FINITE VOLUME ANALYSIS OF A CLOSED DIE HOT FORGING AND COMPARISON WITH WEAR MEASUREMENT OF THE WORN DIE

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ABSTRACT

This work, the analysis of die wear will be observed. Computer simulation results will be compared with the measurement of die taken from industries and calculation of wear coefficient from comparison in of simulation by MSC.SuperForge software and the measurement from die will be completed. Coordinate Measurement. Machine is used to model the perform work piece and measurement on the worn die surface. Pro/ENGINEER is used for 3D modeling of the parts and mesh generation of the dies and the perform work piece. The Finite Volume analysis of a closed die hot forging and wear measurement of the worn die, the following conclusions have been reached, Due to the sliding velocity between 0.2 and 0.5 m/sec and the contact pressure between 100 and 300 MPa on the contact interface of the die and the work piece, the mechanical wear is predominant wear model. In wear analysis of dies, at the regions where high effective stresses may occur, the plastic deformation of dies must be taken into account. On the regions close to the parting line, due to high effective stresses plastic deformation appears. In the bottom part of the cavity, where the effective stresses are relatively lower, plastic deformation does not appear in these regions. Operation temperature, contact pressure, sliding velocity and contact time have great effects on the depth of wear. In the flash land, because of sliding velocity above 1 m/sec, the oxidational wear mechanism is observed with $k = 0.063 x 10^{-13}$ Pa^{-1}.From the simulation of hot forging process and comparison with the measurement of the worn die, the dimensional wear coefficient of $(6.5 \pm 0.6) \times 10^{-13}$ Pa^{-1} (wear coefficient 1.66×10^{-3}) can be used as a good approximation for hot forging processes, under the same conditions.

Keywords-Wear Model, Wear Coefficient, Metal Forming, Hot Forging, and Closed-Die Forging

I. INTRODUCTION

Forging has a special place because it helps to produce parts of superior mechanical properties with minimum waste of material. The starting material has a relatively simple geometry; this material is plastically deformed in one or more operations into a product of relatively complex configuration. Forging usually requires relatively expensive tooling. Thus the process is economically attractive when a large number of parts must be produced.

In forging process the life of dies is very important due to economical reasons and also finishing quality of productions. The factors influencing die life are thermal fatigue, plastic deformation, wear, etc. Amongst these, wear is the predominating factor in hot forging process. Lange reported that wear is the dominating failure mechanism for forging dies, being responsible for approximately 60% of failures

1.1 Worn Die Measurement & Modeling of the Work piece

Surface measurement of the worn die and the perform work piece by using Coordinate Measurement Machine, also modeling of the perform work piece by help of CAD software and using result of surface measurement. This part is forged in there forging steps as shown in Figure 1. Before starting the forging process, billets is prepared in the length of 130 mm with diameter of 80 mm. Material of the work piece is X-20 Cr14 steel. These prepared billets are fed into the heater to reach the temperature of 1000°C. Material of the die is AISI L6 tool steel. Before starting the forging process, the dies are heated to 400°C in order to prevent die failure due to thermal stress. For the forging operation "1600 ton" mechanical crank press is used. The wear analysis will be done for the finishing die which is important for final production quality

Step-1 Step-2 Step-3 Step-4

Fig.1 forging operations steps.

1.2 Measurements by Using Coordinate Measuring Machine

We are using Machine Model No. PC-DMIS. This machine for Windows is a full-featured, measurement. It changes the high-level commands required to measure parts into the detailed steps compulsory to drive a Coordinate Measuring Machine. The parameters that are used for measurement are shown in Table. 1. The first step in Coordinate Measuring Machine part programming is to define which probes will be used during the inspection process. PC-DMIS supports a wide variety of probe types, for this measurement the extension of 200 mm length and tip with 1 mm diameter are selected that are shown in Fig. 2. After this step the surface measurement can be done by selecting PATCH method and defining needed parameters. In this process four boundary points should be define to form the edges of surface limits which is going to be measured.

