EVALUATION OF WEAR COEFFICIENT OF HOT FORGING DIES IN HAMMER FORGING

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By

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CERTIFICATE

This is to certify that the Thesis entitled, **"Evaluation of Wear Coefficient of Hot Forging Dies in Hammer Forging"**, being submitted by *Sukhwinder Singh Panesar* in partial fulfillment of the requirements of the award of degree Master of Engineering (Cad/Cam & Robotics Engineering) at Thapar University, Patiala is a bonafied work carried out by him under my guidance and supervision and no part of this thesis has been submitted for the award of any other degree. The matter is of desired standards for the award of the degree mentioned above.

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Date

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NOMENCLATURE

μ	coefficient of friction
σ_n	normal stress
τ	frictional shear stress
τ_{yield}	flow stress in shear
Δd:	depth of wear (mm) at each time increment
P	contact pressure (Pa),
Δ L	sliding distance (mm)
H	hardness of die (Pa).
U	sliding velocity (mm/s)
K	non-dimensional wear coefficient,
k	dimensional wear coefficient (Pa^{-1}).
d_{fin}	final wear depth at the end of one cycle.
d_{true}	true depth of wear

ABSTRACT

Hot Forging is a manufacturing method that is applied to a wide variety of high strength automotive components. To satisfy demands for lower costs and shorter production preparation times, it is vital that we are able to predict the die life. In general, the possible causes of die failure in metal forming include catastrophic fracture, excessive bulk plastic deformation, and wear. Failure due to catastrophic fracture and excessive bulk plastic deformation may be eliminated by implementing an appropriate tool design with adequately selected tool material. However, in most situations, wear does not result from a single mechanism. Wear of dies is a complex time-dependent phenomenon that primarily depends on the four components of the system: die, workpiece, interface conditions, and processing conditions. The interaction of various wear mechanisms at a contacting interface makes the analysis of wear behavior very complicated.

In this study, the wear analysis of a closed die used in Hammer Forging has been done. The hot forging operation was carried out at a workpiece temperature of 1100°C and die temperature of 200°C for a batch of 1000 components on a 1000 kg Airlift Hammer. The workpiece and die materials were AISI_1018 mild steel and AISI_H13 Tool Steel, respectively. The die for analysis was provided by ESSEN FORGE Pvt. Ltd. located at Ludhiana, Punjab. The simulation of forging process for the die and the workpiece was carried out by Finite Volume Method using MSC.SuperForge. The depth of wear in the die, die filling and temperature distribution have been investigated. In a single stroke, the depth of wear was evaluated using Archard's wear equation with a constant wear coefficient of $1\times10^{-12}\,\mathrm{Pa}^{-1}$. For comparing the wear analysis results with the experimental worn die, the surface measurement of the worn die was done on CMM at CENTRAL TOOL ROOM at Ludhiana. By comparing the numerical results of the die wear analysis with the worn die measurement, the dimensional wear coefficient was been evaluated for different points of the die surface and finally a value of dimensional wear coefficient is evaluated.

The simulation was performed at different temperatures and the relationship of the wear coefficient with the temperature was established. Wear Coefficient shows an increasing trend with increase of temperature.

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION TO FORGING

The Forging technology is known for producing parts of superior mechanical properties with minimum waste. It is a manufacturing process where metal is pressed, pounded or squeezed under great pressure into high strength parts. Metals or alloys are plastically deformed to the desired shapes by a compressive force applied with the help of a pair of dies. One die is stationary and the other has a linear motion. Forging process can be carried out both in hot and cold state of the metal. But, unless otherwise mentioned, forging process is considered to be “hot forging” process.

Forgings may be produced in either open or closed dies. In open dies forging which is also known as “Flat die forging”, the hot metal is struck or pressed between two flat surfaces or open contoured dies. The compressive force is progressively applied locally on different parts of metal stock. In closed die forging process, cavities or impressions are cut in the die block. The compressive force is applied to the entire surface and the metal is forced to take its final shape and dimensions as it flows into and fills the cavities.

The major equipment used in forging process are Hammers, Forging Presses, Forging Machines or Upsetters.

Figure 1.1 shows various steps involved in the Forging Process. The raw material is made available in the form of billets or slugs, which is then heated or warmed in the furnace. Forging operations are carried out using the suitable forging process and machines. After forging, some operations like machining, trimming, heat treatment etc are performed before the cleaning and final inspection of the component.

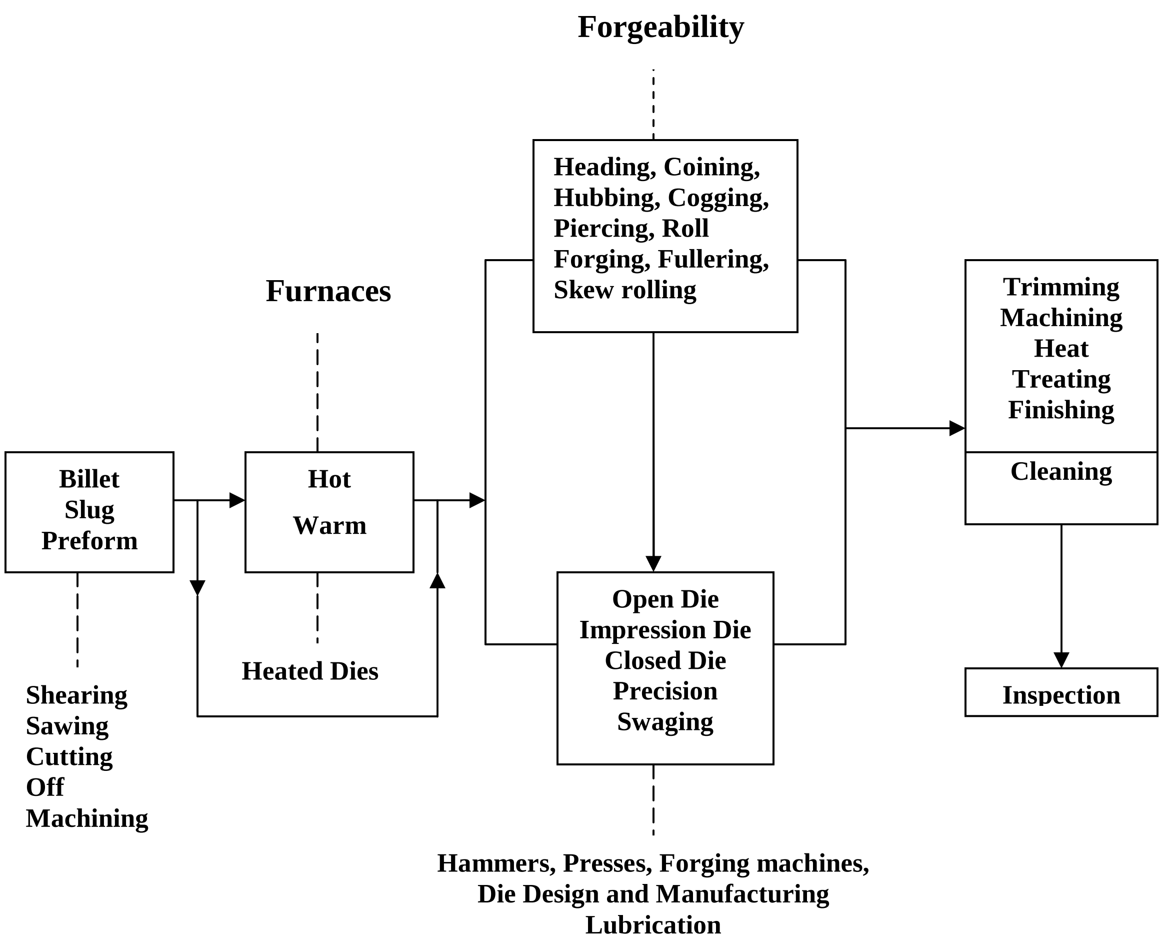


Figure 1.1: OUTLINE OF THE FORGING & RELATED OPERATIONS

1.2 CLASSIFICATION OF FORGING PROCESSES

There are various classifications applied for the forging process. In general, forging processes can be classified as:

- Temperature: Hot Forging, Cold Forging, Warm Forging
- Type of Machine Used: Hammer Press, Horizontal Upsetting Machine, Roll Forging, etc.
- Type of die set: Closed die, Open die

1.2.1 Classification of Forging Process According to Temperature

In *hot forging*, the billet is heated above its recrystallization temperature thus avoiding strain hardening. A greater degree of deformation can be achieved in a single operation than in cold or warm forging method. Die wear is also reduced in hot forging. However, the requirements for uniform and controllable die heating systems, formation of the scale and low dimensional accuracy are the main disadvantages of this process.

The temperature of metals being *cold forged* may range from room temperature to several hundred degrees. The primary advantage is the material savings achieved through precision shapes that require little finishing. While cold forging usually improves mechanical properties, the improvement is not useful in many common applications and economic advantages remain the primary interest. Tool design and manufacture are critical.

Warm forging has a number of cost-saving advantages that underscore its increasing use as a manufacturing method. This process is performed with the workpiece heated to a range that is generally above the work hardening temperature and below the temperature at which scale forms. Such forgings can be manufactured with excellent definition and can incorporate features that are not possible with conventional forgings. Compared with cold forging, warm forging has the potential advantages of: reduced tooling loads, reduced press loads, increased steel ductility, elimination of need to anneal prior to forging, and favorable as-forged properties that can eliminate heat treatment. Shafts, gears and automotive front wheel drive tulips are some examples for warm forged components.

