IMPROVEMENTS IN HOT FORGING PROCESS - USING ALTERNATIVE DIE MATERIALS AND FINITE ELEMENT ANALYSIS FOR WEAR PREDICTION AND DIE DESIGN OPTIMIZATION.

THESIS

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ABSTRACT

In hot forging, the high temperature and pressure conditions cause significant die wear and plastic deformation of dies. This not only causes frequent replacement of the dies but also affects dimensional in accuracy and surface finish of the forged parts. Frequent die changes result in not only increase in production costs but also in loss of productive time.

The objective of this research study was to investigate the forging process of the sponsoring company and suggest improvements which could increase the life of dies used in the process. Literature study showed that there are potential materials and coatings which can be used to increase the die life. Finite Element simulations were used to predict temperatures in the hot forging tooling. As more and more parts are produced, the temperatures in the tooling were found to increase and reach a quasi steady state. Stress analysis of dies could identify locations of high stresses which could assist in improving the forging process in the future.

The wear prediction methodology was successful in predicting the wear profile in one of the two dies studied. The wear analysis can help design dies with longer life and produce parts with better dimensional accuracy. Finite Element Analysis was also successfully used to find the shrink fit interference which could provide sufficient compression for the extrusion tooling with a ceramic insert.
DEDICATION

This document is dedicated to my family.
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CHAPTER 1 INTRODUCTION

In hot forging, the metal deforms plastically above its recrystallization temperature. Hot forging process subject the dies to severe thermal and mechanical fatigue due to high pressure and heat transfer between the dies and the workpiece. High cyclic surface temperatures result in thermal softening of the surface layers of the dies, subsequently increasing die wear and susceptibility to heat checking. [Deshpande et. al., 2009]

Cost of forging tooling has proved to be one of the most important factors in the overall process cost. Die costs range from 10% to 15% of the whole process cost [Doege, et al., 1996]. This includes cost of die material, machining the dies and subsequent heat treatment. Set up times can range anywhere from under 10 minutes to over 3-4 hours, these practices result in additional direct wages in material handling, tool rework and other overhead costs. [Babu, 2004]

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 of the forged part [Tulsyan, 1993].

In hot forging, dies fail mainly 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 are found to be the most common form of failure during forging.
CHAPTER 2 DESCRIPTION OF FORGING PROCESS AND PROBLEM STATEMENT

This study was sponsored by a major manufacturing company which produces engine valves. Engine valves are manufactured by hot forging i.e. by Extrusion-Coining Process. Die failure (abrasive wear, heat checking, or minor cracks formed on dies or punches) contributes to increase in production costs. In addition, die wear has an adverse effect on the dimensional accuracy and surface finish of the forged valves. [Painter et. al, 1995]
Hence, it is desirable to reduce the wear rates and increase the die life.
In hot forging of engine valves, the billets (of circular cross section) are cut from bar stock, two at a time, by a mechanical shear with straight edge blades. In some cases, to avoid microcracks and obtain clean sheared surfaces, the billets are warm sheared (especially for the harder and stronger materials). The billets are then tumbled to remove sharp edges on the sheared billets and avoid the “digging” of these sharp edges on the dies. The sheared billets are then heated in an induction furnace (adjacent to the press) to temperatures up to 1200°C. Then the heated billets are automatically fed to the first forming operation (extrusion) on the mechanical press.
The forging tooling was similar to that used by Painter et. al., [1996] (Figure 2.1). The flowchart of overall press operation is seen in Figure 2.2. This first forming operation extrudes the billet to form the valve stem. Extrusion ratio is about 3:1 of the initial diameter of the billet. Lubricant is used to control heat transfer from the billet to the dies,
to cool the punch/die and reduce interface friction. This intermediate form is lifted out of the extrusion assembly by the turret arm. The turret then transfers the part to the coining die.

Figure 2:1: Forging Tooling Schematic [Painter, et. al., 1996]

In the second operation, the valve head is formed by the coining die (Figure. 2.1). There is little or no change in the dimensions of the valve stem during the coining operation. Again, a lubricant is used to moderate the heat transfer and reduce friction. After coining, the valve is ejected from the press to cool. The extrusion and coining operations occur simultaneously during each cycle of the press.

Figure 2:2 Flowchart for valve forging process
All parts are manufactured on mechanical presses which can operate under intermittent (after each stroke the ram stops for automatic part transfer) and continuous (the automatic part transfer is synchronized with the press stroking rate i.e. slowed down to allow for part transfer) modes of operation. Intermittent mode of operates at a range of 60 to 90 strokes per min and continuous mode operates up to 30 strokes per min. The machines can produce about 25-30 parts per min. [Deshpande et. al., 2009]

The dies used for forging engine valves (both extrusion and coining tooling) are made of tool steels such as H10 and H13, which have the properties required for hot forging. In hot forging, the dies should be able to retain their strength and hardness at high temperatures. Special heat treatment methods are used to get the desired strength and hardness for the dies. In some cases, the dies are also nitrided to increase the surface hardness of the dies and to reduce the abrasive wear. There is “no” or very little flash so that the coining operation uses basically a trapped die. Due to the kissing surfaces the valve head can be forged within close tolerances. [Deshpande et. al., 2009]

In the extrusion die assembly, lubricant is pumped (flooded) into the die cavity from above the extrusion bushing. Primarily, the extrusion die and bushing are lubricated. The extrusion punch is lubricated only by the lubricant that is collected on the surface when the punch reciprocates into the extrusion bushing during every stroke.

Both extrusion and coining die assemblies are mounted on a single mechanical press. The distance between the extrusion and coining die centers depends on the feeding mechanism. The presses operate by intermittent mode in which the press speed is in the range of 60 to 90 strokes per minute. The press ram movement is interrupted (the ram stops at the Top Dead Center (TDC)) after each stroke for removal of the forged part.
from the die). There are load cells attached on the press frame to measure the total press load (extrusion + coining). [Deshpande et. al., 2009]

The extrusion and coining process cycles are as described below:

- **Process Cycle – Extrusion**

  ![Process Cycle Diagram](image)

  **Figure 2:3: Valve extrusion process sequence** [Deshpande et. al., 2009]

  The extrusion process sequence is illustrated in Figure 2.3 and consists of:-

  Billet Transfer (t_a – t_0): The time for which the billet is exposed to the environment, i.e. from the time it exits the induction heater until it is placed inside the extrusion bushing.

  Clutch activation time (t_b – t_a): It is the time taken by the press driving mechanism to start the ram movement.

  Forging Stroke (t_c – t_b): It is the time taken by the press to move from the Top Dead Center (TDC) to Bottom Dead Center (BDC) and back to Top Dead Center.

  Extrusion/Deformation time (t_2 – t_1): It is the time from when the punch touches the billet until it reaches BDC. The deformation time is determined from press kinematics.
Knockout ($t_d - t_c$): The knockout punch starts to move upwards to push the forged part out of the extrusion die. The knockout starts 40 ms after the ram starts to move upwards from BDC.

Part removal ($t_f - t_d$): The time required for the turret to transfer the extruded part from the extrusion die to the coining die.

Lubrication ($t_g - t_l$): The time during which the lubricant is pumped into the die. The lubrication, in the extrusion process, is applied by pumping (flooding) the die with a thick oil based lubricant through the lube ring that is permanently fixed to the top of the extrusion die assembly.

Post Lubrication dwell ($t_h - t_g$): It is the time from when the lubricant pumping is stopped until the start of the next forging cycle.

The total cycle time for extrusion is ($t_h - t_a$).