Fig.2 Coordinate Measuring Machine

Table 1. The parameters used for surface measurement

Maximum Increment in	4 mm
Minimum Increment in	0.6 mm
Increment in Direction 2	6 mm
Maximum Angle	6
Minimum Angle	0.6
Move Speed	50%
Touch Speed	5%

By using surface measurement method the coordinate measurement of die and pre-form work piece has been done. As shown in Figure.3 the measurement of die is in form of parallel curves of different sections. Result of perform work piece measurement must be used in CAD program to make solid model, for this reason the output result of work piece measurement is in form of measured points .By exporting data points to CAD program it is possible to draw smooth curves through the points and obtain a solid model. If the result of work piece measurement exports to CAD program was in measured curves instead of points, during solid modeling of part errors would occur due to roughness of imported curves from measurement and it is not possible to generate solid model of perform work piece.

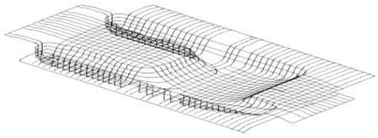


Fig. 3 Result of the worn die surface measurement & point tracking on the perform work piece Surface

1.3 Modeling of the Parts

In this work, Pro/Engineer is used for computer modeling of parts. After measurements, the output results would be imported to CAD program for surface generation and solid modeling.

To create parts and assemblies by defining features such as extrusions, sweeps, cuts, holes, slots, rounds, instead of specifying low-level geometry like lines, arcs, and circles. This means that the designer can think of his computer model at a very high level, and leave all the low-level geometric detail for Pro/E to figure out. They are specified by setting values of attributes such as reference planes or surfaces, direction of creation, pattern parameters, shape, dimensions, and others. Parametric means that the physical shape of the part or assembly is driven by the values assigned to the attributes of its features. It is possible to define or modify a feature's dimensions or other attributes at any time. Any changes will automatically propagate through your model. It is also possible to relate the attributes of one feature to another. Solid Modeling means that the computer model created is able to contain all the information that a real solid object would have. It has volume and therefore, if you provide a value for the density of the material, it has mass and inertia. By using advantages explained above Pro/ENGINEER will be used for modeling of parts. After obtaining points measured from perform work piece by CMM, first step is to pass curves through points in parallel sections. The result of this process is shown is Figure 4. Since the work piece has plan symmetry the modeling can be done for half of the work piece and at the end mirror the symmetry part.

Fig. 4 Measured points by CMM

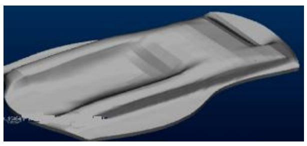


Fig. 5 Solid model of the perform work piece

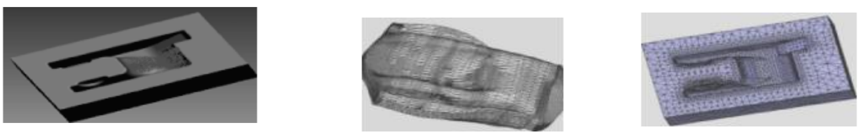


Fig. 6 Lower die for final step of the forging

It would be convenient if triangles were always equilateral, quadrilaterals always squares and hexahedra always cube. It is almost impossible to model complex systems with a mesh of ideally shaped elements. It is matching the mesh density to stress gradients and a deformation pattern which is the elements varies in size, unequal side lengths and is warped. In this mesh generation two matters must be considered; aspect ratio and distortions. The element aspect ratio is the quotient between the longest and the shortest element dimensions. This ratio is by definition greater than one. If the aspect ratio is 1 and the element is considered to be ideal with respect to this measure. The aspect ratio is element and problem dependent,

Aspect ratio < 3 for linear elements.

Aspect ratio < 10 for quadratic elements.

Higher-order numerical quadrature for a given displacement function are less sensitive to large aspect ratios than linear elements. Material nonlinearities are more sensitive to changes in the aspect ratio than those in linear regions. If a problem has a deflection in a single direction, elements may have relatively large aspect ratios, provided that the shortest element dimension is in the direction of the maximum gradient. Distortion is due to Skewing of elements and their out-of-plane warping is important considerations. Skewness is defined as the variation of element vertex angles from 90 degrees for quadrilaterals and from 60 degrees for triangles. Warping occurs when all the nodes of three-dimensional plates or shells do not lie on the same plane. In this cases contact penetration may occur because of distortion on the interface of contact bodies.\

1.4 Simulation & Analysis.

Computer simulation of hot forging process has been done to obtain the wear depth of die; it has been observed that to analyze the current forging process and comparing the result of wear analysis obtained from the simulation to the real-life experimental results. According to the analysis, a new wear coefficient for this work which may be applied to the similar hot metal forming process will be introduced. The value of wear coefficient for hot metal forming process, more accurate prediction can be done for die life during design of die.

