on the die surface.

In order to predict the abrasive wear and plastic deformation, subroutine programs for Deform-2D were developed to a) calculate the tempering parameter from the calculated...
steady state temperature distribution of the die, b) modify the flow stress data based on the calculated tempering parameter, and c) compute the amount of wear with the advanced Archard’s wear model. Finally, the wear parameters (K and a) are mathematically optimized (to give the minimum difference between the predicted wear and actual wear profiles) and then verified by comparing the predictions with the experimental results.

![Methodology Diagram](image)

**Figure 5:** Methodology used for predicting plastic deformation and wear in hot/warm forging (11).

The predicted wear, from the FEA simulation and wear equation results, is compared to the measured wear data, from the CMM measurements modified for plastic deformation, in Figure 6. The comparison shows that the prediction is very close to the input information (as it should be).

Prediction of plastic deformation and wear parameters (K and a) can assist in optimizing the forging process to improve die design and predict the suitable forging conditions such as billet temperature, press speed and lubrication to get better die life.
2.2 CERAMIC AND CARBIDES DIE MATERIALS

Potential use of ceramics and carbides has been found be gaining interest for use in warm and hot forging applications. Ceramic inserts and coatings are well established in the machining industry for reducing tool wear and enhancing the tool performance. Some of the ceramic materials have marked improvements over the traditional hot work die materials (Cr-Mo-W based steels) used in hot forging.

The benefits of using ceramic materials for forging dies is possible only by optimal design of dies such that the ceramic dies are not subjected to stresses which can lead to failure due to cracking. As ceramics have low tensile strength and high cost, their applications are limited to small inserts which are fitted onto larger hot work steel dies/container rings. Ceramic dies are usually under compressive pre-stress to prevent brittle fracture due to internal pressures during forging. Furthermore, the compressive
state of stress has to be maintained at various temperatures when the ceramic dies and container rings are at different temperatures.

Silicon Nitride, Sialon and Silicon carbide are some of the potential ceramic materials that can be used for hot forging applications. Hot pressed Silicon nitride is a ceramic that has extremely high hardness, high toughness and wear resistance. Due to adequate thermal shock resistance, hot hardness and resistance to oxidation it can be used in hot forging applications. Silicon Aluminum Oxynitride (Sialon) has similar properties to silicon nitride but even better resistance to oxidation at high temperatures. When compared to hot working tool steels, Sialons retain their hardness more efficiently at elevated temperatures (See Figure 7) (12). They were developed to solve the difficulties involved in fabrication of silicon nitride.

![Figure 7: Comparison of hot hardness of ceramic die material (Sialon) and advanced hot working tool steel grades (12).]

Syalon 101™ is a beta-sialon type ceramic manufactured by International Syalon, which has high toughness, strength and chemical and thermal stability (Table 2). It can be used up to temperature as high as 1000° C. It has been successfully used for extruding and drawing copper, brass and nimonic alloys. This material is currently being tested for forging of steels as indicated by US Alloy Die Steel Corporation. (www.usaalloydie.com)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT Tensile strength</td>
<td>450</td>
<td>Mpa</td>
</tr>
</tbody>
</table>

Table 2: Properties of Syalon 101
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT Compressive strength</td>
<td>&gt;3500 Mpa</td>
</tr>
<tr>
<td>RT Young’s Modulus</td>
<td>288 Mpa</td>
</tr>
<tr>
<td>RT Hardness (Vickers HV$_{0.3}$)</td>
<td>1500 Kg/mm$^2$</td>
</tr>
<tr>
<td>Fracture Toughness $K'_{IC}$</td>
<td>7.7 MPam$^{1/2}$</td>
</tr>
</tbody>
</table>

Ceramic dies have also been tested in Japan for warm forward extrusion dies. Nissan motor company has tested cermet dies made of MoB (ceramic). The material is powder formed and sintered. In production tests, two die materials were tested on forward extrusion (Figure 8) of outer race part under warm forging conditions. It was observed that the MoB cermet dies could withstand high temperatures (800 °C) even better than nickel based super alloy (12).