1.2.2 Classification of Forging Process according to Type of Forging Machines

Forgings can be classified into four main categories according to the type of machine used. These are,

- Hammer Forging (Board Drop Hammers, Power Drop Hammers, Air-Lift Gravity Drop Hammers, Counterblow Hammers)
- Press Forging (Mechanical Presses, Hydraulic Presses, Multiple Ram Presses, Friction Screw Presses)

- Horizontal Forging Machine
- Roll Forging

Forgings made by using mechanical press is discussed in this section, since these type of forging machines are the most commonly used forging equipment in industry.

With the exception of the counterblow hammer, forging hammers have a weighted ram, which moves vertically in a downward stroke; thus, exerts a striking force against a stationary component of the anvil near the base of the hammer. The upper half of a pair of dies is fastened to the weighted ram, and lower half to the anvil cap. Initially heated billet is placed on the lower die, and the striking force is imposed on the work metal by the upper die and ram, causing it to deform plastically with each successive blow. The hammer is an energy-restricted machine. During a working stroke, the deformation proceeds until the total kinetic energy is dissipated by plastic deformation of the forging stock and by elastic deformation of the ram and anvil when the die faces contact with each other. Some of the energy is dissipated as heat loss.

Forging presses generally incorporate a ram that moves in a vertical direction to exert a squeezing action on the workpiece. Depending on the source of the power, forging presses are classified as mechanical or hydraulic. The operation of hydraulic press is relatively simple and is based on the motion of a hydraulic piston guided in a cylinder. Hydraulic presses are essentially load- restricted machines. Maximum capacities exceeding those of the largest power drop hammers are developed by hydraulic presses. Since most of the load is available during the entire stroke, relatively large energies are available for deformation. Within the capacity of a hydraulic press, the maximum load can be limited to protect the tooling and within the limits of the machine, the ram speed can be varied continuously during an entire stroke cycle with an adequate control system. In general, presses can produce all types of the forgings that can be produced by hammers and in addition some alloys of moderate ductility that would break under the blows of a hammer can be forged.

The mechanical forging press is an efficient machine, and it is the most widely used equipment for closed-die forging. The drive of the most mechanical presses is based on a slider-crank mechanism that translates rotary motion into reciprocating linear motion. The eccentric shaft is connected through a clutch and brake system directly to the flywheel. For larger capacities, the flywheel is located on the pinion shaft, which drives the eccentric shaft. The constant clutch torque is available at the eccentric shaft, which transmits the torque and the flywheel energy to the slide through the connecting rod. The flywheel, which is driven by an electric motor, stores energy that is used during deformation of the forged part.

There are some advantages and disadvantages of forging presses. The crank and eccentric presses are displacement-restricted machines. The slide velocity and the available slide load vary in accordance with the position of the slide before the bottom dead center. Higher production rates are possible with presses than with hammers. Because the impact is less in presses than in hammers, the dies can be less massive, thus requiring less tool steel to make the dies.

1.2.3 Classification of Forging Process according to the type of Die Set

Open-die forging, also called upsetting, is performed when a workpiece is placed on a lower die and its height is reduced by the downward movement of the top die. Friction between the end faces of the workpiece prevents the free, lateral spread of the ends of the workpiece and results in a barrel shape. Open-die forging is distinguished by the fact that the metal is never completely confined or restrained, and that the dies used are rather simple and universal. All types of hammers or presses may be used in open-die forging. Forgings are made by this method if:

(a) The forging is too large to be produced in closed dies; under open dies it is produced in many steps by forging only a part of it in each step, or

(b) The quantity required is too small to justify the cost of complex closed dies. Practically all of forgeable ferrous and non-ferrous alloys can be open-die forged, including age-hardening superalloys and corrosion-resistant refractory alloys.

Open-die shape capability is wide and this process can produce step shafts, hollows cylindrical in shape, ring like parts, and contour-formed metal shells like pressure vessels. Multiple open-die forging operations can be combined to produce the required shape, or these forging methods can be tailored to attain the proper amount of total deformation and optimum grain-flow structure, thereby maximizing property enhancement and ultimate performance for a particular application. Forging an integral gear blank and hub, for example, may entail multiple drawing or solid forging operations, and then upsetting. Similarly, blanks for rings may be prepared by upsetting an ingot, then piercing the center, prior to forging the ring.

In the simplest form of *impression-die forging*, commonly referred to as closed-die forging, a cylindrical or rectangular workpiece is placed in the bottom die. The dies contain no provision for controlling the flow of excess material. As the two dies are brought together, the workpiece undergoes plastic deformation until its enlarged sides touch the sidewalls of the die impressions. At this point a small amount of material begins to flow outside of the die impressions, forming flash. In the further course of the die approach, this flash is thinned gradually. As a consequence, it cools rapidly and presents increased resistance to deformation. In this sense, the flash becomes a part of the tool and helps to build up high pressure inside the bulk of the workpiece. This pressure can aid material flow into parts of the impression previously unfilled so that, at the end of the stroke, the die impressions are nearly filled with the workpiece material.

Impression-die forging can produce a variety of three dimensional shapes with a wide range in weight. Because metal flow is restricted by the die contours, this process can yield more complex shapes and closer tolerances than open-die forging processes.. Most engineering metals and alloys can be forged via conventional impression-die processes, among them carbon and alloy steels, tool steels, and stainless, aluminum and copper alloys, and certain titanium alloys.

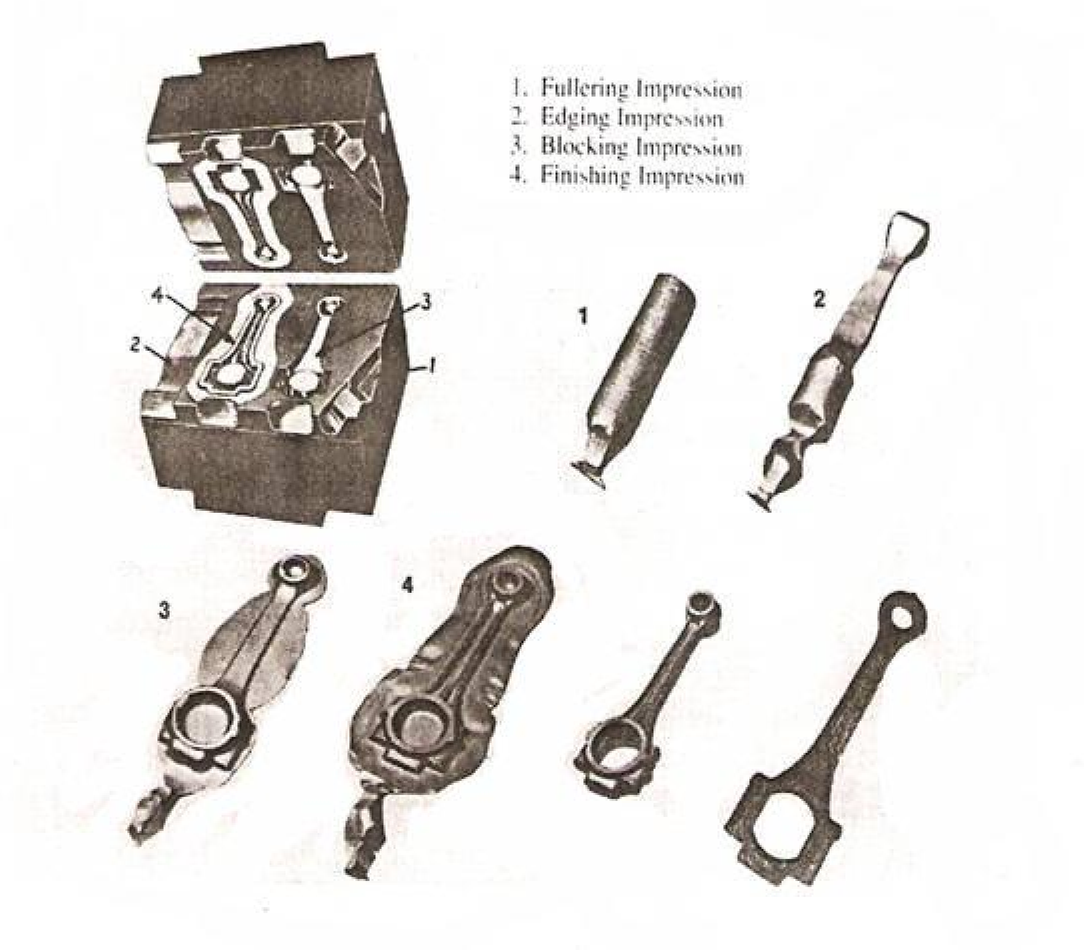


Figure 1.2: Process of Impression Die Forging

Figure 1.2 shows the process of impression die forging:

(a) Stages in impression-die forging of a connecting rod for an internal combustion engine.

(b) Fullering and

(c) Edging operations to distribute the material when pre-shaping the blank for forging

1.3 COMPARISON OF FORGING WITH OTHER MANUFACTURING PROCESSES

- As compared to *Castings*, the Forgings are stronger and more reliable. Preworking in forging refines defects and give directional strength. Forgings offer better response to heat treatment while castings require close control of heating and cooling processes.