1.5 Forging Operation Analysis

MSC.SuperForge is used for the simulation and analysis. There are five common process parameters that are identical in all the simulations in order to obtain accurate results: work piece and die models, material properties, ram speed, initial temperature, and friction model. The models for upper die, lower die and work piece geometry should be imported to the program. MSC. Super Forge requires a closed volume surface model for both work piece and dies. Models should be imported to MSC. Super forge in proper formats,

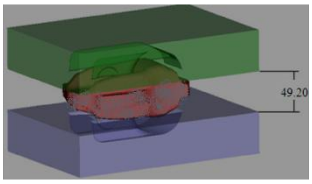


Fig. 7 Work piece in initial contact with die.

The position of them with respect to each other and the forging direction may not be correct. These models are firstly aligned along the Z axis with using “Moving Option Toolbar”. Once the objects are aligned along the Z axis, user can drop the work piece in place and position the dies against the work piece in initial contact by using "Positioning" option. The alignment of the dies and the work piece and initial position of them is shown in figure. 7. In MSC.SuperForge, forging operation direction is aligned on the Z axis, therefore after importing the models for the dies and the work piece,

1.6 Properties of Material

MSC.SuperForge provides elastic-plastic models for work piece material, for dies rigid-plastic models are used. The work piece material is X20Cr13 .Heat Resisting Stainless steel. Figure.8 shows the work piece stress-strain curve at a constant temperature of 1100^{o}C for three different strain rates.

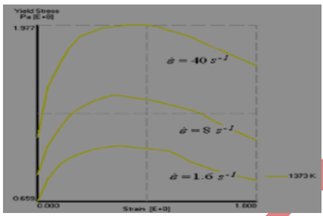


Fig.8.stress-strain curve at 1100^{o}C and different strain rates

The die material is alloy tool steel AISI L6, Plasticity model for this material is as below

$$\tilde{\sigma} = \max[\ Y\ , C\,\bar{\varepsilon}^{N}\ ] \qquad (1)$$

Whereas:

- Y= Minimum Yield Stress: 645 MPa
- C=Yield Constant: 1.1735 GPA
- N=Strain Hard Exp.: 0.128

The thermal properties and chemical compositions of the work piece

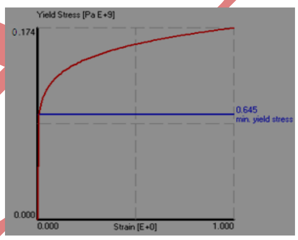


Fig.9 Die material plastic behavior

The software has six different types of forging machines that any of them can be applied for forging simulation, these are Crank press, Multi-blow Hammer, Screw Press, Hydraulic Press, Mechanical Press with Scotch Yoke drive and an alternate press defined by a table of time vs. speed. The Properties of forging equipments are given in Table 2.

Table 2. Properties of forging equipment

Type of Press	**Crank Press**
Capacity of press	1600 tonf
Crank Radius	120 mm
Rod Length	800 mm
Crank Speed	80 rpm

With the help of parameter given in Table 2 to the press, the velocity of the crank press can be obtained during its operation. Figure.9 shows the velocity of press as a function of time. At the beginning and at the end of press operation the velocity is zero. The maximum velocity of the press is 1.232 m/sec after 0.266 sec of press operation.

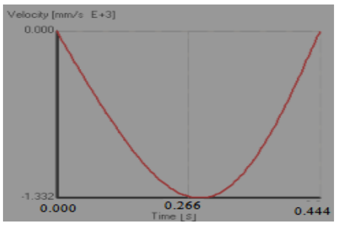


Fig.10 The velocity of the crank press as a function of time.

The initial temperatures of work piece and dies have great effect on the simulation of hot forging process as they influence the plastic behavior of materials. In industry, the dies are generally preheated before using in hot forging process. The initial temperatures in this study are

Initial temperature of work piece: 1200 ^oC

Initial temperature of die: 400 ^oC

Second parameters are used for the simulation:

Heat transfer coefficient to ambient:	50 watt/m^2.K
Heat transfer coefficient to work piece:	6000 watt/m^2.K
Emissivity for heat radiation to ambient:	0.25

The die has rough surfaces and is forced to move tangentially with respect to one another, frictional stresses will develop at the interface. A friction model should be applied to both of the dies. For forging operations involving relatively low contact pressure between dry contact surfaces. If the frictional shear stress reaches a critical value, the work piece will slip along the die. According to Coulomb's law of friction, this value is given by:

$$\tau = \mu . \sigma_n \quad (2)$$

the coefficient of friction and *n* denotes the normal stress at the work piece-die interface.