![Forward extrusion of outer race part using MoB dies (13).](image)

In a study conducted by (14), ceramic and carbide materials were compared with hot working die materials (H21 and MHSS). Carbide had approximately 125% greater thermal conductivity compared to steels, which in turn is 200% greater than that of ceramic(Figure 9). Thermal expansion was 180%-200% greater than that of ceramic and carbide. Thermal conductivities influence the temperature gradient in the dies. The interaction between the thermal conductivities and thermal expansion influences the surface stresses and the thermal fatigue in the die surface. FE simulations were conducted for warm upsetting of automotive transmission shaft (Figure 10). The die insert was tested with four materials. Due to low thermal conductivity of ceramic material, the die surface temperature was observed to be higher compared to other materials during forging (Figure11). Also elastic modulus of carbides was 200% greater than that in steel and 80-90% greater than that of ceramic.
Figure 9: Comparison of thermal properties of carbides and ceramic to steels (ThCond: Thermal Conductivity; ThExp: Coefficient of Thermal Expansion) (14).

Figure 10: Schematic representation of the warm forging (upsetting) die assembly (14).
In investigation of ceramic inserts by (15), two assembly techniques were explored as shown in Figure 12a. Of these two techniques, brazing was observed to be more flexible since it allows the application of inserts in complex tool geometries in wear critical areas. One of the drawbacks of this method, however, is the residual stresses generated from brazing. Thermal shrinking on the other hand is better suited for axisymmetric geometries. The different insert geometries investigated are shown in Figure 12b. The effect of different interference fits and preheat temperatures was not investigated in these studies (15).

Tests were also conducted to use ceramic inserts in hot forging of gears. Ceramic inserts were brazed in locations where there is maximum wear. During the trials it was observed that the solder quality has to be controlled consistently in order to prevent premature failure of the die in service. A hot forging die with 16 inserts was being tested for precision forging of spur gears (Figure 13). Research is currently in progress to ensure the durability of active brazed ceramic inserts and to optimize the joining region (16).
Two types of insert designs investigated viz. shrink-fit and brazed

Different types of shrink-fit designs investigated in forging trials

Figure 12: Die designs investigated in forging trials with ceramic inserts (15).

a) Schematic of gear forging tooling  b) Steel die with brazed Ceramic inserts

Figure 13: Flashless hot forging of gears using ceramic (Si3N4) inserts (16)
Research trials were also done by Nagano Tancoh Co. (17) to use ceramic die inserts in place of H13 tool steel in manufacturing engine valves by hot forging. Sintered silicon nitride was used to make the die inserts. Two different coining tooling designs were investigated for performance of shrink fit and die life (Figure 14). Tests were also conducted by Kwon and Bramely (18) to compare the performance of H13 with Zirconia and silicon nitride inserts, laboratory results indicate that there is improvement in die life and better dimension control of the forged parts. Although the exact magnitude of improvement in dies life was not disclosed.

![Figure 14: Tooling designs used for ceramic inserts (14) (17).](image)

3. DIE COATINGS AND SURFACE TREATMENTS

Hot forging dies are subjected to severe wear (adhesive and abrasive), high stresses and temperatures. The die surface and near surface region is subjected to the most severe conditions during forging and hence most defects and causes of failure of the dies originate from this region. Die surface treatments such as nitriding, weld overlays (or hardfacing) and chemical and physical vapor deposition of heat resistant ceramic materials have been observed to substantially increase the life of the hot work dies. The classification and size of various surface treatments and coatings and their typical depths is as shown in Figure 15(4). Most die surface treatments are used to increase the hardness of the surface as the die wear decreases with increase in hardness. The
ranges of surface hardness by various surface treatments and coatings for tool steels are as shown in Figure 16 (4).

Nitriding is the most commonly used surface treatment for hot forging dies. Boriding (also called boronizing) and surface welding are also used in many cases. Surface welding is also used to rebuild worn dies. The vapor deposition techniques such as PVD, CVD are more commonly used for cold forging applications but also have some success in hot and warm forging applications. The cost of surface treatment is an important criterion in selection of the coating. Figure 17 although not very recent, provides a rough understanding of the relative costs of various surface treatments.

Figure 15: Classification of various surface treatments and coating and typical depths of surface modified by various processes (4).
Figure 16: Ranges of surface hardness of various surface treatments and coatings (4).