- **Process Cycle – Coining**

![Diagram of forging process cycle](image)

Figure 2.4: Coining process sequence [Deshpande et al., 2009]
The process sequence for the coining operation (Figure 2.4) is similar to that for extrusion. The coining process consists of:

- Part location from extrusion to coining die (\( t_a - t_0 \)): The time for which the billet is exposed to environment, i.e. from the time the knockout of the extruded part starts until it is finally placed on the coining die.
- Post lube air blow (\( t_b - t_a \)): The air is blown (after lubrication of previous cycle) onto the surface of the coining die and punch from the nozzles located on the periphery of the coining tooling.
- Clutch activation time (\( t_c - t_b \)): It is the time taken by the press driving mechanism to start the ram movement.
- Forging Stroke (\( t_e - t_c \)): It is the time taken by the press to move from the Top Dead Center (TDC) to Bottom Dead Center (BDC) and back to TDC.
- Coining/Deformation time (\( t_2 - t_1 \)): It is time from when the punch touches the extruded preform until it reaches the BDC. The deformation time is determined from press kinematics.
- Knockout (\( t_e - t_d \)): The knockout punch starts to move upwards to push the forged part out of the coining die.
- Part removal (\( t_g - t_e \)): The time required for the turret to transfer the forged valve out of the coining die.
- Pre Lube Air Blow (\( t_h - t_g \)): Air is blown onto the coining punch and die surface from the nozzles.
- Lube Spray (\( t_i - t_h \)): The lubricant is sprayed onto the coining die and punch from the nozzles.
• The total cycle time for coining is \( (t_i - t_a) \) : (which is same as that for Extrusion)

2.1. Potential issues in the forging operation

After surveying of the forging operation it was observed that the primary problem during valve manufacture is during the extrusion process, where the die wear is severe. The extrusion die and bushing are replaced more often than any other the die component. The primary reasons for failure of dies are wear and plastic deformation. Apart from wear in extrusion operation, other potential problems were also identified which are described here. [Deshpande et. al., 2009]

2.1.1. Die failure in Extrusion die

Due to the high velocity and pressure during the extrusion process, the temperature observed in the extrusion die is more than in any other die component. In the valve throat region, the die failure is primarily due to plastic deformation, adhesive and abrasive wear (See Figure 2.5). Heat checking cracks are observed on the top edge and the region where the billet sits prior to extrusion (cracks may also be due to digging of billet edge into the die surface). The dimensional accuracy and surface finish of the valves.

Figure 2.5: Factors affecting die failure in Extrusion Die
2.1.2. Factors causing die failure in Extrusion bushing

In the Extrusion Bushing, die failure is primarily due to guttering or cracking that is observed in the valve head region which is just above the extrusion die. This is understandable because, as soon as the punch hits the billet, the pressure is built up in Extrusion Bushing and the billet rubs against the ID of the extrusion bushing under pressure and relatively high sliding speed.

2.1.3. Factors affecting die failure in Extrusion punch

In the extrusion punch, wear is observed on the valve tip (also rounding of the edge), which may be due to high forming pressure and temperature. Guttering or cracking is also observed (Figure 2.6) on the sides of the punch. This may be due to rubbing/sliding action of the punch in Extrusion Bushing.

![Figure 2:6: Factors affecting die failure in Extrusion Punch](image)

2.1.4. Control of volume in the extruded preform

The volume and shape of the extruded preform (Figure 2.7) is important in getting required geometry of the valve as well as to reduce the machining after the valve is formed. The extrude head height is controlled by the position of the punch. The extrude head height has to be precisely controlled such that there is no excess flash during the
coining operation. Excess head height may also lead to “locking” of the press.

![Diagram of extruded preform](image)

Figure 2.7: Shape of the extruded preform

2.1.5. Optimum geometry of the Extrusion die for the extruded preform

In valve forging, it is always desirable to have the shape of extruded preform similar to that of the formed valve as it reduces the amount of relative sliding between the billet and coining die [Dahl et. al, 1999a]. Painter, et. al. [1996] observed that die wear is proportional to the sliding distance. The geometry of the valve preform affects the stresses in the valve during the coining operation. Hence, it is always desirable to get the “best” geometry of the valve preform prior to the coining operation. The shape of extruded preform in the neck region is controlled by the geometry (radii of curvature) of the extrusion die. The position of extruded preform in Coining die is shown in Figure 2.8.
2.1.6. Effect of billet geometry and orientation in the Extrusion Bushing upon the process

The shape of the billet may affect the temperature and stresses in the extrusion die. The flow of metal and stress on the die depends on the diameter and length of the billet. Moreover, if there is a clearance between the billet and the inner surface of the Extrusion bushing, the billet may sit tilted at an angle prior to extrusion. Sharp edges on the billet may cause digging on the Extrusion Die surface. To avoid sharp edges (by rounding them), the billets are tumbled prior to forging.

2.1.7. Effect of Knock-out upon straightness of stem

After the valve preform is extruded, it is pushed out of extrusion die by the knockout punch. The extruded preform stem is at a temperature that is even higher than the initial temperature of the billet (due to the energy generated during deformation). As the preform is knocked out from the dies, the valve stem may buckle (Figure 2.9) due to low stiffness of the valve stem at high temperature. This buckling of the extrude preform depends on the temperature distribution on the extruded preform, the speed of the knockout action as well as the force required for knockout.
Figure 2.9 Possible buckling of extruded preform during knockout (exaggerated)

2.1.8. Bottom Dead Center (BDC) of a mechanical forging press

In a mechanical press, the BDC is the lowest possible position the ram can reach as it reciprocates while forming the part (billet). The press is designed and operated such that it has sufficient force and energy to form the part and return back. In valve forging, the ram must have sufficient capacity to carry out both the extrusion and coining operations simultaneously. However, it is very likely that the coining operation requires more maximum force than the extrusion operation. This can be quantified by FEA or by load sensors attached to the press. The maximum forging loads occur as the press reaches BDC (Figure 2.10).

The extrusion and the coining stations may be located at equal distance from the press central axis. However, the forces required at each location may not be the same. These unbalanced loads would lead to tilting of the ram, bending of the press frame. Hence, to obtain good thickness tolerance, the press should have kissing surfaces, i.e. the dies have flat surfaces that contact each other at the end of each stroke of the forging press. This allows very close control of the thickness even if the flow stress and friction conditions
change during the production run. [Altan et al, 2005]. This is practiced for coining dies only.

Figure 2:10 Qualitative Load-sliding displacement curves [Altan et al, 2005]
CHAPTER 3 RESEARCH FOCUS / OBJECTIVES

Hot forging processes subject the dies to extreme temperatures due to heat transfer between the dies and workpiece. The thermal cycling of the die surface causes softening in the surface layers of the die, which decreases wear resistance. In valve extrusion, due to larger reduction in cross section of the workpiece, substantially increases the material flow velocity. This velocity, in conjunction with the pressure at which the material flows, affects the wear rate of the die material.

The main focus of this study was to increase the die life in valve forging process. As part of this focus the following objectives were selected for this research study

- Review the literature to find die materials and coatings which can suitable for hot forging tooling.
- Determine the process conditions such as die temperatures and stresses for extrusion and coining operations during start-up (cold dies) and steady state conditions using finite element simulations.
- Measures the wear on the worn extrusion and coining dies using Coordinate Measuring Machine (CMM) and predict the wear by applying wear models (based on previous studies and literature) and finite element simulations.
- Investigate the use of ceramic inserts for extrusion tooling and design the tooling to find the right shrink fit interference. The ceramic inserts were proposed for improved die life and avoid frequent change of worn out dies.
In this study, the strategy was to model the forging operations (extrusion and coining) as realistically as possible using FEA. Thus, we will gain a good understanding as to how various process variables affect the tool life and product quality. Thus this understanding will then help us to optimize these operations to reduce tool wear.
CHAPTER 4 LITERATURE REVIEW

4.1. Review of wear models used for predicting wear on forging dies

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. [Dahl et al., 1999]

[Tulsyan et al., 1993] and [Painter et al., 1993] investigated the use of the finite element code, DEFORM, together with a post-processing code (written by the authors) to predict die wear in extrusion of automotive exhaust valves. Coefficients in the equation were then determined by regression to approximate the wear profiles observed in experiment. Die and workpiece hardness was determined by hardness-temperature polynomials input by the user. The abrasive and adhesive models used by [Painter et al., 1995] given in Equation 1.1 & 1.2 respectively:

\[ Z_{ab} = K_{abr} \frac{p^{a_1} v^{b_1} \Delta t}{T^{c_1}} \]  \hspace{1cm} \text{Equation 4:1}

\[ Z_{ad} = K_{adh} \frac{p^{a_2} v^{b_2} \Delta t}{T^{c_2}} \]  \hspace{1cm} \text{Equation 4:2}

Where \( Z_{ab} \) = abrasive wear depth, \( Z_{ad} \) = adhesive wear depth, \( K \) = experimental coefficients, \( m \) = hardness coefficient, \( p \) = local pressure, \( V \) = local sliding velocity,
\[ \Delta t = \text{incremental time interval}, \ H_d = \text{die material hardness (function of die temperature)}, \ H_w = \text{workpiece hardness (function of workpiece temperature)}, \ a_1, b_1, c_1, a_2, b_2, c_2 = \text{experimental constants}. \]

For wear prediction, the value of \( a_1, b_1, a_2, b_2 \) was taken as 1. For abrasive wear on steel dies, \( c_1 = 2 \) and for adhesive wear \( c_2 = 1 \), although according to some literature the hardness coefficients may vary between 0.5 and 2.5.