The alternative model to Coulomb's law of friction is Teresa's friction model, which is the law of plastic shear friction. According to this model, if the frictional shear stress exceeds a constant fraction *m* of the flow stress in shear, yield, the work piece starts to slip.

$$\tau = m . \tau_{yield} \quad (3)$$

A value of zero represents perfect sliding, which means there is no shear or friction at the work piece-die interface. A value of one represents sticking friction, which means that the friction shear stress equals the flow stress of the material in shear. For forging operations involving relatively high contact pressures, it is generally more appropriate to use the law of plastic shear friction.

In this work, plastic shear friction model is used as friction model for the simulation. The coefficient of friction and the interface friction factor assumed as 0.4 and 0.06, respectively.

1.7 Simulation

In this work, stroke of the operation, size of the finite volume work piece and die element sizes, output step size, problem type are defined. The suggested problem type for hot forging with flash by MSC.SuperForge is backward extrusion. In this work this type of problem is selected. A solver optimizer is implemented in this simulation control unit; thus, the user can change finite volume element size at any time and also coarsen the work piece to decrease the number of elements. Parameters that are used in this stage are shown in Table 3 sample view of a completed simulation process can be seen in Figure 12.

Table 3. Operation parameters assigned to complete the simulation.

Problem type	**Hot forging-closed die with flash**
Initial contact distance	49.20 mm
Flash thickness	5 mm
Upper die displacement	43.20 mm
Work piece element size	2.2 mm
Die element size	2.2 mm
Number of output steps	25

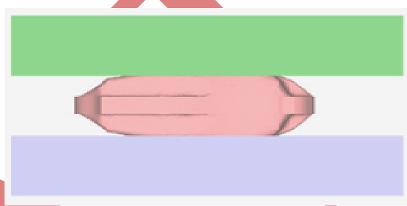


Fig.11 Simulation Performed in MSC.SuperForge

The wear model which is used in MSC.SuperForge is based on Archard's wear model, offers depth of wear to be a function of sliding length, hardness, normal stress and wear coefficient. The relation is given by:

$$\Delta d = K \times \frac{P \times \Delta L}{H} \qquad (4)$$

Where:

d= depth of wear (mm) at each time increment t (s),

K=non-dimensional wear coefficient, P=contact pressure (Pa),

L=sliding distance (mm) at time increment t, H= hardness of die (Pa).

In Equation 4 the sliding distance can be replaced in term of sliding velocity, and value of

$\frac{K}{H}$ can be replaced by dimensional wear coefficient k Pa^{-1}.

$$\Delta L = U \times \Delta t \qquad (5)$$

$$k = \frac{K}{H} \qquad (6)$$

Where:

U= sliding velocity (mm/s) at time increment t, and

K=dimensional wear coefficient (Pa^{-1}).

Equation 5.4 can be rephrased as:

$$\Delta d = k \times (P.U.\Delta t) \quad (7)$$

To obtain final depth of wear for one cycle, Equation 5.7 can be written in summation form of each increment wear depth,

$$d_{fin} = \sum_{1}^{n} k.P_i.U_i.\Delta t_i \quad (8)$$

Where:

d_{fin}=Final wear depth at the end of one cycle,

i =Number of increment,

n =Total number of increments that forging is simulated in one cycle.

The value of wear coefficient which is used in MSC.SuperForge to calculate the wear depth is $k = 1x\ 10^{-12}$ Pa^{-1}. Other parameters like contact pressure, sliding velocity, forging operation time and total number of increments will be calculated by numerical simulation.