Figure 17: Approximate relative cost of surface treatments (19).
3.1 Nitriding

Nitriding is a common technique used to increase the hardness of the die surface. The increase in hardness is due to the diffusion of nitrogen into the die surface. Nitriding is observed to reduce the wear rate by as much as 50% (20). Furthermore, the nitride layer also improves thermal fatigue resistance of the dies because it imparts compressive residual stresses. It also improves the tempering resistance due to the diffusion layer. Although there is improvement of hardness and fatigue resistance (due to residual compression), nitriding decreases the toughness of the die surface. As a result, chipping of the nitrided edges can occur in some applications especially around sharp corners.

The nitrided surface can be obtained by gas, liquid and plasma (Ion) mediums. Nitriding is usually performed at temperatures between 400°C to 560°C. The nitrided surface is made of two zones (Figure 18). The most outer layer is called the compound zone (hard white color) which is made of intermetallic compounds of nitrogen and iron (Fe4N). The inner layer is called the diffusion layer which has fine precipitates of iron and other alloy elements which cause the increase in hardness in this zone (Fe3N). The proportion of nitrogen decreases until the original structure (base metal) is observed. The formation of the white compound layer is usually undesirable as this hard brittle layer may spall during forging operation. The thickness of the brittle white layer depends on the nitriding technique used.

![Figure 18: Change in the base metal after nitriding.](image)

3.1.1 Hardness profile of nitrided die surface

The depth and hardness of the nitride layer depends not just on the nitriding process parameters such as temperature, nitrogen medium composition, nitriding time but also on the composition of the material being nitrided. Die materials containing high amounts of chromium, vanadium and molybdenum can form nitride layer which is shallow and very hard. Low alloy chromium steels such as 6G and 6F2 form deeper nitride layer which are tougher but not as hard [Advanced Heat Treat Corp.] (20).

The influence of salt bath nitriding time on the surface hardness of H13 hot work tool steel was presented by (21). It can be observed that the hardness of the surface layers does not increase significantly beyond 15 hours of nitriding time (Figure 19).
Figure 19: Hardness profiles for various salt bath nitriding times with H13 hot work die steel (21).

The effect of alloying elements on hardness profiles was investigated by (22). The hardness profile [HV0.5 Vickers hardness scale] for three of the materials tested is shown in Figure 20. The three materials tested are manufactured by Bohler Udderholm. W300 and W302 are equivalent to AISI H11 and AISI H13 respectively. W360 is a specialty hot work tool steel. More materials properties of these materials may be obtained from www.bucorp.com. Silicon content in the die material was found to have major effect on the depth of nitriding. It was also observed that addition of 1% Al was found to increase the hardness of the dies. The hardness profiles of ion nitriding of various commercially available forging die materials can be obtained in (23).
3.1.2 Compressive residual stress distribution due to nitriding

Nitriding of dies cause near-surface residual compressive stresses which can improve fatigue resistance of die materials. The microhardness [HV0.1 Vickers hardness scale] and residual stress depth profile for plasma nitrided and nitrocarburised H11 die steel (Figure 21) was investigated by (24). It can be observed that the residual stresses are compressive in the nitride layer (near the surface). The nitriding parameters can be optimized to get favorable residual stress distribution on the die surface.
Figure 21: Comparison of microhardness [HV0.1 Vickers hardness scale] and residual stress depth profile for A) Plasma nitrided and B) Nitrocarburised H11 die steel (24).
3.2 Weld overlays (Hardfacing)

Weld overlays are used to produce deposits that are metallurgical bonded to the surface of the dies. Weld overlays can be used as an economical technique to deposit a hard layer on localized wear prone die areas. They can also be used to repair, dimensional restoration and maintenance of die molds. In hot forging applications, hard heat resistant materials such as cobalt (carbide hardening alloys) or nickel alloys (intermetallic hardening alloys) are welded onto the surface of hot work die steels to improve the life of the dies (20). The performance of cobalt based weld overlays (Stellite 6) was compared with other surface treatments (nitrided) and coatings (AlTiN and TOKTEK) in hot forging by (25), for dies with weld overlays the die life was higher compared to other techniques.

The room and high temperature wear behavior of nickel and cobalt based weld overlays on hot forging dies was studied by (26). The composition of the materials used is given in Table 3. The wear tests were conducted on high temperature pin on disk tribometer with test material in conformal contact against the disk. Test results show that Inconel 625 has the least amount of wear among the three coatings at high temperature although the wear was high at room temperature (Figure 18). For better thermal fatigue resistance of weld overlays, it is desired to reduce the difference in the thermal expansion between the weld overlays and its substrate in order to minimize the residual stresses induced when cooled from the welding temperature. Stress relief annealing may be required to reduce the stress gradient (27).