More recent studies differ with earlier models on the hardness considerations; the conventional Archard model defines die hardness only as a function of temperature, leaving thermal softening effects neglected, it is known that die hardness decreases with the number of operations in high-temperature forming processes; in order to include the effects of time and temperature on hardness, thermal softening curves were used by Behrens. [Behrens, 2008]

Behren’s model computes the wear depth at each forging cycle (Equation 1.3). The general formula sums from the first forging until a certain life cycle of the die (n). \( \sigma_N \) stands for the contact normal pressure, \( v_{rel} \) refers to the relative velocity between workpiece and tool, and \( \Delta t \) represents one time increment (inc). In this case, hardness (H) depends on temperature and process duration t, wear coefficient (k) needs to be calibrated in order to calculate wear quantitatively [Behrens, 2008]. It is important to note that particularly for this proposed model the workpiece temperatures reach up to 1300°C, which will lead the forging die to a tempering range, under this statement hardness will be calculated by: first estimating a tempering parameter (dependant on time and temperature), and then such parameter will be included in a quadratic function of hardness for the die material, \( H(\theta, t) \).
In a recent study, conducted by the ERC/NSM for the Forging Industry Research and Education Foundation (FIERF), the theoretical die wear is predicted by FEM and by applying wear models. Then the theoretical predicted profile is compared (and improved) with the experimental die profile until the profiles agree [Groseclose et. al., 2008]. The die wear was estimated in warm forging of steel pinion shafts using FEM and application of a wear model (Equation 1.4). In some of the previous studies, the wear model exponents used for pressure and hardness were different. In that case, the units for the pressure and hardness do not match and the abrasive wear coefficient \((K)\) is not a dimensionless number.

A single exponent was used for both pressure and hardness. This makes the wear coefficient \((K)\) a dimensionless number (as required). The methodology used for applying wear models is given in Figure 4.1.

\[
W(c) = \sum_{j=1}^{c} \int K \left( \frac{P}{H(j)} \right)^a v dt
\]

Equation 1.4

\(W(c) = \) wear depth at the forging cycle \((c)\), \(K = \) abrasive wear coefficient, \(P = \) normal pressure on the contact surface, \(H(j) = \) die hardness at the forging cycle \((j)\), \(v = \) sliding velocity at the contact surface, \(c = \) number of total forging cycles, and \(a = \) experimental constant.
4.2. Review of Die materials and coatings

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 of the forged part. [Tulsyan, 1993].

The property of the die materials can be locally influenced by the surface engineering techniques such as heat treatments and surface coating techniques. By proper selection of surface engineering techniques, die life can be increased dramatically [Babu et al, 1999].

4.2.1. Die materials for forging of steel
In hot 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.

4.2.1.1. 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 [Altan et. al., 1983].

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. 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. [Altan et al., 2005] [Deshpande et. al., 2010]

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 of the commercially available hot work tool steels are listed in Table 4.1. This table is based on the study by [Babu et al, 1999].

More commercially available hot work die steels which are suitable for use in extrusion tooling for forging of engine valves are listed in Table 4.2. 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. [Deshpande et. al., 2010]

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 4.2). 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.

Table 4:1: Some of the hot work tool steels and other materials commercially available in United States. [Babu et al, 1999]

<table>
<thead>
<tr>
<th>COMMERCIAL NAME</th>
<th>AISI</th>
<th>C</th>
<th>Ni</th>
<th>Si</th>
<th>W</th>
<th>Cr</th>
<th>V</th>
<th>Mo</th>
<th>Co</th>
<th>OTHER</th>
</tr>
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<tbody>
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<td>H11</td>
<td>0.38</td>
<td>1</td>
<td>5.3</td>
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<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>THYROTHERM 2344 EFS</td>
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<td>1</td>
<td>5.3</td>
<td>1</td>
<td>1.4</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CARTECH 833; PLUS UDD OVAR SUP CRU NUDIE V; CPM-NUDIE EZ FIN DC + XTRA</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
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<td></td>
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<td>5</td>
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<td>2.85</td>
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<tr>
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<td>0.55</td>
<td>1.7</td>
<td>0.7</td>
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<td>THYROTHERM 2714</td>
<td>6F3</td>
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Table 4.2: Composition of materials considered suitable for extrusion tooling [Deshpande et. al., 2010]

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<tr>
<th>Make</th>
<th>Material</th>
<th>Composition</th>
<th>Recommended Initial hardness range (HRC)</th>
<th>Comments</th>
</tr>
</thead>
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<td></td>
<td></td>
<td>C</td>
<td>Si</td>
<td>Mn</td>
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<td></td>
<td></td>
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<td>0.2</td>
<td>0.25</td>
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<td>Bohler</td>
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<td></td>
<td>W302</td>
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<td>W303</td>
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<td></td>
<td>Used by Hirschvogel for warm extrusion of steel pinion shafts. Matrix HSS type. With high wear resistance</td>
</tr>
<tr>
<td>Nachi</td>
<td>DURO F1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Also used by Hirschvogel. Matrix HSS type</td>
</tr>
</tbody>
</table>

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

Figure 4.2: Heat treatment cycle of hot work tool steels [Roberts, 1998]
The tempering curves for the nine die materials are given in Figure 4.3. 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.

After the dies are tempered the “initial” room temperature hardness can be determined. During hot 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 drawn 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 4.4. 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. The variation of the hot strength of the dies is similar to that of the hardness (Figure 4.5). [Deshpande et. al., 2010]

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. [Deshpande et. al., 2010]
Figure 4.3: Comparison of tempering curves [Deshpande et. al., 2010]

Figure 4.4: Comparison of hot hardness curves [Deshpande et. al., 2010]
Ceramic and Carbides die materials

Ceramic inserts and coatings are well known 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. [Deshpande et. al., 2010]

The potential 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 prestress 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. [Deshpande et. al., 2010]

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. When compared to hot working tool steels, sialons retain their hardness more efficiently at elevated temperatures (See Figure 4.6) [Altan et al., 2007] [Deshpande et. al., 2010]. They were developed to solve the difficulties involved in fabrication of silicon nitride.

![Figure 4:6: Comparison of hot hardness of ceramic die material (Sialon) and advanced hot working tool steel grades. [Altan et al., 2007]](image)

There have also been successful applications of cermets/ceramic dies in Japan. Nissan motor company is using cermets/ceramic dies made of MoB (ceramic). The material is powder formed and sintered. In production tests, two die materials were tested on forward extrusion (Figure 4.7) 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. [Altan et al., 2007].

![Diagram of die inserts](image)

Figure 4.7: Forward extrusion of outer race part using MoB dies [Mitamura, 1999]

In a study conducted by [Shirgaokar, 2008], 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 4.8). 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 4.9). 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 (Figure 4.10). Also elastic modulus of carbides was 200% greater than that in steel and 80-90% greater than that of ceramic.
Figure 4:8: Comparison of thermal properties of carbides and ceramic to steels (ThCond: Thermal Conductivity; ThExp: Coefficient of Thermal Expansion) [Shirgaokar, 2008]

Figure 4:9: Schematic representation of the warm forging (upsetting) die assembly [Shirgaokar, 2008]
In investigation of ceramic inserts by [Behrens, 2005], two assembly techniques were explored as shown in Figure 4.11a. 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 4.11b. The effect of different interference fits and preheat temperatures was not investigated in these studies. Figure 4.12 shows the wear performance for the ceramic dies compared to nitrided hot work tool steel for two different forging (workpiece) temperatures after 500 forging cycles. Silicon nitride showed superior wear resistance (3 to 6 times less wear) among the die materials selected. [Behrens, 2005]
a) Two types of insert designs investigated viz. shrink-fit and brazed

b) Different types of shrink fit designs investigated in forging trials

Figure 4:11: Die designs investigated in forging trials with ceramic inserts

[Behrens et al., 2005]

Figure 4:12: Performance of ceramic die materials in forging trials.

[Behrens et al., 2005]
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 considered for precision forging of spur gears (Figure 4.13). Research is currently in progress to ensure the durability of active brazed ceramic inserts and to optimize the joining region.