II. RESULTS & DISCUSSION OF THE FINITE VOLUME SIMULATION

The Finite Volume simulation of this work by using MSC. Super Forge took about 38 hours to complete one forging cycle. The operation time of forging, which is obtained from numerical studies, is equal to 7.74×10^{-2} s, total increments for the simulation is 11675. The results can be obtained in output increments which set to 25;

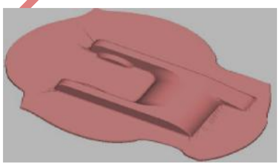


Fig.12 Perform work piece **Fig.13 Result of simulation- finished Product**

We are obtaining depth of wear from numerical result; other parameters like contact pressure, sliding velocity, effective stress, surface temperature and work piece die contact will be used to analyze wear generation on the die surface. In Figure 12 the velocity of the upper die is shown during the forging operation. At t = 0, beginning of the forging operation, the work piece and the upper die are in initial contact. At this moment the velocity of the upper die is about 2 m/sec. At t = 0.077 s the upper die reaches to its maximum displacement and the forging process will be completed.

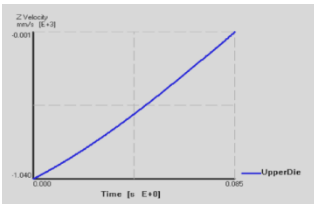


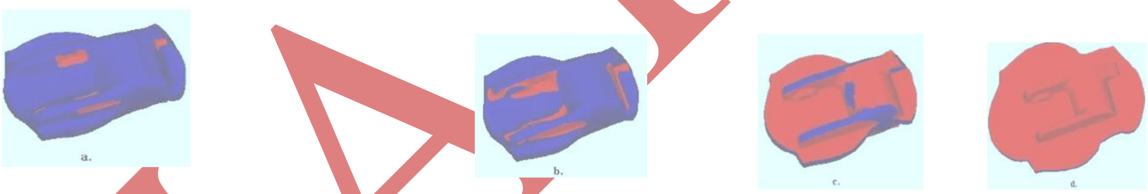
Fig. 14 The velocity of the upper die as a function of operation time.

2.1 Wear Analysis Of The Die

The original die profile form CAD data and the worn die profile measurement by Coordinate Measuring Machine are shown in figure 13 on one half of the profile. Since wear is result of surfaces contact, surfaces contact has effect on amount of wear; the process of the die filling in the selected cross section1 is given in Figure.14 at different stages of the simulation of forging operation. Figure 15 shows cross section 1 of the die that the result of wear analysis

2.2 Parameters Wear Analysis Affecting

Effect of wear coefficient in wear analysis other parameters like contact pressure, sliding distance, contact time between die and work piece, and temperature increase on the surface of the die have great effect on die analysis. Since wear is result of contact between surfaces, the contact pressure and sliding distance have great effect on wear depth. It is obvious that these parameters have meaning when contact happens between work pieces and die surface. Then for wear analysis, it is important to study the time that different points of die are in contact with work piece. Therefore, even some points have high value of contact pressure and sliding length, but there is a small value of wear. In this case, time of contact must be studied. For example some point are in contact from the beginning to the end of operation (100% of operation time), and there are some points, like thin rips, that they come to contact few percentage of operation time, say 20%, then amount of wear would be much higher in first point than second point even during contact there are higher contact pressure or sliding length at second point. The maximum contact pressure and the maximum velocity during operation and values in parenthesis, in



a.14% b.35% C.75% d.100%

Fig. 15 Contacts between dies and work piece in different stages. red color shows contact between die and work piece.

Affects wear is the surface temperature of the die. A high temperature billet is in contact with the die relatively at lower temperature. Due to large temperature differences, there will be rapid change in the temperature of die. This change of temperature is cause of two main factors. The final surface temperature of the die can be obtained from the simulation of hot forging process. In this case study, the highest temperature is about to 370 ^{o}C. Since the initial temperature of die is 300 ^{o}C, there is no large increase in the die temperature.

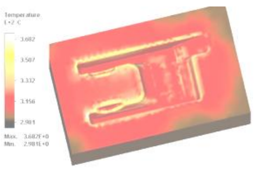


Fig. 16 Temperature distribution of the die at the end of process time

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2.3 Wear Analysis

Cross sections in 2 and 3 will be selected for analysis in the same way as done in the previous sections. New value of dimensional wear coefficient will be evaluated and by using this new value a modified wear profile will be compared with the measured worn die profile.