- As compared to *Machining*, Forgings offer broader size range of desired material grades, grain flow provides higher strength. Forging yields lower scrap and make more economical use of material. It requires fewer secondary operations as compared to machining.

- As compared to *Welding/Fabrication*, Forgings are more consistent and have better metallurgical properties, have simplified production. Material savings are more in forging. Also the design and inspection processes are cost effective.

- As compared to *Powder Metallurgy*, Forgings are stronger and give higher integrity in the structure. Greater design flexibility is there and it requires fewer secondary operations. Less costly materials are used as compared to those used in powder metallurgy.

1.4 FORGEABILITY

The forgeability of a metal can be defined as its capability to undergo deformation by forging without cracking or defects. This definition can be expanded to include the flow strength of the metal. Thus a material with good forgeability is one that can be shaped with low forces without cracking. A commonly used test of forgeability is to upset a solid cylindrical specimen and observe any cracking on the barreled surface. The greater the deformation prior to cracking, the greater the forgeability of the metal. If notch sensitivity of the material is high, surface defects will affect the results by causing premature cracking.

In another test of forgeability called hot-twist test, a round specimen is twisted continuously in the same direction until it fails. The test is performed at various temperatures, and the number of turns that each specimen undergoes before failure is observed. The optimal forging temperature is then determined. This test is particularly useful in determining the forgeability of steels, although upsetting tests can also be used for that purpose. Small changes in the composition of or impurities in the metal can have a significant effect on forgeability.

Hydrostatic pressure has a significant beneficial effect on the ductility of metals and nonmetallic materials. Experiments have indicated that the results of room-temperature forgeability tests are improved, i.e. cracking takes place at higher strain levels, if the tests are conducted in an environment of high hydrostatic pressure. Based on the results of various tests and observations, the forgeability of several metals and alloys is determined and shown below. It is based on such considerations as the ductility and strength of the metal, forging temperature required, frictional behavior and quality of the forging obtained.

1.5 FORGING DIES

Forging Dies are the main tools used in forging process for getting the desired shape and geometry of the workpiece. Forging dies can be open or closed depending upon the type of product to be manufactured.

The forging dies are designed and made according to the forging drawing which is made up proceeding from the drawing of a ready article taking into account the following: machining allowances, forging tolerances, overlaps if necessary, corner radii, stamping drafts. It must also be decided to where to locate the parting line of the die.

1.5.1 Causes of Die Failure

The three basic cause of premature die failure are overloading of the die, wear and over heating. Although fewer die failure can be attributed to *Overloading* than to wear or overheating, an overloaded die wears rapidly and may break. Overloading can be avoided by careful selection of die steel and hardness,proper application of working pressure, proper die design to ensure correct metal flow.

Wear is inherent in the flow and spreading of hot metal in the impression of a forging die. Wear is particularly severe if the design of the forging is complex or in other respects difficult-to-forge, if the metal being forged has a high hot strength, or if there is scale on the work metal. Although wear cannot be eliminated, its effects can be minimized by good die design, careful selection of die composition and hardness, and a forging technique that includes proper heating, and correct die lubrication.

As a die becomes hotter, its resistance to wear decreases. *Over heating* causes most of the premature die wear that occurs in forging. Overheating is likely to occur in areas of the die impression that project into the cavity. In addition, overheating may result from continuous forging. Since forging temperature typically range from 370 to 1260° C, temperature of the die block will also cover a broad range. In forging steel, thin projections or plugs may reach 425 to 550°C, but the temperature within the die block usually is in the range from 150 to 350° C. Dies for forging steel and other metals that must be forged at high temperatures are susceptible to heat checking, or the development of minute cracks in the die impression.

1.5.2 Factors affecting Die Life and Wear

Die life depends on several factors, including die material and hardness, work-metal composition, forging temperature, condition of the work metal at forging surfaces, type of equipment used, and workpiece design. Changing one factor almost always changes the influence of another, and the effects are not constant throughout the life of the die.

Die material and *hardness* have great influence on die life. AISI H13, AISI L6 and DIEVAR are hot work tool steels that are commonly used for hot forging operations. The suggested hardness for hot forging operation tools for forging steel work pieces is between 42 and 55 HRC.

Each *workpiece material* being forged has a different resistance to plastic deformation and, therefore, a different wear action against the die surfaces. The resistance of hot steel to plastic deformation increases as the carbon or alloy content increases. Other factors being constant, the higher the carbon or alloy content of the steel being forged, the shorter the life expected from the forging die.

It is important that the initial *temperature* of both the die and the billet be optimized. Die temperature should be kept low so as to retain the hardness, but it should be high enough not to cause excessive die chilling due to temperature differential in the workpiece. Die temperature and the time elapsed between lubricant application and contact with the workpiece play decisive roles in the evaporation of the carrier. At very low temperatures of die, there would be a large temperature difference between the die and workpiece. As a result the die will fail due to thermal shocks. At very high die temperatures, the hardness of die decreases which leads to die failure due to permanent deformation.

To reduce die wear, the manufacturers (say those producing valves) often operate the mechanical press at a reduced speed of 45 to 60 strokes per minute (spm) instead of 80 or 90 spm, which is the usual speed for such a press. The press speed can be further optimized to reduce die wear during extrusion.

Selection of the proper process lubricant based on its properties and method of application can improve die life and workplace conditions. All these parameters described above are not constant throughout the process. Thus, the factors affecting die life should be considered and set accordingly considering the deviations, before designing the dies and the forging process.

In this chapter we've studied about the forging process and its classification, its comparison with other manufacturing processes and about forging dies. Forging technology is the one which produces superior mechanical parts over wide range of sizes and materials. Forging Dies are the main tools used in the forging process. They should be designed optimally to get the desired geometry of components over a period of time. An attempt has been made to analyze the wear phenomenon in dies in this study. The literature survey regarding dies and die life follows in next chapter.

CHAPTER 2: LITERATURE SURVEY

Several researches have been done on wear phenomenon of hot forging operation including the wear model and, wear prediction, wear reduction, etc. In hot forging process main appearance of wear is due to mechanical wear mechanism. Conditions like high pressure (close to hardness of die material), high sliding velocity (over 1 m/sec) and flash temperature (over 700°C) that cause other wear mechanisms such as melt wear and oxidation wear, hardly appears during operation, although oxidation wear may appear on flash land due to high sliding velocity. Mechanical wear mechanism seems to be appropriate for hot forging operations wear analysis.

The following section details the literature available and relevant to the present study of wear in forging dies:

Arjaan Buijk et al [1] evaluated MSC.SuperForge by comparing its simulation results with the simulation results of DEFORM™-3D, a validated finite-element based forging simulation package. A 3D extrusion process using a streamlined die design was selected for the evaluation, since this process produces a relatively complex I-section extruded shape. A secondary objective of the study is to investigate shear extrusion dies in 3D extrusion processes with MSC.SuperForge. Although streamlined extrusion dies are generally preferred over sharp corner shear dies for extrusion because streamlined dies produce lower extrusion loads and more uniform material flow, streamlined extrusion dies are more difficult to design and more expensive to manufacture than shear dies. Until this current study, however, few attempts have been made to analyze 3D metal flow in shear die extrusion processes due to difficulties in simulating the more complex material flow. The finite-volume technology in MSC.SuperForge overcomes these difficulties and the package was effectively used to simulate various feeder plate designs for a shear die extrusion process.

Rado Turk et al [2] presented an overview of wear models for predicting of tool wear in hot forging and applications of recently introduced new approach of tool wear prediction on industrial tools are given. In this paper was described for systematically enlarging the database (a time consuming process) and how to utilize this limited data for predicting wear. The procedures for extrapolation and interpolation by CAE NN were applied. Extrapolation was carried out on the basis of known individual wear data at lower number of strokes and this enables reliable prediction of wear at higher number of strokes.

Ramazan Kacar et al [3] showed through experimental results that the different microstructures cause a great influence on the wear resistance performance of the steels. Water quenched samples with martensite structure have the highest hardness and wear resistance performance. That is because, water cooled samples contained higher amount of carbon in the solid solution. On the other hand, air or sand cooling from forging temperature results in a decrement of hardness and wear resistance in steel-1 and steel-2. However, air cooled samples showed slightly higher wear resistance than sand cooled samples due to finer grain sizes and the larger pearlite and/or precipitation contributions. Sliding wear behaviour of two types of medium carbon microalloyed steels containing various microstructures was investigated on a 320 mesh SiC paper at a sliding speed of 0.33 m/s with a load of 6N and sliding duration of 4 min under dry sliding conditions (the sliding distance, 80 m).

N. Huber et al [4] presented a very efficient, incremental implementation of Archard's wear model on the global scale for pin wear and disc wear in a pin-on disc tribometer. The results from the model were in good agreement with experimental results. The identified wear model was implemented in a finite element based tool (Wear-Processor) for 3D wear simulations and the results compare favorably with that from the global wear modeling scheme.

C. Boher et al [5] assessed some wear mechanisms of a martensitic tool steel at various test temperature. The tribological tests were performed on a high temperature pin-on-disc tribometer designed in laboratory. Experiments were carried out for different disc temperatures ranging 20°C to 950°C. The disc was heated up by a high frequency induction heating. Wear mechanisms were investigated by Scanning Electron Microscopy

(SEM) and Energy Dispersive Spectrometry (EDS). In addition, the state of the art on tribology of oxides was undertaken. The oxides and their thickness play an important part in friction and wear behaviour. In this study, the wear mechanisms are essentially composed of abrasion, plastic deformation and fatigue.