[Behrens, 2007]

![Schematic of gear forging tooling](image1)

![Steel die with brazed Ceramic inserts](image2)

Figure 4.13: Flashless hot forging of gears using ceramic (Si₃N₄) inserts

[Behrens, B., 2007]

Research trials were also done by Nagano Tancoh Co. [Koitabashi, 1995] 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 4.14). Tests were also conducted by Kwon and Bramely [Kwon et al., 2000] 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.
Syalon 101™ is a beta-sialon type ceramic manufactured by International Syalon, which has high toughness, strength and chemical and thermal stability (Table 4.3). 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 4.3: Properties of Syalon 101(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>
<tr>
<td>RT Compressive strength</td>
<td>&gt;3500</td>
<td>MPa</td>
</tr>
<tr>
<td>RT Young’s Modulus</td>
<td>288</td>
<td>MPa</td>
</tr>
<tr>
<td>RT Hardness (Vickers HV&lt;sub&gt;0.3&lt;/sub&gt;)</td>
<td>1500</td>
<td>Kg/mm³</td>
</tr>
<tr>
<td>Fracture Toughness K&lt;sup&gt;1&lt;/sup&gt;C</td>
<td>7.7</td>
<td>MPam&lt;sup&gt;1/2&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
4.2.2. Die coatings and Surface treatments

Die surface treatments such as nitriding, weld overlays (or hardfacing) and chemical and physical vapor deposition of heat resistant ceramic materials can substantially increase the life of the hot work dies. The ranges of surface hardness by various surface treatments and coatings for tool steels are as shown in Figure 4.15 [Roberts, 1999]. The classification and size of various surface treatments and coatings and their typical depths is as shown in Figure 4.16 [Roberts, 1999]. Most die surface treatments are used to increase the hardness of the surface as the die wear decreases with increase in hardness. Nitriding is the most common 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 forging applications. The cost of surface treatment is an important criterion in selection of the coating. Figure 4.17 although not very recent, provides a rough understanding of the relative costs of various surface treatments. [Deshpande et. al., 2010]

Figure 4:15: Ranges of surface hardness of various surface treatments and coatings [Roberts, 1998]
Figure 4:16: Classification of various surface treatments and coating and typical depths of surface modified by various processes [Roberts, 1998]
Figure 4.17: Approximate relative cost of surface treatments [Davis, 2001]

4.2.2.1. Nitriding

Nitriding is a case hardening process, where nitrogen is introduced into the surface of a metal alloy. Nitriding processes are classified by the medium that donates nitrogen. In Gas nitriding nitrogen is introduced to the surface of hot metal (at 500-570°C) via nitrogenous gas, usually ammonia. Quenching is not required. Liquid (salt bath) nitriding takes place at similar temperature range as gas nitriding (510-580°C) but employs salt bath containing cyanides or cyanates and has lost favor due to environmental considerations. Ion (plasma) nitriding uses glow discharge technology to introduce nitrogen to the surface of the metal. Technique requires high-voltage electrical energy to form plasma in low pressure medium. This accelerates the gas (Nitrogen) particles in the
medium and creates an ion bombardment of the work piece [Billur, 2010]. Ion (plasma) nitriding is the preferred technique among the nitriding techniques as the formation of brittle white zone can be minimized which is not the case for other nitriding techniques. Nitrided die surface can have hardness as high as 70 HRC. [Deshpande et. al., 2010]

Nitriding is used in applications where the strength and wear resistance is more important compared to the toughness. This is due to the fact that the nitrided surface although hard has low toughness and hence it is seldom used in hammer forging die applications. Nitriding is observed to reduce the wear rate by as much as 50% [Davis, 1995]. It is also observed that the nitride layer also imparts thermal fatigue resistance to the dies due to the residual compression state and also the tempering resistance due to the diffusion layer (explained later). Although there is improvement of hardness and fatigue resistance (due to residual compression), nitriding decreases the toughness of the die surface. As a result of this chipping of the nitrided edges can occur in some applications.

The nitrided surface is made of two zones (Figure 4.18). The outer most layers called the compound zone (white color) which is made of intermetallic compounds of nitrogen and iron. The inner layer is called the diffusion layer which has fine precipitates of iron and other alloy elements which causes the increase in hardness in this zone. The proportion of nitrogen decreases until the original structure (base metal) is observed. [Deshpande et. al., 2010]

The depth and hardness of the nitride layer depends on the nitriding time and the composition of the base metal. Die materials containing high amounts of chromium, vanadium and molybdenum can form nitride layer which is shallow and very hard.
The effect of alloying elements on hardness profiles was investigated for hot forming die by [Schneider et al., 2006]. The hardness profile for three of the materials tested is shown in Figure 4.19. 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 microhardness and residual stress depth profile for plasma nitrided and nitrocarburised H11 die steel (Figure 4.20) was investigated by [Leskovsek, 2008]. It can be observed that the residual stresses are compressive in the nitride layer (near the surface). These residual stresses lead to improved fatigue resistance during forging [Advanced Heat Treat Corp.] [Davis, 1995]. [Deshpande et. al., 2010]

Figure 4:18: Change in the base metal after nitriding.

Figure 4:19: Hardness profiles of Bohler W300IB (1.2343), W302 (1.2344) and W360 IB [Schneider et al., 2006]
Figure 4.20: Comparison of microhardness and residual stress depth profile for A) Plasma nitried and B) Nitrocarburised H11 die steel [Leskovsek, 2008]
4.2.2.2. 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. [Shirgaokar, 2006] [Deshpande et. al., 2010]

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. [Shirgaokar, 2006]

Commonly used coatings were TiN, [(Ti, Al) N], CrN, TiB2, etc. either as monolayer, multilayer or duplex coatings (i.e. with a prior gas or plasma nitriding surface treatment) [Shirgaokar, 2006]. Table 4.4 contains information on some of the coatings found in literature along with various deposition processes and characteristic properties [Salas, 2003]. The critical load 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.
Table 4.4: Some of the commonly used coatings along with the process used and laboratory test [Salas et al., 2003]

<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/nitried layer</td>
<td>Low P plasma</td>
<td>3780 ± 300</td>
<td>( L_{c1} = 75-77 )</td>
<td>–</td>
<td>Cohesive and adhesive failures</td>
</tr>
<tr>
<td></td>
<td>sputtering + ion处annealing</td>
<td>(HV,0.05)</td>
<td>( L_{c2} = 104 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ti,Al)N/nitried layer</td>
<td>Low P plasma</td>
<td>1180</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>sputtering + ion处annealing</td>
<td>(HV,0.05)</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>TiN</td>
<td>r.f. magnetron sputtering</td>
<td>3347 ± 324</td>
<td>( L_{c1} = 15 )</td>
<td></td>
<td>Good, Ductile failure</td>
</tr>
<tr>
<td></td>
<td>(HK)</td>
<td></td>
<td>( L_{c2} = 50 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CrN</td>
<td>r.f. magnetron sputtering</td>
<td>2300 ± 224</td>
<td>( L_{c1} = 8 )</td>
<td>–</td>
<td>Brittle failure</td>
</tr>
<tr>
<td></td>
<td>(HK)</td>
<td></td>
<td>( L_{c2} = 23 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr2N</td>
<td>r.f. magnetron sputtering</td>
<td>2102 ± 85</td>
<td>( L_{c1} = 7 )</td>
<td>–</td>
<td>Brittle failure</td>
</tr>
<tr>
<td></td>
<td>(HK)</td>
<td></td>
<td>( L_{c2} = 26 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiN</td>
<td>Low T° MO- PACVD</td>
<td>2000</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(HK,0.06)</td>
<td></td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>TiN/TiCN</td>
<td>Low T° MO- PACVD</td>
<td>3000</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(HK,0.06)</td>
<td></td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Zr(C,N)</td>
<td>Low T° MO- PACVD</td>
<td>1000–1200</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(HK,0.06)</td>
<td></td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Ti,C,H/ nitried layer</td>
<td>High pressure plasma</td>
<td>1400</td>
<td>( L_{c1} = 10-80 )</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>nit. + UEMS</td>
<td>(HV,50)</td>
<td>( L_{c2} = 15-22 )</td>
<td>17 different</td>
<td></td>
</tr>
<tr>
<td>CrN</td>
<td>r.f. and d.c. reactive magnetron sputtering</td>
<td>4–26.8 GPa</td>
<td>( L_{c1} = 17-57 )</td>
<td>–</td>
<td>CrN coatings</td>
</tr>
<tr>
<td>TiN</td>
<td>CVD + plasma nit.</td>
<td>800–1600</td>
<td>( L_{c1} = 18-36 )</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TiN</td>
<td>Arc Evap. + PACVD</td>
<td>( L_{c1} = 20-100 )</td>
<td></td>
<td></td>
<td>Substrates: SS, M2 and WC</td>
</tr>
<tr>
<td>CrN</td>
<td>Arc evaporation + nanolayer</td>
<td>17.7–23.5 GPa</td>
<td>( L_{c1} = 80-100 ) ( L_{c2} = 130-140 )</td>
<td>Very good ( \times 4-30 ) of arc evap. TiN</td>
<td>Cohesive failure before nanolayer</td>
</tr>
<tr>
<td>TiN</td>
<td>PVD</td>
<td>2480 ± 80 MeV</td>
<td>( L_{c1} = 32-4 )</td>
<td>Moderate</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(HV)</td>
<td></td>
<td>( L_{c2} = 57 -4 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CrN</td>
<td>PVD</td>
<td>1410 ± 90 MeV</td>
<td>( L_{c1} = 15 -1 )</td>
<td>Good</td>
<td>–</td>
</tr>
<tr>
<td>(Ti,Al)N</td>
<td>e-beam evap. + magnetron sputtering</td>
<td>3500 ± 80 GPa</td>
<td>( L_{c1} = 32 -2 )</td>
<td>Very good</td>
<td>–</td>
</tr>
<tr>
<td>TiB2</td>
<td>PVD</td>
<td>4000 ± 160 MeV</td>
<td>( L_{c1} = 14 -1 )</td>
<td>Very good</td>
<td>–</td>
</tr>
<tr>
<td>Cr–Cr2Si</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.
[Klimek, 2003]. Figure 4.21 shows the temperature ranges used in various coating techniques (Oerlikon-Balzers) [Shirgaokar, 2006]. 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) [Shirgaokar, 2006]