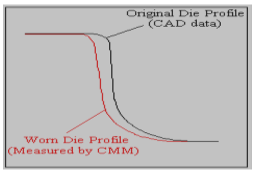
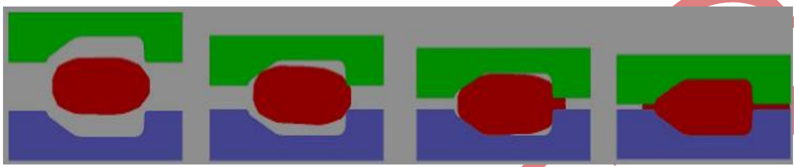


Fig. 17 Section 2 of the die & comparing the original die profile with the worn die profile



(i) 0% *(ii) 46%* *(iii) 74%* *(iv) 100%*

Fig. 18 Die filling process in cross section 2. in different time stages of the forging simulation

Wear depth analysis that obtained from forging simulation by Finite Volume Method show that the maximum value reaches to 6.5×10^{-3} mm close to the parting line. The minimum depth of wear is about 4×10^{-5} mm at the bottom line of the die profile, this area is one of the last spots to be filled during the forging process with small contact time, therefore the amount of wear is very small due to small contact time, as shown in Figure 17 after 74% progress of the forging operation time this point would come into contact with work piece. The values of wear depth at the end of the first forging operation cycle simulation are shown in Figure 18. The values in parentheses show the wear depth after batch size of 678. By using these values it is possible to draw wear profile and compare the numerical results with the measurement of the worn die.

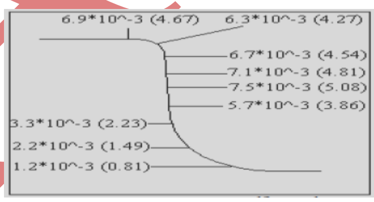


Fig. 19 Wear depth (mm) for k $= 1 \times 10^{-12}$ Pa^{-1} in one cycle, in section 2.

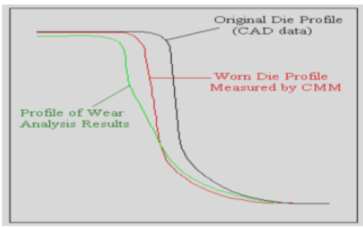


Fig.20. Comparison of wear analysis result and the worn die measurement in section 2

We are obtaining good results there should be some evaluation on wear coefficient in order to get acceptable results compare to measured worn die profile by comparing the result of wear analysis profile form forging operation simulation with the worn die profile measured,. The largest value is 7.75×10^{-13} at the middle of the profile and the smallest is equal to 0.11×10^{-13} at the bottom line of the profile. Values of wear coefficient are about 4×10^{-13} close to the parting line. The average value of dimensional wear coefficient in different points is equal to 6.65×10^{-13}. By using this average value of the wear coefficient it is possible to calculate new depth of wear at points and new profile can be obtained.

In this work, the wear analysis has been done for a hot forging finishing die, provided by Amtex Auto Ltd. FVM was used to simulate the hot forging process. The die wear option of MSC.SuperForge was used to obtain wear depth of the die. The parameters affecting the wear like contact pressure, sliding velocities, plastic deformation, surface temperature and etc, were obtained from numerical results of the forging simulation.

The mechanical press with capacity of 1500 tons was used for the forging. During the forging operation, after 94% of the operation time ($t = 6.3 \times 10^{-2}$) of operation, the effective stresses reach to their maximum value in the die through the forging process. The maximum effective stress is close to 700 MPa. By reaching to this value, plastic deformation occurs in the die due to high effective stress and also fatigue due to the repetitive forging processes in a batch. Both wear and the plastic deformation of the die would be studied at the points of the die with high effective stress.