M.Zamani et al [6] examined the wear profile on the die surface during the hot forging operation for an axisymmetric cross-section. In the field of metal forming, reliable estimations of die wear and its distribution on the die surfaces can greatly influence the life of the forging dies. The amount of wear was calculated for two wear models by implementing a rigid thermo-viscoplastic finite element analysis into the metal forming process. The first model consists of the classical model which proposes that the amount of the wear is proportional to the die pressure and sliding length. Whereas, the second model assumes that the wear is proportional to the energy dissipated on the tool/workpiece contact interface. Finally, the influence of the friction on the amount of die wear and the material flow was discussed. From the study, it was found that these models are in agreement with each other. They are also consistent with the prediction of the location of heavily worn areas on the die surface. It was also concluded that the increase of friction coefficient does not enhance the die wear in general.

D. Kircher et al [7] studied the sliding wear behaviour of 40CrMoV13 Steel against C35E in the 700 to 850 °C temperature range under ambient conditions. This steel is used frequently as hot forging die material. This study focused on the effect of the test temperature and the role of the oxide scales. The purpose of these experiments was to obtain tribological data (friction coefficient, wear rate, etc.), in order to include it in numerical simulations of damage to hot forging tools for the purpose of optimizing the tools' lifespan.

Jerry K. Keska [8] described an example of how the research on tribology can be integrated into the undergraduate classroom for an introductory class in mechanical technology by reporting results generated in such processes. The research results were verified by using two concomitant systems to determine the wear, and were compared with results reported by J. F. Archard and W. Hirst. The materials used in this experiment were nylon, aluminum, low carbon steel, and stainless steel. In the research, a developed pin-on-disk test system was utilized to generate an abrasive wear on pins that had a diameter of three-eighths of an inch and an initial length of about two and a half inches. In this paper, a pin-on-disk test was carried out as an open-ended project in an introductory class in mechanical technology.

R. Gras et al [9] studied the wear mechanisms of the tempered martensitic X38CrMoV5 steel (AISI H11) under high-temperature and dry-sliding wear. The investigations were carried out with high-temperature pin-on-disc tests. The pin was cut from bars of X38CrMoV5 steel treated at 42 and 47 HRC. The disc was made of common steel (AISI 1018, XC18). Temperature of the disc ranges from 20 to 950 °C. Before the test starts, the disc was first pre-heated for 1 hr. The experiments were performed under constant load and velocity. The friction coefficient decreases quasi-linearly with the rising disc temperature up to 800°C. Over this temperature, it decreases drastically for the 42HRC steel but remains linear for the 47HRC steel. Scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS) investigations revealed that wear is essentially due to abrasion, plastic deformation and fatigue. Set of cracks due to contact rolling fatigue was observed on the pin and the disc. Those cracks were located on the transferred scale on the pin and on the oxide scale of the disc wear track. The cross-section observations of the pin revealed a plastically deformed zone beneath the surface. In this sub-surface layer, the tempered martensitic microstructure seemed to be more aligned due to friction and the plastic deformation.

Edwin de Vries et al [10] formulated a method to simulate processes of forging and subsequent heat treatment of an axial symmetric rod in Eulerian description and the feasibility was investigated. This method uses finite volume meshes for tracking material deformation and an automatically refined facet surface to accurately trace the free surface of the deforming material. In the method, the deforming work piece flows through fixed finite volume meshes using Eulerian formulation to describe the conservation laws. Fixed finite volume meshing is particularly suitable for large three-dimensional deformation such as forging because remeshing techniques are not required, which are commonly considered to be the main bottleneck in the simulations of large deformation by using the finite element method. By means of this finite volume method, an approach was developed in the framework of metallo-thermo-mechanics to simulate metallic structure, temperature and stress/strain coupled in the heat treatment process. In a first step of simulation, the heat treatment solver was limited in small deformation hypothesis, and uncoupled with forging. The material is considered as elastic-plastic and takes into account of strain, strain rate and temperature effects on the yield stress. Heat generation due to deformation, heat conduction and thermal stress are considered. Temperature-dependent phase transformation, stress-induced phase transformation, latent heat, transformation stress and strain are included. These approaches were implemented into the commercial computer program MSC/SuperForge and a verification example with experimental data was given as comparison.

Katsuaki Kubota et al [11] summarized the influencing variables and causes of hot forging die failures for automotive components. Characteristics of hot forging die failures were exemplified. An important role of microfractography is stressed in engineering failure analysis for hot forging die failures. Then failure analyzed examples for hot forging die failures and their countermeasures were presented with influencing variables such as die materials, die design, die manufacturing and forging operations. Finally a couple of recommended works for engineering failure analysis for hot forging die failures for automotive components were touched on briefly.

Sung Wook Chung et al [12] carried out full three-dimensional finite volume method (FVM) simulation for two types of Mg alloys. The load-stroke curve, effective strain, effective stress, and strain rate were obtained during the virtual superplastic forging process. The above results for fine-grained Mg alloy showed localized flow behavior because of the change in dominant deformation mechanism at a high strain rate above ca. 0.8 s^{-1}. However, RS P/M Mg–Zn–Y alloy showed relatively uniform metal flow at the same strain rate.

Chorng Der Lee et al [13] proposed a method to find the friction factor of the die/workpiece interface for the forging process without the need for measurement of the shape changes of the workpiece. The methodology was mainly based on the concept of the inverse analysis and required only the defining of the problem inversely, without the need for mathematically inverting the problem. Comparison of the results of the proposed method with those obtained by the conventional calibration curve method showed good agreement between them, indicating that the proposed method was quite acceptable. Using the proposed model to predict the influence of die velocity on the friction factor showed that the friction factor decreases when the die velocity is increased, further confirming the validity of the proposed approach.

H.B. Campos et al [14] analyzed the failure by excessive plastic deformation of the high relief ring in the bottom die during the third stage of a gear blank forging using a finite element method. An evaluation of the effective stress and temperature evolution at critical points of the high relief ring was completed. It was established that the plastic deformation was caused by excessive stresses applied on the high relief ring, which were associated with an additional upset that was employed in order to compensate for a lack of die filling under normal upsetting conditions. A solution to the problem involves a better cooling of the high relief ring during forging and die geometry changes that would allow the elimination of the additional upset.

Janez Kramberger et al [15] performed computer simulation of the forging process using the finite volume method (FVM). The process of forging is highly non-linear, where both large deformations and continuously changing boundary conditions occur. In most practical cases, the initial billet shape is relatively simple, but the final shape of the end product is often geometrically complex, to the extent that it is commonly obtained using multiple forming stages. Examples of the numerical simulation of the forged pieces provided were created using Msc.SuperForge computer code. The main results of the analysis are deformed shape, temperature, pressure, effective plastic strain, effective stress and forces acting on the die.

Sayuri Kondo et al [16] described a newly developed technology that can be used to predict the temperature and wear of the dies used in hot forging. Through an examination of axisymmetric, it was found that amount of wear in the dies can be forecasted using a model composed of the cumulative friction work of the metal flow on the surface of the dies and yield strength of die materials at elevated temperatures. It was also found that the die temperature can be predicted by applying a cooling model that considers the relationship between the heat transfer coefficient and the Reynolds number of the lubricant jets that are generally used in hot forging. Using the cooling and die load models, the hot forging die life with sufficient accuracy at the process design stage was determined. A process design CAE system was also developed, based on the wear and cooling models, which is capable of predicting the die wear life and temperature.

C.G. Kang et al [17] proposed two estimating methods for predicting the die life due to wear or plastic deformation during hot forging considering the deviation of the preheating temperature of the billet. The characteristics of the billet during electroplating or induction heating are very complex in the preheating process. Therefore, an induction heating of billet has become increasingly important as a means of reducing the heating time and an effective control of heating temperature. In this paper, to calculate the temperature distribution of the billet in the preheating process according to the parameters such as heating time, frequency and current density in high-frequency induction heating, an induction heating program has been developed. Then, FE-simulation with the proposed wear and the plastic deformation models has been carried out for the hot forging sequence of a spindle part widely used in the present continuous hot forging die. The results showed that die life is greatly affected by the wear under the conditions that exist in a given deformation process and the maximum wear occurs at the corner of the finisher die. These proposed methods of the die life could be used effectively for quantitative prediction of the die life in the hot forging process. These results might also be extended further for the study of optimization of the die change schedule to grind the die.

G. Castro et al [18] studied the influence of nitriding time in the wear behaviour of an AISI H13 hot work steel used on forging dies. AISI H13 steel was nitrided by a patented sursulf bath, varying nitriding time from 1 to 24 h. Optical microscopy and microhardness deep profile through the nitrided layer were performed for each nitriding time. Standard pin-on-disk wear test were conducted at temperature similar to that attained during forging process. Sliding distance was varied from 450 to 1500 m. It was observed that friction coefficient does note change with nitriding time and wear rate varies as a function of the sliding distance due to the presence of different wear mechanisms. Thus, for short sliding distances wear rate depends on two mechanisms: plastic deformation and abrasive wear, whereas for large sliding distances the mechanisms controlling wear rate are abrasive and oxidative wear. Based upon laboratory results, performance tests on hot-forging tools were carried-out under industrial conditions. Crankshaft forging dies were sursulf nitrided during 7 and 13 h, for which the number of forged parts was 4065 and 10381, respectively. These results showed that increasing the nitriding time and thus the thickness of nitrided layer give rise an increase of the forging die durability

D.H. Kim et al [19] suggested die cooling methods to improve die service life with regards to wear and plastic deformation in a hot forging process. The yield strength of die decreases at higher temperatures and is dependent on hardness. Also, to evaluate die life due to wear, a modified Archard's wear model was proposed by considering the thermal softening of die expressed in terms of the main tempering curve. The effects of die cooling methods such as cooling hole and direct spray cooling on the life of finisher die during the hot forging of an automobile part were described. It was shown that the cooling hole method during hot forging is necessary for an effective die service life to be obtained.