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

Figure 4.21: 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)

### 4.2.2.3. Coating Architecture of vapor deposition techniques

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 (Cooke, 2004; Salas, 2003; Klimek, 2003). 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 [Ma, 2001]. The composition and thickness of nitride layer has an effect on the adhesion onto the dies. Hot forging trials by [Leskovsek, 2009], 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 4.22) [Deshpande et. al., 2010]. The coatings were found to adhere better when the nitrided dies were polished prior to coating.

Figure 4.22: Local flaking of TiCN coating and the propagation of cracks into the nitrided substrate. [Leskovsek, 2009]
Some studies (Salas et al, 2003) investigated the use of multilayer coatings such as titanium aluminum nitride [(Ti, Al) N] along with the use of an “adhesion” layer. Figure 4.23 shows a schematic of such a deposited layer.

![Diagram of multilayer coating](image)

Figure 4.23: Schematic representation of a multilayer coating on a hot working tool substrate (Salas et al, 2003).

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 [Rodriguez-Baracaldo, 2007]. 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 4.24). 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.

Figure 4:24: 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
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 [Pellizzari, 2001] 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 [Starling, 1997] 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 4.25.

![Figure 4.25: Light micrographs of thermal fatigue test samples](image)

H13+TiN  H13+CrN  H13+nitride+TiN
CHAPTER 5 FINITE ELEMENT ANALYSIS OF THE FORGING PROCESS

The extrusion and coining die assemblies consists of multiple components. In the extrusion die assembly, the extrude die and bushing are assembled into container/holder by shrink fit method. Similarly, in the Coining die assembly, the Coining die is assembled into the container/holder. This is done to have a compressive state of stress in Extrusion Die when it is put into service at room temperature. The purpose of designing a shrink-fit die assembly (prestressing) is to exert compressive stresses (both hoop and radial) onto the die insert in order to counter the tensile stresses generated during deformation.

For the finite element analysis, the present study focuses on only one valve material. The FE modeling of the valve forging process was done using commercial FE code DEFORM. To obtain the steady state die temperature distribution, Multiple Operation module in DEFORM 2D was used. The die geometry data and process sequence were obtained from sponsoring company.

The input material data for simulation of the forging process was obtained from DEFORM’s material library. In some cases, when the material data in DEFORM was absent or insufficient, the data was obtained by either direct communication with sponsor or from research literature.
5.1. **Extrusion**

An axisymmetric model was created in Deform 2D for die temperature and stress analysis. [Deshpande et. al., 2009]

5.1.1. **Temperature analysis of extrusion operation**

The axisymmetric FE model for the die assembly for the die temperature analysis, the workpiece is modeled as plastic object (hence the flow stress data was used). The dies are modeled as rigid and hence the elastic deflections during the actual forging process were not considered for temperature analysis.

The forging (extrusion) simulation sequence is as shown in Figure 5.1. The billet is initially heated in the induction furnace to a uniform temperature of 1190°C. It is then transferred from the furnace to the Extrusion Bushing. The billet loses some of its heat as it is transferred from the furnace to the Extrusion Bushing. A heat convection coefficient of 0.02 kW/m2-K was used to account for heat loss to the environment. This results in a non uniform temperature distribution in the billet as shown in Figure 5.2. The initial process conditions for the forging operation such as billet temperature, tooling temperature as well as forging press(mechanical) characteristics were given by the project sponsor.
The process timings for the forging (extrusion) cycle were calculated based on frame by frame analysis of the valve extrusion process video (given by sponsor).

The heat transfer coefficients were assumed based on studies done by [Burte et. al., 1989] and [Shirgaokar, 2008]. For lubrication operation, the temperature of the lubricant was
assumed to be 100°C. This was based on the estimated temperature of the lubricant as it is pumped from the Lube ring which is present on top of Extrusion Bushing. The friction and heat transfer coefficients used for the extrusion process are listed in Table 5.1.

**Table 5.1 Friction and heat transfer coefficients for extrusion operation**

<table>
<thead>
<tr>
<th></th>
<th>During Deformation (forming)</th>
<th>During rest of the forging cycle (billet resting in die)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Friction coefficient</td>
<td>Heat transfer coefficient (HTC)</td>
</tr>
<tr>
<td>Steel die and billet</td>
<td>0.3</td>
<td>15 kW/m².K</td>
</tr>
<tr>
<td>Between steel dies</td>
<td>-</td>
<td>11 kW/m².K</td>
</tr>
</tbody>
</table>

During lubrication, the dies in contact with lubricant are assumed to have a HTC of 35 kW/m².K.

In any forging process, the dies get heated as the parts are forged one after another. This absorbed heat is lost to the atmosphere, lubricant or is exchanged between the dies. As more parts are forged, the temperature distribution in the dies (which are in contact with the workpiece) changes until it reaches a quasi steady state (at which there is no increase in the max. temperature in the dies). To get close to the steady state temperature distribution in the dies, the extrusion cycles were repeated for 50 cycles using the Multiple Operation module present in DEFORM2D. The variation of max. temperature for the 1st, 25th and 50th cycle is shown in Figure 5.3.
The location of maximum temperature varies at different stages in the forging cycle. The maximum temperature in the extrusion die during the 50 cycle is shown in Figure 5.4.

The maximum temperature is on the surface of the die during deformation. After deformation, as the lubricant cools the die surface the die temperature drops and the location of maximum temperature is inside the extrusion die at the end of the cycle.

Under steady state conditions, it is observed that there is 46% drop in maximum temperature during the dwell time i.e. from end of the deformation (extrusion) until the knockout starts. The maximum temperature further drops by 47% and 27% during the pre spray dwell (i.e. time between start of knock out of the workpiece from the die and start of pumping of lubricant) and lubrication respectively. The max. temperature in the extrusion die at the end of forging cycle is 149°C, this is a drop of 81 % from the temperature that is observed just before the punch reaches BDC.
As the inner dies (i.e. Extrusion Die and Bushing) get heated, the heat from the inner dies is absorbed by the other dies in the die assembly.

5.1.2. **Stress analysis of Extrusion operation**

The stress analysis of the extrusion tooling was also done in DEFORM 2D. The dies were assumed as elastic (previously they were assumed as rigid for the temperature analysis) to get the stresses in the tooling during extrusion. To understand the variation of the stresses as the dies absorb heat, the temperature distribution (obtained previously during temperature analysis) prior to the first, 10\(^{th}\), 25\(^{th}\), 40\(^{th}\) and 50\(^{th}\) extrusion was applied to the new elastic dies. The extrusion die, bushing and the extrusion die holder are assembled by shrink fit prior to assembling with other components of tooling. As the dies are clamped together along the vertical direction, it was assumed that there is no vertical displacement.
The shrink fit in the die assembly results in compressive tangential stress distribution in the extrusion die and bushing. During the forming operation, the die is subject to internal pressure which counteracts against the initial compressive stress state. This design assists in keeping the die assembly in a stress range (compressive or tensile) such that it does not exceed the yield stress (that may cause failure due to cracking) in the die assembly during forging. The shrink fit tangential compressive stress distribution in the extrusion die (Figure 5.5) is evident when we consider a cross section AA in the tooling. The stress distribution changes as the temperature of the die set changes during forming causing expansion of the die set components.

Figure 5:5: Tangential stress distribution in Extrusion [Deshpande et. al., 2009]

The effective stress distribution during the deformation of the 50th cycle is shown in Figure 5.6. After extruding the billet into preform shape, it is transferred from the extrusion bushing to the coining die by automatic transfer system. The environment
temperature is assumed as 20°C. The heat convection coefficient for heat loss from billet to the environment was taken as 0.02 kW/m\(^2\)-K. The change in temperature distribution in preform during the transfer from extrusion to coining tooling is shown in Figure 5.7.