Table 3: Composition of weld overlays used (26)

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>Fe</th>
<th>Ni</th>
<th>Co</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellite 6</td>
<td>1.2</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>28</td>
<td>-</td>
<td>5</td>
<td>2.5</td>
<td>2.5</td>
<td>Bal.</td>
<td></td>
</tr>
<tr>
<td>Stellite 21</td>
<td>0.25</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>27</td>
<td>5.5</td>
<td>2.5</td>
<td>2.5</td>
<td>Bal.</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Inconel 625</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21</td>
<td>9</td>
<td>-</td>
<td>1</td>
<td>Bal.</td>
<td>-</td>
<td>4 Nb</td>
</tr>
</tbody>
</table>
3.3 Ceramic coatings and Vapor deposition techniques

Chemical and physical vapor deposition techniques can also be used to deposit thin layers of ceramic compounds which improve the wear resistance and life of tool steels. The thickness of the vapor deposition coating is lower than other surface engineering techniques. In hot forging, the coatings should be able to withstand high temperatures and pressures that can lead to descaling of the coatings from the substrate. Hence, adherence of the coating to the die surface is imperative. In some applications, multiple layered coatings are used to improve the life and performance of the coatings. Coatings on nitrided die steels have also been observed to further enhance the life of the dies (27).

Most of the literature on coatings for wear reduction is concentrated on processes such as die casting or extrusion of aluminum alloys with few studies applying ceramic coatings to hot forging. Thus, the results from these studies, in terms of actual wear resistance of the coatings, may not apply directly to hot forging of steel. However, the coating characterization studies as well as the investigations on the interaction between different coating types and substrate pre-treatments are applicable. Table 4 contains information on some of the coatings found in literature along with various deposition processes and characteristic properties (28). The critical load mentioned in Table 4 is the measure of adhesion of the coatings to the hot work die surface. It is defined as the...
normal load required stripping off the coating from the die surface. The coatings are required to resist abrasive wear, chemical wear and corrosion (27).

Table 4: Some of the commonly used coatings along with the process used and laboratory test (28).