R. Tulsyan et al [20] identified that abrasive wear was the primary mode of wear, and computer simulation was used to investigate the effect of process variables, such as press speed, initial billet temperature, and die preheat temperature upon abrasive wear. The result generated by this study could be applicable to other part geometry and not limited just to exhaust valves.

Jalaja Repalle et al [21] identified various uncertainties that affect the forging process and evaluated their cumulative effect on the forging tool life. Because the forging process simulation is time-consuming, a response surface model was used to reduce computation time by establishing a relationship between the process performance and the critical process variables. A robust design methodology was developed by incorporating reliability-based optimization techniques to obtain sound forging components. A case study of an automotive-component forging-process design was presented to demonstrate the applicability of the method.

I.Perus et al [22] presented a new approach which combined the use of a conditional average estimator neural network (CAE NN) with the exploitation of results obtained by the finite element method (FEM) and also data from other sources for prediction of tool wear in hot die forging along the entire arbor radius. Consequently new parameters as well as the results of experimental work were taken into account. In the paper a brief overview of models for prediction of tool (die) wear were discussed. The theoretical background of CAE NN, as well as its application to the modeling of the tool wear phenomenon, was presented. Some results of FEM analysis of the hot forging process that serve as input parameters in the CAE NN model were also briefly discussed. Two relevant practical applications were shown. In the first example, tool wear was modeled at a higher number of strokes (blows), by knowing wear at a lower number of strokes. In the second example, the number of strokes was the output parameter—the number of strokes causing predetermined wear at any point of the tool engraving curvature (arbor radius) was predicted. A comparison between the measured and predicted values of wear demonstrated good agreement that was assessed by a corresponding coefficient of determination

Thomas C. Grobaski et al [23] in this research provided a preliminary step into developing a complete forging die life model. The research involved analyzing the initial effects of (1) friction, (2) work-piece temperature, (3) die temperature, and (4) forging press stroke speed on effective die stresses, die surface temperatures, die/workpiece sliding velocities, die/work-piece contact pressures, and die surface temperatures were examined. To obtain the results the forging process was modeled (SolidEdge 3D Solid Modeling Software), simulated (MSC.Superforge Software), and statistically setup and examined using two-level full factorial design of experiments (Analyzed with Minitab & MS. Excel). The product reviewed was a 10inch diameter differential ring gear forged at the American Axle Manufacturing, North Tonawanda, New York forging plant. The ring gear is used in the rear differentials for Ford and GM trucks

Dong-Hwan Kim et al [24] explained the effects of lubricant and surface treatment on the life of hot forging dies. The thermal load and thermal softening, that occur when there is contact between the hotter billet and the cooler dies in hot forging, cause wear, thermal cracking and fatigue, and plastic deformation. Because the cooling effect and low friction are essential to the long life of dies, the proper selection of lubricant and surface treatment is very important in hot forging process. The two main factors that decide friction and heat transfer conditions are lubricant and surface treatment, which are directly related to friction factor and surface heat transfer coefficient. Experiments were performed for obtaining the friction factors and the surface heat transfer coefficients in different lubricants and surface treatments. For lubrication, oil-base and water-base graphite lubricants were used, and ion-nitride and carbon-nitride were used as surface treatment conditions. The methods for estimating die service life that are suggested in this study were applied to a finisher die during the hot forging of an automobile part. The new techniques developed in this study for estimating die service life can be used to develop more feasible ways to improve die service life in the hot forging process.

We've observed from the literature studied above that the there are different methods of analyzing the die life in Hot Forging and several methods of increasing the die life has also been discussed. From the current scenario prevailing in the Forging industry, it becomes imperative to find some optimal and economical means of performing die wear analysis taking view of the technology and skilled professionals available in this field. The current study is based on performing the analysis using a

Forging simulation software MSC.Superforge. The results obtained from the simulation are compared with those obtained from real life experiments. The wear coefficient is then evaluated and its variation with the die temperature is established.

CHAPTER 3:
MEASUREMENTS AND MODELLING OF THE DIE

This chapter includes the worn die measurement on the CMM (Coordinate Measuring Machine) and the modeling of the workpiece and original die with the help of the CAD software CATIA V5R16. The results are then used for the analysis.

The worn die for this case study is procured from ESSEN FORGE Pvt. Ltd. which is located at Ludhiana, Punjab. The die is used for the forging of Hubs used in agricultural equipments. Before starting the forging process, billets are prepared in the length of 45 mm with diameter of 130 mm. Material of the workpiece is AISI_1018 mild steel. These prepared billets are fed into the heater to reach the temperature of 1100°C. Material of the die is H13 tool steel. (Material Properties of the workpiece and die are written in APPENDIX A).

Before starting the forging process, the dies are heated to 200°C in order to prevent die failure due to thermal stress and to prevent large temperature difference between die and billet. For the forging operation "1000 kg" Airlift Hammer is used. Wear analysis will be done for the die, which is important for final production quality. Figure 3.1 shows the forging die used in this case study.

(a) (b)

Figure 3.1: Forging Die used in the Case Study

(a) Die before Cleaning,

(b) Die after Cleaning.

3.1 MEASUREMENTS BY USING CMM (COORDINATE MEASURING MACHINE)

Measurements for the worn die have been done at Central Tool Room located at Ludhiana. The Coordinate Measuring Machine available is ZEISS PRISMO NAVIGATOR. This model is a full-featured, geometric measurement package. It translates the high-level commands required to measure parts into the detailed steps necessary to drive a Coordinate Measuring Machine (CMM). This machine can measure uncertainties upto 1 μm. It provides maximum precision and process stability with short measuring times for the ever narrower tolerances.

Figure 3.2: CMM used for Measurement of Worn Die

Different kinds of probes are available in this machine for the measurement of complex surfaces. A red colored Ruby stone is used for scanning the surface.

Figure 3.3: Probes of the CMM and the Die to be measured

The output from this machine is in the form of measured points which are then joined to get the required curves. The output file is in .VDA format which is converted into . IGS format and opened with CAD software CATIA V5R16.

3.2 MODELING OF PARTS USING CATIA

In this study CATIA V5R16 is used for the modeling of the die and the workpiece. Solid Models of the finished workpiece, billet and the dies are generated in this software. CATIA is a suite of programs that are used in the design, analysis, and manufacturing of a virtually unlimited range of products.