Figure 5:6: Variation of Effective stresses in Extrusion Die during extrusion (in function of extrusion time in %) [Deshpande et. al., 2009]

Figure 5:7: The change in temperature distribution in preform as it is transferred from extrusion to coining tooling [Deshpande et. al., 2009]
5.2. Coining

5.2.1. Temperature analysis of coining operation

An axisymmetric model was created in Deform 2D (similar to that created for extrusion) for die temperature and stress analysis.

The coining simulation sequence is similar to that used for extrusion. The friction heat transfer coefficients were assumed similar to those assumed for extrusion operation.

To get the quasi steady state temperatures in the dies (similar to the extrusion operation), the coining cycle was repeated for 50 cycles using the Multiple Operation module present in DEFORM2D. The variation of max. temperature in the coining punch and die for the 1st and 50th cycle is shown in Figure 5.8 and Figure 5.9 respectively. Note that the location of max. temperature changes during the coining cycle. It is usually on the surface during deformation and is inside the die at the end of the cycle. As expected, the temperature of the dies and punches drastically increases during the deformation (coining) and drops after the punch reaches BDC.
Under steady state conditions (50th cycle), the max. temperature in the coining die at the end of the dwell drops by 42% from that observed at the end of deformation.
and further drops by 40% during pre lubrication dwell. It further drops by 4% and 9% during the air blow II and lubrication respectively. Similarly, for the coining punch, the max. temperature drops by 40% during dwell and 26%, 3% and 8% during pre lubrication dwell, air blow II and lubrication respectively. The temperature variation at different points on surface of coining die (under steady state conditions) is shown in Figure 5.10.

![Coining Die](image)

<table>
<thead>
<tr>
<th>Position</th>
<th>Start of Cycle Temp. (°C)</th>
<th>Max. Temp. (at end of Deformation) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>97</td>
<td>85</td>
</tr>
<tr>
<td>P2</td>
<td>97</td>
<td>227</td>
</tr>
<tr>
<td>P3</td>
<td>104</td>
<td>303</td>
</tr>
<tr>
<td>P4</td>
<td>107</td>
<td>332</td>
</tr>
<tr>
<td>P5</td>
<td>105</td>
<td>396</td>
</tr>
</tbody>
</table>

Figure 5:10 Temperature variation at P1, P2, P3, P4 and P5 at the end 50th forging cycle [Deshpande et. al., 2009]

5.2.2. Stress analysis of Coining operation

For stress analysis of the coining operation, the tooling was assumed as elastic. To understand the variation of the stresses as the dies absorb heat, the temperature distribution prior to the first, 10th, 25th, 40th and 50th coining cycle was applied to the dies.
The boundary conditions for the dies were assumed to be zero in vertical displacement as they are clamped along the height direction.

The shrink fit in the die assembly causes compressive tangential stress distribution in the coining die. This design assists in keeping the dies in a stress range such that it does not exceed the yield stress (and failure due to fracture) of the dies. The tangential compressive stress distribution (Figure 5.11) changes as the heat absorbed during forming causes expansion of the die assembly components.

The effective stress distribution in the coining punch and die during the coining (deformation) operation of the 50th cycle (steady state) is shown in Figure 5.12 and Figure 5.13 respectively.

![Tangential Stresses in Coining Tooling](image)

Figure 5:11: Tangential stresses in coining tooling [Deshpande et al., 2009]
Figure 5.12: Effective stress distribution in the coining punch during coining operation of 50th cycle (0% is start and 100% is end of coining) [Deshpande et al., 2009]

Figure 5.13: Effective stress distribution in the coining die during coining operation of 50th cycle (0% is start and 100% is end of coining) [Deshpande et al., 2009]
5.3. Wear analysis of forging dies

After visual inspection of extrusion and coining dies, it was concluded that the dies usually failed due to wear and plastic deformation on the surface. Hence, it was considered that further investigation of the damage on the forging die surface would help in designing dies with improved life. Moreover, prediction of die wear (for a given material and other similar parameters such as lubrication and process timings) by applying wear models was thought to be useful in minimizing die wear in future. Die samples (vertical half sections) for extrusion and coining dies after use in forging operation, were obtained from the sponsoring company. The surface profiles of these worn out dies (after forging operation) was measured using CMM machine.

5.3.1. Methodology for estimating abrasive die wear

As it was observed that dies after use had signs of abrasive wear and plastic deformation, a methodology was developed for separating the effect of plastic deformation from the wear profile so that the abrasive wear can be predicted using FEA. This methodology is based on the literature on die wear and other studies done by the Engineering Research Center for Net Shape Manufacturing at The Ohio State University. The methodology for prediction of die wear is presented in Figure 5.14.
Figure 5.14 Methodology for prediction of wear profile in hot forging

The methodology involved:

- Prediction of the steady state temperatures obtained by multi operation simulations in DEFORM 2D. The steady temperature of the dies was available from the rigid die simulations done in Section 5.1.

- Predict the plastic deformation of the dies using flow stress data and applying the steady state temperatures.

- Measure the die profile using CMM and extract the wear profile by separating the effect of plastic deformation.

- Apply wear model and optimize the wear parameters such that the difference between the predicted wear profile matches and the extracted wear profile is minimized.
For predicting abrasive wear on the dies, subroutines were developed in DEFORM 2D to calculate the tempering parameter, modify the flow stress based on the tempering parameter and to estimate the wear depth using modified Archard’s wear model (explained in later sections).

5.3.2. Die Profile measurement using Sheffield Cordax CMM

The Sheffield Cordax CMM which was used to measure the wear profile is a touch probe type CMM in which a probe comes in contact with the work piece, to locate the point being measured. The radius of the probe was 1mm. Touch probe radius compensation was used to get the exact location of the points where the probe comes in contact with the workpiece.

The die profile measurement is explained using the extrusion die as an example in Figure 5.15. Similar method was used for measuring the coining die. The extrusion die half section was not clamped on the CMM table using regular clamps or bolts due to small size, requirement of surface measurement of the die profile and limited surfaces to fix them. The die was held using a magnet on a block, which was attached to the CMM table using bolts. It was assumed that the magnet can sufficiently attract the workpiece so that there is no movement of the die during the measurement of the profile.

Only part of the bottom surface of the die was used to attach the magnet as the rest of the bottom surface was used as a reference plane for the measurements. The block was used to raise the die enough for the probe to measure the bottom surface.
(a) Measure the inside profile 

(b) Measure the outside profile

Figure 5:15: Arrangement of die on CMM table [Deshpande et. al., 2009]

As the wear and plastic deformation on the die surface may or may not be symmetric about the vertical axis of the die, three profile lines were measured and were processed using Matlab to get an average inner profile. To get the vertical axis of the part, four outer profile lines were used to fit an average vertical axis for the die. The measured points on the extrusion die are shown in Figure 5.17.

The distance interval between every point measured on the CMM was 0.09mm and 0.11mm for the inner profile, and outer profile respectively.
(a) Measure the inside profile  (b) Measure the outside profile for find center line

Figure 5.16: Measured points for the profile of Extrusion Die [Deshpande et. al., 2009]

The three dimensional CMM data (XYZ coordinate) was converted into two dimensions (RZ coordinates) such that the origin is located (where the central vertical and the base line of the dies meet). Matlab was used to process the data and get the die profile.

After converting the three inner die profiles from XYZ coordinates into RZ coordinates an average inner profile is generated. This average inner profile is compared with the original geometry of the die to get the horizontal deviations at any position on the die surface. The measured die profiles for extrusion (scale = 5X) and coining dies (scale = 20X) is shown in Figures 5.17 and Figure 5.18 respectively.
Figure 5:17: Plot showing the original die geometry and measured real die profile of Extrusion die
5.3.3. Wear model

In this study, a modified form of Archard’s wear model is used to predict the wear depth. The total wear depth is expressed as the integral function with respect to time (t) (Equation 5.1). In this equation, $W_n =$ wear depth after every cycle, $K =$ wear coefficient, $a =$ experimental constant, $P =$ normal contact pressure, and $V =$ sliding velocity. The hardness of the material is given by Equation 5.2, where $d_j =$ distance from the initial die surface after $j^{th}$ cycle, $M_j =$ tempering parameter after $j^{th}$ cycle, $T =$ instantaneous temperature ($^\circ$ C), $F_{\text{soft}} =$ thermal softening factor and $F_{\text{hot}} =$ hot strength factor.
\[
W_n = \sum_{j=1}^{a} K \left( \frac{P}{H_{hot}(d_j,M_j,T)} \right)^n Vdt \tag{5.1}
\]

\[
H_{hot}(d_j,M_j,T) = H_{ini}(d_j) \cdot F_{soft}(M_j) \cdot F_{hot}(T) \tag{5.2}
\]

For each simulation step of the steady state forging stroke, temperature, pressure and sliding velocity data from every nodal point on the contact surface of the workpiece are collected. As the three above parameters change with time during the forging stroke, the time instant for each simulation step is also noted.