<table>
<thead>
<tr>
<th>Coating</th>
<th>Coating Process</th>
<th>Micro-hardness</th>
<th>Critical load (N)</th>
<th>Wear resistance</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiN/nitrided layer</td>
<td>Low p plasma nitriding+ ion Plating</td>
<td>3780±300 (HV₆₀₀)</td>
<td>L₉₀ = 75–77, L₂₀ = 104</td>
<td>–</td>
<td>Cohesive and adhesive failures</td>
</tr>
<tr>
<td>(Ti,Al,N)/nitrided layer</td>
<td>Low p plasma nitriding+ ion Plating</td>
<td>1180 (HV₆₀₀)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TiN</td>
<td>r.f. magnetron Sputtering</td>
<td>3347±324 (HK)</td>
<td>L₉₀ = 15, L₅₀ = 50</td>
<td>Good</td>
<td>Ductile failure</td>
</tr>
<tr>
<td>CrN</td>
<td>r.f. magnetron Sputtering</td>
<td>2306±234 (HK)</td>
<td>L₉₀ = 8, L₅₀ = 23</td>
<td>–</td>
<td>Brittle failure</td>
</tr>
<tr>
<td>CrN</td>
<td>r.f. magnetron Sputtering</td>
<td>2102±86 (HK)</td>
<td>L₉₀ = 7, L₅₀ = 26</td>
<td>–</td>
<td>Brittle failure</td>
</tr>
<tr>
<td>TiN</td>
<td>Low T° MO. PACVD</td>
<td>2000 (HK₆₀₀)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TiN/TiCN</td>
<td>Low T° MO. PACVD</td>
<td>3000 (HK₆₀₀)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Zr(C,N)</td>
<td>Low T° MO. PACVD</td>
<td>1000–1200 (HK₆₀₀)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TiC/Al/N/</td>
<td>High pressure Plasma</td>
<td>1400 (HV₆₀₀)</td>
<td>L₉₀ = 10–80</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>nitriding layer</td>
<td>r.f. and d.c. reactive</td>
<td>4–28.6 GPa</td>
<td>L₉₀ = 13–22, L₅₀ = 17–57</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TiN</td>
<td>CVD + plasma nit.</td>
<td>800–1600 (Hv)</td>
<td>L₉₀ = 18–36</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TiN</td>
<td>Arc Evap. + PACVD</td>
<td>L₉₀ = 20–100</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CrN</td>
<td>Arc evaporation + annealing</td>
<td>17.7–23.5 GPa</td>
<td>L₉₀ = 80–100, L₅₀ = 150–190</td>
<td>Very good</td>
<td>–</td>
</tr>
<tr>
<td>TiN</td>
<td>PVD</td>
<td>2490±80 Hv</td>
<td>L₉₀ = 32±4, L₅₀ = 57±4</td>
<td>Moderate</td>
<td>–</td>
</tr>
<tr>
<td>CrN</td>
<td>PVD</td>
<td>1410±90 Hv</td>
<td>L₉₀ = 15±1, L₅₀ = 27±5</td>
<td>Good</td>
<td>–</td>
</tr>
<tr>
<td>(Ti,Al,N)</td>
<td>e-beam evap. + magnetron</td>
<td>2300±80 Hv</td>
<td>L₉₀ = 32±4, L₅₀ = 47±2</td>
<td>Very good</td>
<td>–</td>
</tr>
<tr>
<td>TiB₂</td>
<td>PVD</td>
<td>4000±160 Hv</td>
<td>L₉₀ = 14±1, L₅₀ = 28±2</td>
<td>Very good</td>
<td>–</td>
</tr>
<tr>
<td>Cr–Cr, Si</td>
<td>Hot pressed</td>
<td>5.2–10.7 GPa</td>
<td>–</td>
<td>Good</td>
<td>–</td>
</tr>
</tbody>
</table>
The conventional CVD process requires high temperatures in the range of 900 - 1100°C thus limiting its application. Plasma assisted CVD (PACVD) is a more viable option due to its ability to provide a uniform coating on complex geometries at significantly lower temperatures (500-550°C) i.e. below the tempering temperatures of hot work tool steels (29). Figure 19 shows the temperature ranges used in various coating techniques (Oerlikon-Balzers). Coating systems are commercially available through companies such as Oerlikon-Balzers. BALINIT® ALCRONA coating is recommended coating for hot forging applications. This coating is made of ALCrN and can withstand temperatures as high as 1100 °C (Oerlikon-Balzers) (27).

![Figure 19: Coating thickness vs. temperature ranges for competing technology](image)

Figure 19: Coating thickness vs. temperature ranges for competing technology 1- Plasma spraying, 2- Electrolytic and chemical deposition, 3- Phosphating, 4- Nitriding 5- Boriding, 6-CVD, 7-PVD, PACVD (Oerlikon-Balzers)

### 3.3.1 Coating Architecture

Coating architecture refers to the number of coating layers as well as any pretreatment given to the substrate in the form of nitriding, boriding etc. Wear resistance and adhesion of the coating to the substrate depends greatly on the coating architecture.

The effect of prior surface treatment of the substrate on coating wear performance has been investigated in numerous studies (28) (29) (30). These “duplex” coating techniques consist of gas or plasma nitriding of the substrate (tool steel) followed by a PVD or CVD deposition of the ceramic coating. The nitriding is found to enhance the performance of the coating by providing a gradual transition from the mechanical and thermal properties of the substrate to that of the hard coating. Improved adhesion of the
coating is another advantage of the process. The adhesion of TiN coating by PACVD on nitrided H13 dies was studied by (31). The composition and thickness of nitride layer has an effect on the adhesion onto the dies. Hot forging trials by (32), TiCN coating by PACVD technique on plasma nitrided dies. It was also observed that surface preparation of the nitrided die also plays an important role in that the life of the coatings. Detailed SEM inspection of the worn die surface revealed local flaking as well as crack propagation into the nitrided substrate (H11) (Figure 20). The coatings were found to adhere better when the nitrided dies were polished prior to coating.) (10).

![Figure 20: Local flaking of TiCN coating and the propagation of cracks into the nitrided substrate (32).](image)

Some studies (28) investigated the use of multilayer coatings such as titanium aluminum nitride [(Ti, Al) N] along with the use of an “adhesion” layer. Figure 21 shows a schematic of such a deposited layer.
Figure 21: Schematic representation of a multilayer coating on a hot working tool substrate (28).