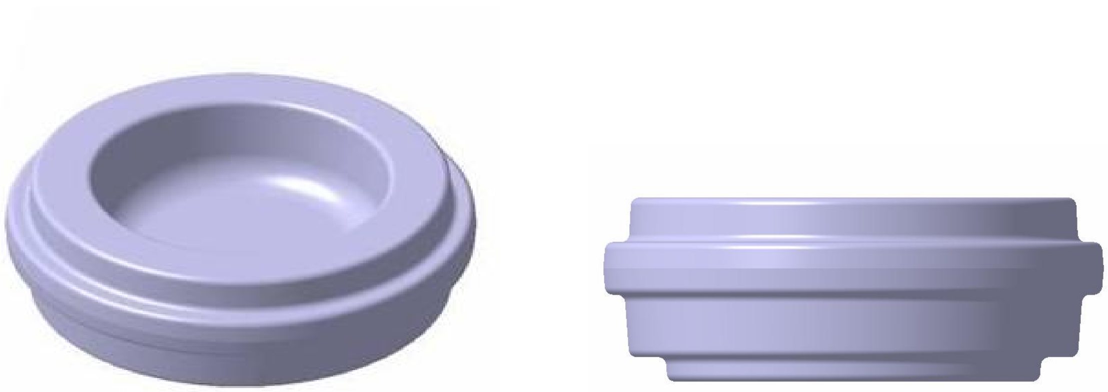


Figure 3.4: Model of the Workpiece

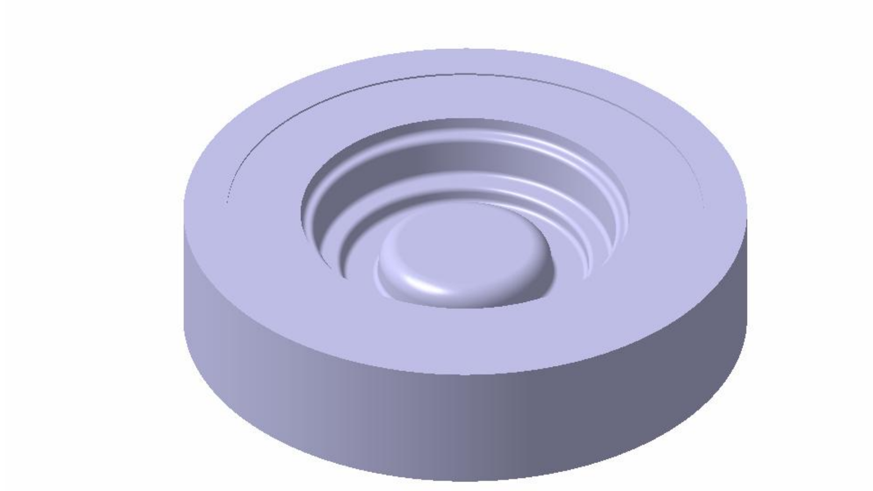


Figure 3.5: Model of Lower Die

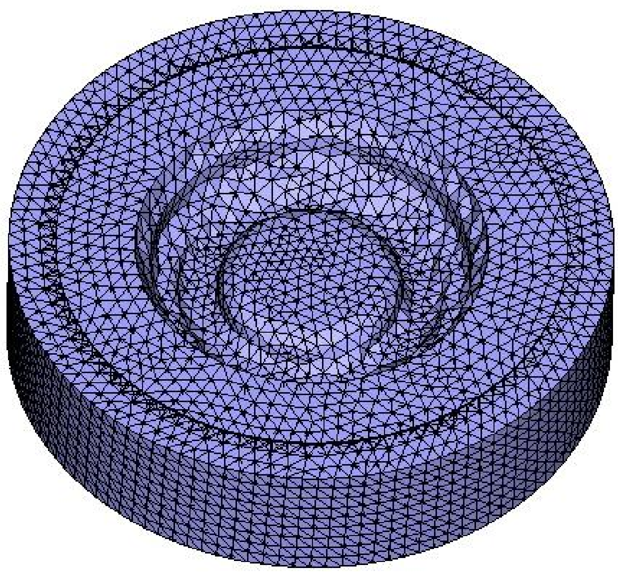


Figure 3.6: Mesh generated in Lower Die

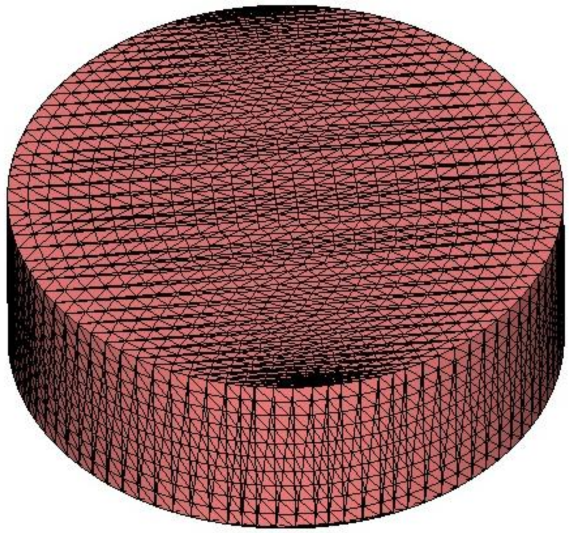


Figure 3.7: Mesh generated in the Billet

CHAPTER: 4

COMPUTER SIMULATION OF THE FORGING PROCESS

By knowing the value of wear coefficient for hot metal forming process, more accurate prediction can be done for die life during design of die. In this chapter, computer simulation of hot forging process has been done to obtain the wear depth of die. The aim of this thesis is to analyze the current forging process and comparing the result of wear analysis obtained from the computer simulation to the real-life experimental results from the industry, and to evaluate the wear coefficient for the current forging process. So, according to the analysis, a new wear coefficient for this case study which may be applied to the similar hot metal forming process will be evaluated.

The computer simulation of Hot Forging with Hammer in this case study took approximately 9 hours on a system with a Pentium processor of 1.73 GHz and 2 Gb RAM. The simulation was completed in six blows.

4.1 ANALYSIS OF FORGING OPERATION

In this study 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:

- Workpiece and die models,
- Material Properties,
- Forging Equipment (Ram Speed),
- Initial Temperature,
- Friction Model.

After identifying these, the simulation type and parameters must be assigned.

4.1.1 Importing Die and Workpiece Models

The solid models of upper die, lower die and the workpiece geometry are imported to the software program. An important consideration should be made while importing, that MSC.Superforge requires a closed volume surface model for both workpiece and dies.

Models should be imported in proper formats i.e. .BDF OR .STL format. In these formats, the surface models consist of triangular shaped facets only.

In MSC.SuperForge, forging operation direction is aligned on the Z axis, therefore after importing the models for the dies and the workpiece, 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 workpiece in place and position the dies against the workpiece in initial contact by using “Positioning” option. The alignment of the dies and the workpiece and initial position of them is shown in figure 4.1:

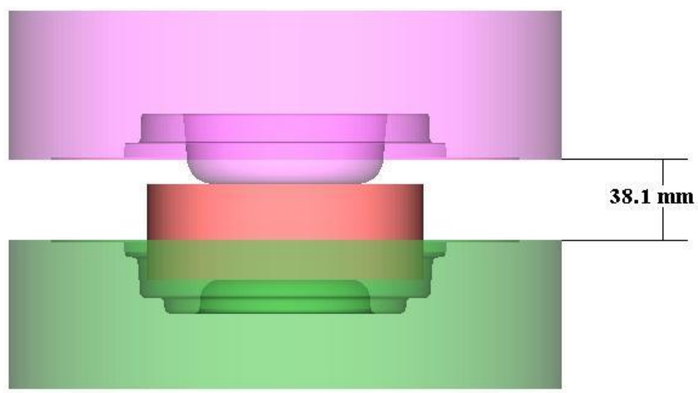


Figure 4.1: Position of dies and workpiece in initial contact

4.1.2 Material Properties

There are the forging specific material models available for either cold forging or hot forging operations in the material library of the software. MSC.SuperForge provides elastic-plastic models for workpiece material, for dies rigid-plastic models are used. In this study, the workpiece material is AISI_1018 mild steel. Figure 4.2 shows the workpiece stress-strain curve at different temperatures [28].

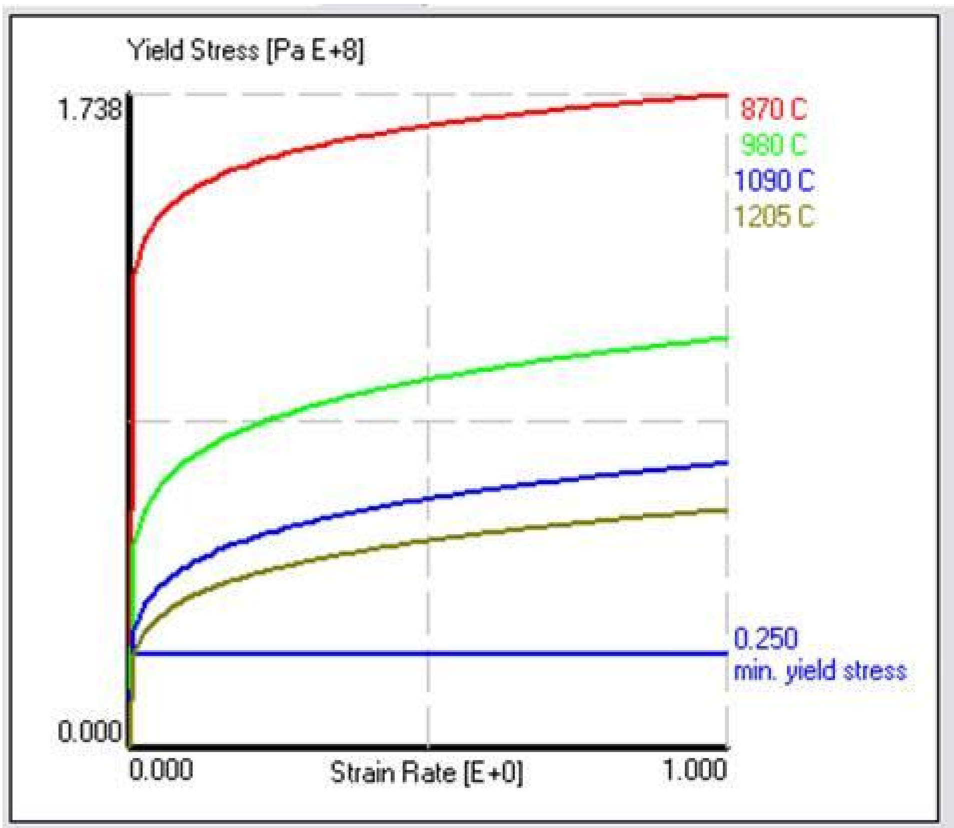


Figure 4.2: Workpiece Material stress strain curves at different temperatures

The die material is Tool steel AISI_H13. This alloy is one of the Hot Work, Chromium type tool steels. It also contains molybdenum and vanadium as strengthening agents. The chromium content assists this alloy to resist softening if used at higher temperatures. H13 finds applications for hot die work, die casting and forging dies.

Material Properties of the workpiece and die steel are given in APPENDIX A [26].