5.3.4. Calculation of hardness

In the wear equation, the hardness is expressed as a function the wear depth i.e. hardness variation in the presence of nitride layer die, die softening with time and temperature cycles and elevated temperature hardness for instantaneous temperature. In case of dies with surface hardened dies, the wear also changes with the wear depth as the nitride layer has relatively higher hardness compared to the base material. During hot forging, the die material hardness at any location of the die changes with the temperature as well as forging cycle. As the number of forging cycles increase, the die surface starts to lose its hardness due to the effect of tempering (die softening). The instantaneous die surface temperature should also be considered for the effect of hot hardness. The Figure 5.19 shows how hardness is calculated considering the nitride distribution, die softening and the hot hardness curves.
Figure 5:19: Hardness calculation from the nitride distribution, die softening and the hot hardness curves. [Deshpande et. al., 2009]

As the extrusion die samples used for the experiments were not nitried, the effect of variation of hardness with depth form the surface was not considered.

- **Nitride layer effect**

The coining die had nitride layer on the surface. The nitriding enhances the surface hardness of the dies and hence better die life. As the forged parts are produced from the dies one after another, the nitride layer get worn out and the hardness goes on decreasing until it reaches the hardness of the base material. Hence, change in the hardness with the depth from the die surface was also considered in wear profile calculation.

In order to consider the change in the initial hardness due to nitride layer, a function with respect to distance from surface \((W)\) is defined given by Equation 5.3. It was assumed that the hardness of the dies decreases exponentially from the initial surface hardness equal to that of the nitride layer to the hardness of the base material.

\[
H_{\text{initial}}(W) = C_0 - C_1 (1 - \exp(-C_2 \cdot W))
\]

Equation 5:3
\[
C_2 = -\frac{\ln\left(1 + (H_{90\%} - C_0) / C_1\right)}{W_{\text{nitride layer}}} = \frac{2.3}{W_{\text{nitride layer}}}
\]

Where \(H_{\text{initial}}\) = initial hardness at the distance from surface \((W)\), \(C_0\) = maximum hardness of the nitride layer, and \(C_1\) = range of hardness between the maximum hardness and hardness of the base metal. The initial hardness distribution curve is as shown in Figure 5.20. And \(C_2\) = function of distance, where the hardness decreases to 90% of the maximum hardness, and \(W_{\text{nitride layer}}\) = total depth of nitride layer.

![Initial hardness distribution curve for Bohler™ W320 of Coining die](image)

- **Using tempering parameter for the effect of thermal softening of dies**

  The forging dies also lose their hardness due to thermal softening effect. During every forging cycle, the dies are subjected to heating when the hot billet is forged on the die surface and cooling when the forged part is removed from the die and lubricant is sprayed on the surface. These heating and cooling cycles lead to reduction in die hardness. It was
assumed that the dies lose their hardness similar to the tempering done during heat treatment.

The tempering parameter (M) was used to calculate the change in the hardness as well as the flow stress of the die material. Refer to Appendix B for the methodology for using tempering parameter.

- **Hot hardness effect**

As hardness of the dies decreases with increase in temperature, the effect hot hardness i.e. the hardness at elevated die temperature, was also used for calculation. As the strength of the material varies similar to its hardness, UTS data was used to obtain the hardness curves for various room temperature hardness.

In order to use UTS at any elevated temperature, factor $F_{hot}(T)$ of tensile strength according to instantaneous temperature $(T)$ is defined in equation, Equation 5.4.

$$F_{hot}(T) = \frac{UTS(T)}{UTS_{room}}$$

Equation 5:4

Where $F_{hot}(T)$ is factor of hot hardness, $UTS(T)$ is the tensile strength at the instant temperature$(T)$, and $UTS_{room}$ is the tensile strength at the room temperature.

By using the relationship between UTS vs the HRC, the hot hardness curves for various initial hardness was obtained. These curves were used to calculate the hot hardness of the dies at a particular hardness. (Figure 5.21)
Figure 5:21: Converted hot strength curve into hot hardness curve according to the initial hardness for Bohler\textsuperscript{TM} W320

5.3.5. **Plastic deformation of die surface**

To obtain the deformed die profile, FEA simulations were conducted using DEFORM 2D. The methodology used to obtain deformed die profile is given in Figure 5.22.

- **Analysis of heat expansion of a die at steady state temperature:** The steady state temperature distribution is obtained initially using by assuming rigid dies (from Section 5.1). This steady state temperature distribution is applied to elastic dies to include the heat expansion of the die for that temperature distribution.

- **Analysis of shrink fitting of die:** The elastic dies are then assembled to get the shrink fit compressive stresses in the extrusion die.

- **Analysis of deformation:** Now, the extrusion die is assumed as Elasto-Plastic. The flow stress data is calculated by using the yield stress and UTS data for the particular temperature. Thermal softening factor is also included in the flow stress
data to consider the number of cycles (see Equation). Single extrusion/deformation operation is simulated to find the plastic deformation of the extrusion die surface.

- **Removal from die assembly:** The extrusion dies are then simulated to understand the effect expansion after removal from the shrink fit die assembly.

- **Die cooling:** To get the die profile at room temperature, the extrusion die cooling is simulated.

![Diagram](Image)

Figure 5:22 Methodology for analysis of plastic deformation of dies.

For analysis of deformation process i.e. for elastoplastic analysis, the effect of die softening was also included. The flow stress function for the die material is modified to include the effect of die softening and change in die hardness. (Equation 5.5)

\[
\bar{\sigma}(\bar{\varepsilon}, \dot{\varepsilon}, T, M) = \bar{\sigma}(\bar{\varepsilon}, \dot{\varepsilon}, T) \times \frac{H_{ini}}{H_0} \times F_{sof}(M)
\]

Equation 5:5
5.3.6. Optimization of wear parameters

Using Matlab, the extracted wear profile (obtained from the CMM data compensated for plastic deformation) was compared with the FEA data, to obtain optimized wear parameters $K$ and $a$ such that the error between the wear value predicted using equation and the actual wear value obtained from extracted wear profile is minimized.

![Graph showing optimization of wear parameters](image)

Figure 5.23: Optimization of wear coefficient $K$ and experimental constant $a$ for extrusion die.

Figure 5.23 show the optimization curves for the extrusion die. For extrusion die, the predicted wear profile (obtained using simulation and wear equation) and the measured wear profile (after compensating for plastic deformation) is as shown in Figure 5.24. It can be noted that the predicted wear profile (from simulation data) does not match extracted wear profile (from CMM measurements after compensating for plastic deformation).
Figure 5.24: Comparison of predicted extrusion die wear profile (obtained using simulation and wear equation) with the CMM measured wear profile (after compensating for plastic deformation).

Similar methodology was used to predict wear profile on coining die. The optimization curves and wear profile comparison for coining die is as shown in Figure 5.25 and Figure 5.26 respectively. For coining die, the comparison shows that the predicted wear profile (from FE simulation) closely matched the extracted die profile (from CMM measurements after compensating for plastic deformation) as expected.
Figure 5:25 Optimization of wear coefficient $K$ and experimental constant $a$ for extrusion die.

Figure 5:26 Comparison of predicted coining die wear profile (obtained using simulation and wear equation) with the CMM measured wear profile (after compensating for plastic deformation).
5.4. Design of Shrink fit for Extrusion Tooling

Of all the dies used in forging of valves, extrusion dies have the lowest life. Frequent die changes also lead to loss of production time due to stoppages. Hence, to increase the die life as well as increase the productivity ceramic dies were proposed. Ceramics are known for their ability to retain their hardness at elevated temperature. A new tooling with ceramic extrusion dies was proposed. The challenge in designing hot extrusion dies is to have dies which retain their hardness longer as they are subjected to heat and pressure. The dies should also have sufficient toughness so that they can resist from cracking due to pressures exerted on the surface of the dies. To avoid cracking (due to tensile fracture) in extrusion dies they are usually pre stressed by using one or more container rings which are shrink fitted on to the extrusion die. The ceramic dies need to be under higher pre stresses as they have lower tensile strength compared to steel.

The ceramic material used was Syalon 101 manufactured by International Syalons (www.syalons.com). Syalon 101 is the commercial name for a β-sialon alloy containing silicon, aluminum, oxygen and nitrogen. It was found to have higher tensile strength, toughness and thermal stability compared to other ceramic materials that could be used for hot extrusion dies.