The coating hardness at elevated temperatures is an important property of the coatings as the wear is directly dependent on the hardness of the coatings. Wear resistance at room and elevated temperature of (TiAl)N PVD coating on gas nitrided H13 dies with different heat treatments was investigated by (33). To determine the wear resistance, ball on disk tests were carried out for the two types of substrate which have been obtained by different surface engineering techniques. For dies with (TiAl)N PVD coating without nitriding, highest wear volume was observed. This was attributed to the low load carrying capacity. Best wear resistance at 600° was observed for specimens with (TiAl)N PVD coating on nitrided surface (Figure 22). The nitride layer enhanced the load bearing capacity of the system and hence reduces the difference in hardness between the substrate and the ceramic coating. It was also observed that diffusion of nitrogen from the nitrided surface into the coating further improves the mechanical properties of the coatings.

During hot forging, the die surface is subjected to drastic changes in temperature from the maximum temperature during forging to the minimum temperature after lubrication hence the coatings should have adequate resistance to thermal fatigue. The thermal fatigue properties of die steels are were investigated by (34) for PVD coatings of CrN and ZrN on H11 dies with and without nitride layer. It was observed that due to the difference in coefficient of thermal expansion and Young modulus compared to substrate thermal crack nucleation takes place. It was also observed that the coatings perform better with the compound zone from the nitrided surface is polished off. Tests conducted by (35) in which the H13 dies were subjected to alternating heating and cooling cycles on a thermal test ring. Microscopy was used to assess the crack dimensions and distribution. The light micrographs of the flat surface of thermal cycled samples are as shown in Figure 23.
Figure 22: Optical profilometry of the wear track for the air hardened H13 steel specimen at 600 °C. A) Uncoated B) Gas nitrided C) (Ti, Al)N PVD layer D) (Ti, Al)N PVD layer + gas nitrided (33).
4. SUMMARY AND CONCLUSION

The focus of this study was to review the die materials and surface treatments present in literature and provide criteria for selection of die materials that can be used for hot and warm forging of steel in mechanical press with good die life. This study presents a method for comparison of commercially available hot work tool steels based on the hardness data available in the material data sheets. Apart from the hardness data, other factors such as material refining technique (ESR, VAR), thermal expansion coefficient, and thermal conductivity also affect the die life. The dies should also adequate toughness and fatigue resistance. Hot work die materials such as Bohler W360, Daido DRM1, and Nachi Duro F1 are better suited for hot and warm extrusion dies which are subjected to high temperatures.

The FIERF sponsored study on warm forging of steel pinion shafts was successful in predicting and plastic deformation on the forging tooling using Finite Element Analysis. Prediction of plastic deformation and wear parameters (K and a) will assist in optimizing the forging process to improve die design and predict the suitable forging conditions such as billet temperature, press speed and lubrication to get better die life.

There have been some successful applications of alternative die materials such as ceramics and carbides have also found in forging tooling primarily due to their ability to retain hardness at high die surface temperatures. Studies present in literature on use of alternative die materials were also reviewed. Surface treatment techniques such as nitriding, weld overlays and ceramic coatings have also been reviewed.

As ceramics have relatively low tensile strength, the pre-stressing (shrink fit) design of dies is important. The dies need to be kept under compressive stress state, as the forging pressure exerts tensile stresses on the dies which can cause failure under tension. Materials such as Silicon Nitride and Sialons have been successfully used in some applications however their application is limited due to the cost and design difficulties. Actual trial may be required to design the shrink fit and other forging variables such as lubrication, press speed and process timings.

Nitriding was found to be the most common surface treatment for the hot work die steels. The performance of nitriding also depends on the composition of the die material as the alloying elements affect the final hardness gradient in the nitride layer. Literature showed that PVD and Plasma assisted CVD were preferred in coating of ceramic materials onto the die surface. Adhesion on the die surface is an important criterion in selection of coating. The adherence of coatings and the wear resistance was higher on dies which are nitrided. These duplex coatings also performed better than multi layered coatings.
BALINIT® ALCRONA (Oerlikon-Balzers) which is made of AlCrN may be used for hot forging dies. Other ceramic coatings such as materials such as CrN, TiAlN, TiCN and ZrN can also be used. Actual testing of the materials may be required for coating selection. The cost of coating the dies is an important factor that influences the final decision on selection of coating method.

REFERENCES

11.[UnPublished Choi’s paper]