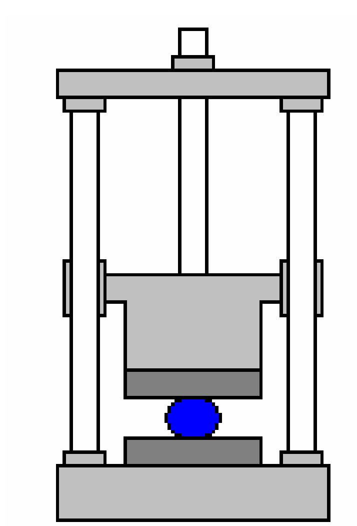
4.1.3 Forging Equipment

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 Airlift Hammer, which is the forging machine used in ESSEN Forge Pvt. Ltd., is used in this study, the required data is entered and these definition are assigned to the upper die. The entered data are given in Table 4.1:

Table 41: Properties of Forging Equipment

Parameter	Value
Type of Forging Machine	Hammer
Maximum Energy	120 kilo Joule
Efficiency	0.5
Mass	1100 kilo gram
Impact Speed	4.6 m/s

The parameters specified for the Hammer in simulation have been taken from the industry and ASM METALS HANDBOOK, "*Forming and Forging*" [25]. Table 4.2 shows capacities and parameters of various types of Forging Hammers [28].



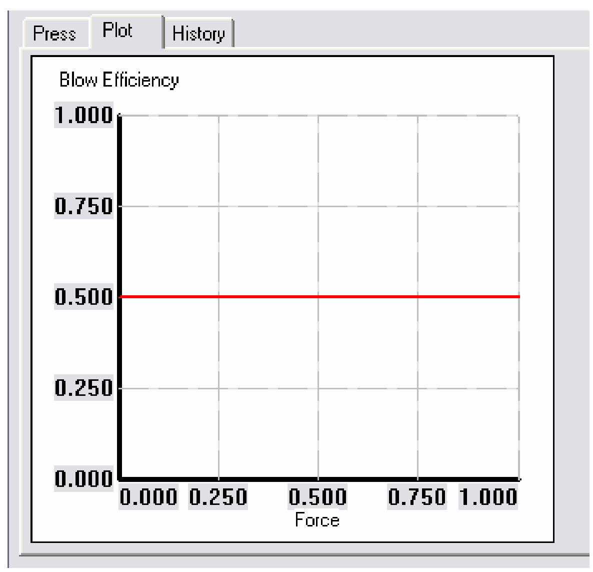


Figure 4.3: The Forging Equipment (HAMMER) used in the study and its Efficiency Plot

Table 4.2: Capacities and Parameters of various types of Hammers [25]

TYPE OF HAMMER	RAM WEIGHT		MAXIMUM BLOW ENERGY		IMPACT SPEED		NO. OF BLOWS PER MINUTE
	kg	lb	kJ	ft-lb	m/s	ft/s	
Board Drop	45-3400	100-7500	47.5	35000	3-4.5	10-15	45-60
Airlift or Steam lift	225-7250	500-16,000	122	90000	3.7-4.9	12-16	60
Electrohydrau--lic Drop	450-9980	1000-22,000	108.5	80000	3-4.5	10-15	50-75
Power Drop	680-31,750	1500-70,000	1153	850000	4.5-9	15-30	60-100

4.1.4 Initial Temperatures

The initial temperatures of workpiece 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 workpiece: 1100°C

Initial temperature of die: 200°C

Other parameters that used for the simulation are [28]:

Heat transfer coefficient to ambient: 50 Watt/m^2.K

Heat transfer coefficient to workpiece: 6000 Watt/m^2.K

Emissivity for heat radiation to ambient: 0.25

4.1.5 Friction Model

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

$$\tau = \mu \cdot \sigma_n$$

where, μ is the coefficient of friction and σ_n denotes the normal stress at the workpiece-die interface.

The alternative model to Coulomb's law of friction is Tresca's friction model, which is the law of plastic shear friction. According to this model, if the frictional shear stress, τ exceeds a constant fraction *m* of the flow stress in shear, τ_{yield}, the workpiece starts to slip:

$$\tau = m \cdot \tau_{yield}$$

A value of zero represents perfect sliding, which means there is no shear or friction at the workpiece-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 study, plastic shear friction model is used as friction model for the simulation. The coefficient of friction is taken as 0.34 [13].

4.1.6 Assigning Simulation type and Parameters

In this step, stroke of the operation, size of the finite volume workpiece and die element sizes, output step size (as percentage of the process time or in defined stroke step sizes), problem type (closed-die, open die, bending, forward extrusion, backward extrusion, rolling and also hot or cold forging) are defined. The suggested problem type for hot forging with flash by MSC.SuperForge is closed die forging. In this study this type of problem is selected. Also, a solver optimizer is implemented in this simulation control unit; the user can coarsen the workpiece to decrease the number of elements. Parameters that are used in this stage are shown in Table 4.3:

Table 4.3: Operation parameters assigned to complete the simulation.

Problem Type	Hot closed die forging with flash
Initial Contact Distance	38.1 mm
Flash Thickness	3 mm
Upper Die Displacement	38.1 mm

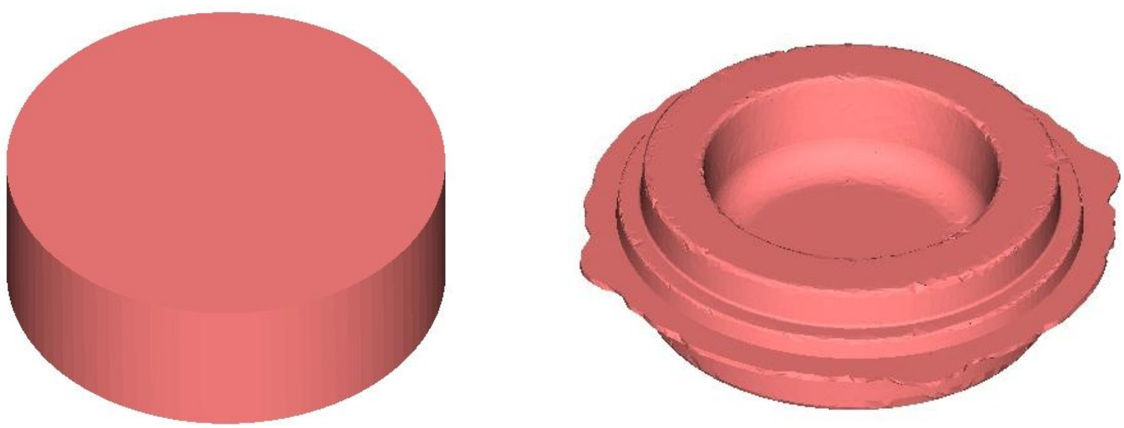


Figure 4.4: Billet (left) and Result of Simulation (right)

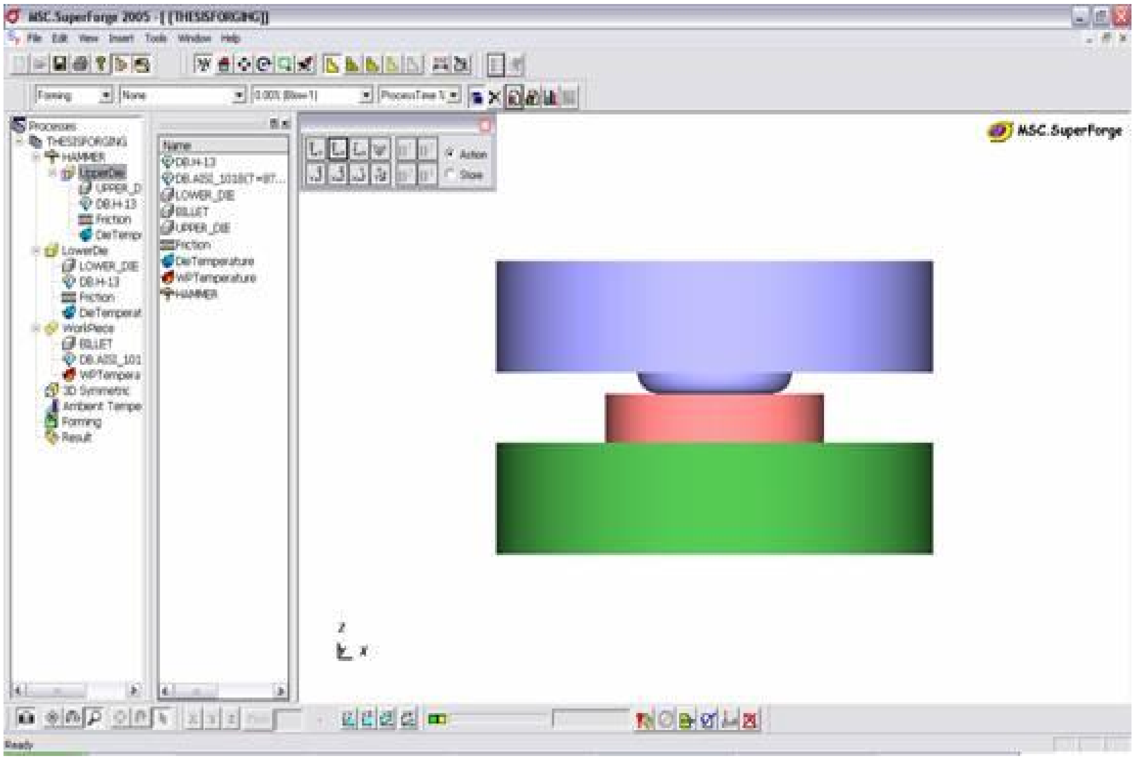


Figure 4.5: Sample View of a Simulation Performed in MSC.SuperForge

4.2 WEAR MODEL USED IN MSC.SUPERFORGE

The wear model which is used in MSC.SuperForge is based on Archard's wear model [28], offers depth of wear to be a function of sliding length, hardness, normal stress and wear coefficient. The relation is given by:

$$\Delta d = K \times \frac{P \times \Delta L}{H} \tag{4.1}$$

where:

Δd: depth of wear (mm) at each time increment Δt (s),

K: non-dimensional wear coefficient,

P: contact pressure (Pa),

ΔL: sliding distance (mm) at time increment Δt and

H: hardness of die (Pa).