5.4.1. Selection of shrink fit interference for extrusion tooling

As the extrusion bushing was having sufficient pre stressing, the shrink fit interference between Extrusion Bushing and extrusion bushing holder was kept same as that used for the existing steel tooling. It is not varied during the simulation.
DEFORM 2D was used to conduct FE simulations and find the right shrink fit value between the ceramic extrusion die and the extrusion die holder.

The following design criteria were used for finding the right shrink fit for the ceramic die:

- The forging die should be designed such that the principal stresses on the tooling should be within the tensile and compressive limit of the ceramic material. In other words, the min. principal stresses should be within the compressive strength limit and the max. principal stresses should be within the tensile strength limit.

- As the ceramic die has high compressive strength (> 3500 MPa) and relatively low tensile strength (450 MPa) the dies are pre stressed (by shrink fit) such that the dies are under compressive stresses.

- The stress analysis is done with tooling initially at room temperature (first forging cycle) and after obtaining feasible shrink fit values, they were be tested as the dies heat up and reach steady state distribution.

- The shrink fit interference between the extrusion bushing and the extrusion bushing holder is kept same as that used for the existing steel tooling. It is not varied during the simulation.

As limited data was available for the mechanical properties of the ceramic material (especially at elevated temperature) the room temperature data from the manufacturer’s website was used for doing simulations. Steady state temperatures were obtained by using multi operation module in Deform 2D (similar to that used in Section 5.1). Stress analysis was done with elastic dies for various shrink fit values. The assumed friction and heat transfer coefficient are given in Table 5.2.
The minimum principal stresses during shrink fit and forging stroke for various shrink fit values during the first forging stroke were calculated. It was observed during simulation that minimum compressive stresses for a given shrink fit decreased during forging operation. This was because the dies are subjected to large thermal gradients causing the die surface layers to try to expand when in contact with the billet. However, the cooler inner region of the die prevents the surface expansion and causes compression of the die surface layers.

The maximum principal stresses during shrink fit and forging stroke for various shrink fit values during the first forging stroke were calculated. The maximum principal stresses were found to increase (both during shrink fit and during forging stroke) with increase in the shrink fit interference. However, the shrink fit values were within the tensile limit of the material.

Table 5:2 Friction and heat transfer coefficients were assumed as below

<table>
<thead>
<tr>
<th>During Deformation (forming)</th>
<th>During rest of the forging cycle (billet resting in die)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction coefficient</td>
<td>Heat transfer coefficient (HTC)</td>
</tr>
<tr>
<td>Ceramic die and billet material</td>
<td>0.1</td>
</tr>
<tr>
<td>Between ceramic die and steel dies</td>
<td>-</td>
</tr>
<tr>
<td>Between steel dies</td>
<td>-</td>
</tr>
<tr>
<td>Steel die and billet</td>
<td>0.3</td>
</tr>
</tbody>
</table>

During lubrication, the dies in contact with lubricant are assumed to have a HTC of 35 kW/m².K.

The feasible shrink fit interference was tested by the sponsor during forging trials. It was observed that the dies did not fail during forging operation due to cracking. Improvements in die life and dimensional accuracy of the valves were also observed.
CHAPTER 6 SUMMARY AND CONCLUSIONS

The objective of this research study was to investigate the forging process of the sponsoring company and suggest improvements which could increase the life of dies used in the process. Wear and plastic deformation of the dies were found to be major factors that contribute to die failure. Literature was reviewed to find studies on die wear prediction for forging dies. Die materials coatings and surface treatments available in the market as well as literature on using them in forging were also investigated. Finite element simulations were used to find the temperatures and stresses distributions in the extrusion and coining tooling. The wear and plastic deformation extrusion and coining dies was studied by measuring the die profile using CMM. Wear models were used to predict the wear profiles on the extrusion and coining dies. FE simulations were also used to design extrusion tooling with ceramic inserts. The effect of change in die temperature and shrink fit interference was also investigated.

The literature review found that there are better commercially available hot working tool steels such as DURO F1 and DRM1 (which can retain their hardness at a higher temperature) compared to H10 and H13 which are used in the existing forging tooling. Sialon was identified as one of the ceramic die material which could be tested for use in hot forging. BALINIT® ALCRONA (Oerlikon-Balzers) which is made of AlCrN
and ceramic coatings such as materials such as CrN, TiAlN, TiCN and ZrN were identified as potential coatings which may be used for hot forging dies. The cost of coating the dies is an important factor that influences the final decision on selection of ceramic die materials and coating as they are usually expensive.

FEA was useful in finding the temperatures in the forging dies as they heat up and reach steady state temperatures. The stress analysis after assembly and during forging (forming of the billet) was useful in identifying regions of high stresses on the dies. The wear prediction methodology was successful in predicting the wear profile in coining dies. However, this methodology could not explain the wear profile in extrusion dies. This may be due to high plastic deformation (compared to coining die) on the extrusion die. More extrusion die samples may be also be studied to make sure that the die profile measurements are accurate. FEA was successfully used to find the shrink fit interference which could provide sufficient compression for the extrusion tooling with ceramic insert. Limited success was found in using shrink fitted ceramic die inserts in hot extrusion due to design limitations.
### LIST OF REFERENCES


<table>
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<tr>
<td>Billur, 2010</td>
<td>Billur, E., Altan, T., “ Tool materials, treatments and coatings for stamping advanced high strength steels (AHSS)”, Center for Precision Forming, The Ohio State University, CPF 2.3/10/01, 2010</td>
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Appendix A
Properties of the Billet Material

1. 21-2N (equivalent to UNS K63017)
The material data was obtained DEFORM’s Material Library and www.matweb.com

Chemical composition of 21-2N

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<th>Cr</th>
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<th>Ni</th>
<th>N</th>
<th>Silicon</th>
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<td>7.0-9.0%</td>
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Young’s Modulus

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Thermal Expansion Coeff.

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<th>Temperature (°C)</th>
<th>Value (1/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>93.333333</td>
<td>1.206 e-05</td>
</tr>
<tr>
<td>204.44444</td>
<td>1.224 e-05</td>
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<tr>
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<td>1.296 e-05</td>
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<td>482.22222</td>
<td>1.314 e-05</td>
</tr>
<tr>
<td>815.55556</td>
<td>1.35 e-05</td>
</tr>
</tbody>
</table>

Density(×1000 kg/m³) 7.7
Poisson’s Ratio 0.3
Appendix B

**Tempering Parameter M**

[Hollomon et. al, 1945] showed that the relation between hardness and time and temperature of tempering can be expressed graphically as a function of a tempering parameter \( M \), where:

\[
M = Temp(k + \log_{10} \text{time}) \quad \text{Equation B.1}
\]

Where \( Temp \) is the tempering temperature (K), \( k \) is a constant with a value of about 20 (for __ material), and time is the holding time (hours).

Equation 1.8 is modified to get the tempering parameter for any forging cycle as shown in Equation 1.9, where \( T_{eq} \) is the equivalent temperature of the nth forging cycle and ‘t’ is the forging cycle time. As the temperatures of die surface change during forging, equivalent temperature (Teq) is used. Teq can be approximately expressed as shown in Equation B.3 where \( T_{max} \) and \( T_{min} \) are the maximum and minimum forging temperatures observed from the start of deformation of the billet until it is knocked out of the dies.

\[
M(n) = T_{eq}(20 + \log_{10} nt) \quad \text{Equation B.2}
\]

\[
T_{eq} = \frac{2T_{max} + T_{min}}{3} \quad \text{Equation B.3}
\]

The relationship between the tempering parameter (M) and hardness (HRC) and Ultimate Tensile Strength is shown in Figure B.1. The relationship between normalized UTS and tempering parameter is shown in Figure B.2.
Figure B.1: Relationship between hardness and Ultimate tensile strength and tempering parameter

In order find the UTS with change in tempering parameter (M), factor of thermal softening $F_{soft}(M)$ is defined as in Equation B.4, where UTS(M) is the tensile strength at the tempering parameter(M) and UTSroom is the tensile strength at the room temperature.

\[ F_{soft}(M) = \frac{UTS(M)}{UTS_{room}} \]

Equation B.4
The relationship between the tempering parameter and the hardness at varying initial hardness is shown in Figure B.3.

Figure B.3: Converted tempering curves into relationships between the tempering parameter and the hardness according to the initial hardness for BohlerTM W320

\[ M(n) = T_{eq} \left(20 + \log_{10} nt\right) \]  

Equation B.5

\[ T_{eq} = \frac{2T_{max} + T_{min}}{3} \]  

Equation B.6

In Equations B.5 and B.6,

\( M(n) = \) Tempering parameter after \( n^{th} \) forging cycle, \( t = \) Forging cycle time