The highest value of normal contact pressure appears at about 80% of the operation time on the top flat surface of the die with a value of 243 MPa. The contact pressure is about 250 MPa on the round corners. On the flash land, the normal contact pressure is about 200 MPa. The maximum sliding velocity occurs in flash land, reaches to about 1.6 m/sec. In the cavity, the sliding velocity is about 0.5 m/sec and in narrow sections it is about 0.3 m/sec which are much smaller than the sliding velocity in the flash land. For the wear analysis, the flash land and three different sections, where large depth of wear was observed, were chosen and the wear coefficients in these sections were evaluated. In this study, dimensional wear coefficient k $(\frac{K}{H})$ was used for the simulation. Using of the dimensional wear H coefficient has advantages due to the fact that the changes of the non-dimensional wear coefficient and hardness of the die would be taken to account at the same time as one parameter. It has been observed that by using constant initial value of dimensional wear coefficient of 10^{-12} Pa^{-1}, the die wear simulation results did not show good agreement with the worn die measurement. For this reason, some evaluation seems necessary to be done on the dimensional wear coefficient. By knowing the depth of wear from the worn die measurement and by obtaining contact pressures and sliding velocities from Finite Volume simulation of the hot forging operation, the wear coefficients have been evaluated for different points. For each section an evaluated value of the dimensional wear coefficient was obtained. These were 6.48×10^{-13}, 5.75×10^{-13} and 4.96×10^{-13} Pa^{-1}, respectively. The wear profiles obtained from the evaluated wear coefficients have shown better result than the constant wear coefficient of 1×10^{-12} Pa^{-1}.The differences of the dimensional wear coefficient in different sections are due to variation in contact pressure and sliding velocity at surface points of the die in different sections. In section 1, the contact pressure and the sliding velocity is relatively higher than other sections, therefore higher value of the dimensional wear coefficient is obtained. It is obvious that at high temperatures, the hardness of die decreases. The temperature of the die surface during the hot forging operation of this study varies between 400°C and 490°C. The Hardness of the die material at this range of temperatures varies between 48 HRC indentation hardness, H, is the average compression stress giving local plastic deformation on the surface) and 47 HRC (H 3× S_y 3750 MPa). By considering hardness of

4100 MPa for the die material and the Corresponding dimensional wear coefficient equal to 5.5×10^{-13} Pa^{-1}, the Non-dimensional wear coefficient would be obtained as 1.66×10^{-3}.

By using the value of 4100 MPa for the hardness of the die material, and the range of 150 MPa and 350 MPa for contact pressure on the die, the normalized contact pressure $\frac{P}{H}$ would be obtained between 1.25×10^{-2} and 5.75×10^{-2} during the forging operation; the sliding velocity varies between 0.1 and 0.5 m/sec. Therefore the normalized sliding velocity ($i.e\ \frac{U}{a}\sqrt{\frac{A_{nom}}{\pi}}$) would obtain between 5 and 100. Higher values of wear coefficient are obtained from the hot forging experiments. It can be observed that the values of wear coefficients obtained in this thesis are higher than the values given as per literature survey. The reasons are due to difference of temperature and the sliding velocity in hot forging operation compare to pin-on-disc wear test conditions.

As per other work for wear analysis of warm forging dies, the value of non-dimensional wear coefficient obtained about 1.510^{-4}. the different materials other than the considered in the thesis were used for dies and forging in R. S. Lee, J. L. Jou, "Application of numerical simulation for wear analysis of warm forging die", J. Mater. Process. Technol., 2003.it has also effective on these results. As sliding velocity exceeds of about 1 m/sec, the tips of asperities would be oxidized, and oxidation wear mechanism would occur. Since the sliding velocity is much higher than 1 m/sec on the flash land of the tested die, oxidation wear mechanism applies in this area. For the oxidation wear mechanism a non-dimensional wear coefficient of 1.19×10^{-13} Pa^{-1} was evaluated.

III. CONCLUSION

The Finite Volume analysis of a closed die hot forging and wear measurement of the worn die, the following conclusions have been reached, Due to the sliding velocity between 0.2 and 0.5 m/sec and the contact pressure between 100 and 300 MPa on the contact interface of the die and the Work piece, the mechanical wear is predominant wear model. In wear analysis of dies, at the regions where high effective stresses may occur, the plastic deformation of dies must be taken into account. On the regions close to the parting line, due to high effective stresses plastic deformation appears. In the bottom part of the cavity, where the effective stresses are relatively lower, plastic deformation does not appear in these regions. Operation temperature, contact pressure, sliding velocity and contact time have great effects on the depth of wear. In the flash land, because of sliding velocity above 1 m/sec, the oxidation wear mechanism is observed with $k = 0.063\times10^{-13}$ Pa^{-1}.From the simulation of hot forging process and comparison with the measurement of the worn die, the dimensional wear coefficient of $(6.5\pm 0.6)\times10^{-13}$ Pa^{-1} (wear coefficient 1.66×10^{-3}) can be used as a good approximation for hot forging processes, under the same conditions.

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