In equation (4.1), the sliding distance can be replaced in terms of sliding velocity and the value of $\frac{K}{H}$ is replaced by dimensional wear coefficient k Pa^{-1}.

$$\Delta L = U \times \Delta t \quad \textbf{(4.2)}$$

$$k = \frac{K}{H} \quad \textbf{(4.3)}$$

where:

U: sliding velocity (mm/s) at time increment Δt, and

k: dimensional wear coefficient (Pa^{-1}).

Therefore Equation (4.1) can be re-written as:

$$\Delta d = k \times \left(P \cdot U \cdot \Delta t \right) \quad \textbf{(4.4)}$$

To obtain final depth of wear for one cycle, equation (4.4) can be written in summation form of each increment wear depth,

$$d_{fin} = \sum_{1}^{n} k \cdot P_i \cdot U_i \cdot \Delta t_i \quad \textbf{(4.5)}$$

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 $k = 1 \times 10^{-12}\,\text{Pa}^{-1}$. Other parameters like contact pressure, sliding velocity, forging operation time and total number of increments will be calculated by calculations.

4.3 WEAR ANALYSIS OF THE DIE

Wear analysis has been done by comparing numerical result of die wear from the forging simulation with the measurement of the worn die by using Coordinate Measuring Machine (CMM). There will be a study in the affected region by choosing a certain cross section (CAD Profile) and comparing numerical results (Wear Analysis Profile) with the measurement of worn die by CMM. Figure 4.6 shows the region where wear is predominant.

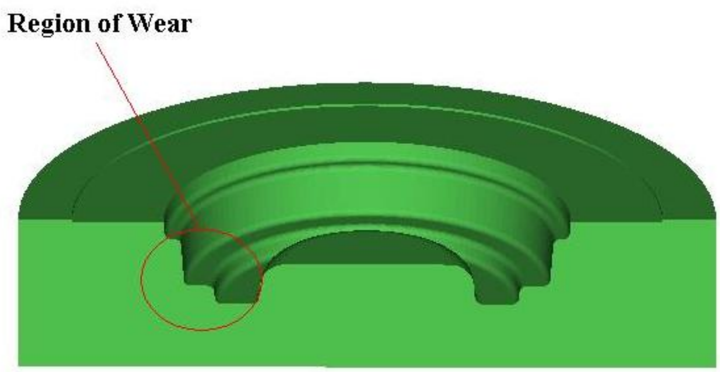


Figure 4.6: Section of the Lower Die

The result of wear analysis of the above region will be discussed. The original die profile from CAD data and the worn die profile measured by CMM are shown in Figure 4.7.

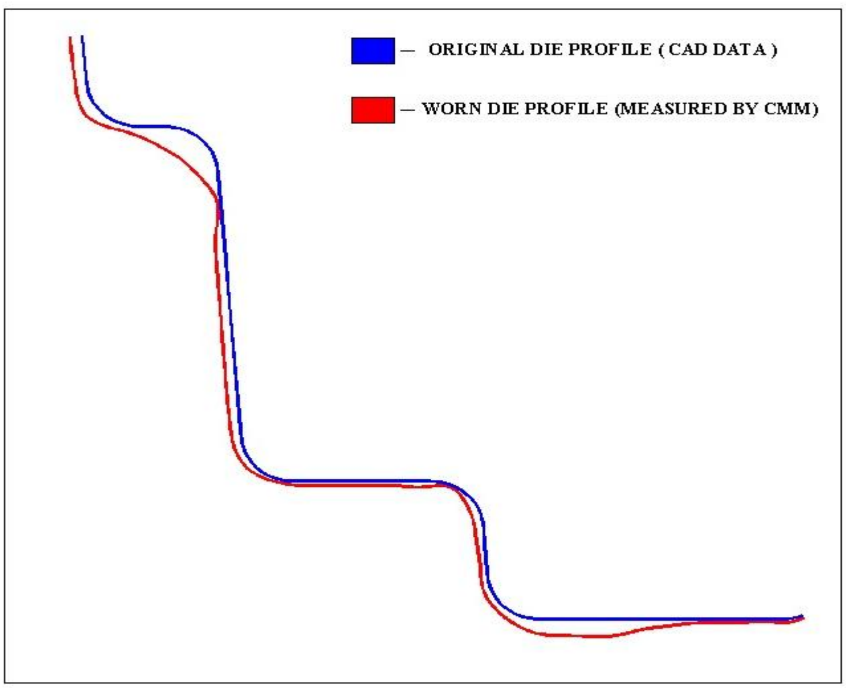


Figure 4.7: Die Profiles of Worn Die and Original Die

The results of wear depth that were obtained from simulation show that this value is large along the curves where the material takes the shape. Here, the maximum value reaches to 3.97×10^{-3} mm and the minimum depth of wear is about 1.91×10^{-4} mm.

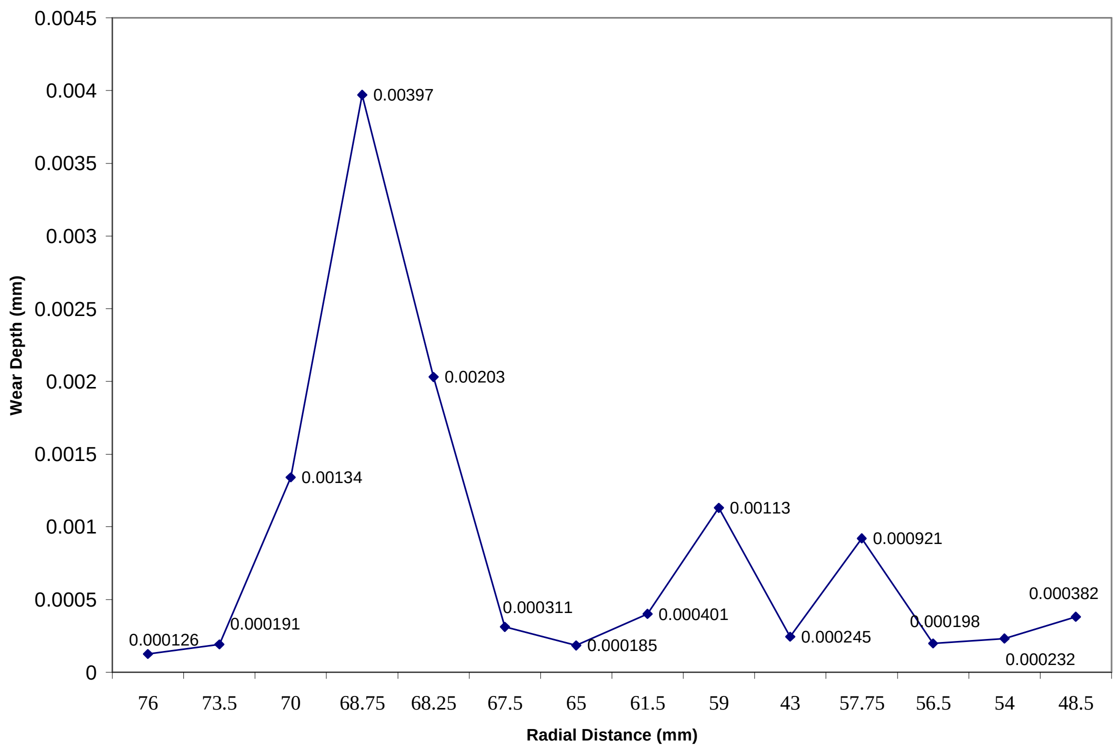


Figure 4.8: Variation of Wear Depth along the Radial Dimension of the die

4.4 EVALUATION OF WEAR COEFFICIENT BY USING WORN DIE MEASUREMENT

From comparison of wear analysis profile and measured worn die profile in Figure 4.10, it can be understood that there are some disagreements between these two. These differences explain the need of modification in wear coefficient which is taken as 1×10^{-12} Pa^{-1} in die wear analysis of MSC.SuperForge. The aim of using finite volume method in wear analysis is to obtain depth of wear to use in proper wear model. The fields of contact stress and sliding velocity can be obtained from numerical results, the wear model used for numerical analysis is in form of

$$d_{fin} = \sum_1^n k \cdot P_i \cdot U_i \cdot \Delta t_i$$

where, d_{fin} is known from numerical results and k has constant value 10^{-12} , by knowing these values, $\sum_1^n (P_i \cdot U_i \cdot \Delta t_i)$ will be calculated.

$$\sum_1^n (P_i \cdot U_i \cdot \Delta t_i) = \frac{d_{fin}}{10^{-12}}$$

Now, by knowing $\sum_1^n (P_i \cdot U_i \cdot \Delta t_i)$ and d_{true} (the true value of wear depth, measured from worn die), a new value of k can be calculated for each point.

$$k = \frac{d_{true}}{\sum_1^n (P_i \cdot U_i \cdot \Delta t_i)}$$

Figure 4.11 shows the evaluated wear coefficient at different points on the die. It changes from 1.13×10^{-12} to 9.44×10^{-13}. The average value of Wear Coefficient calculated in this study is 7.92×10^{-13}.

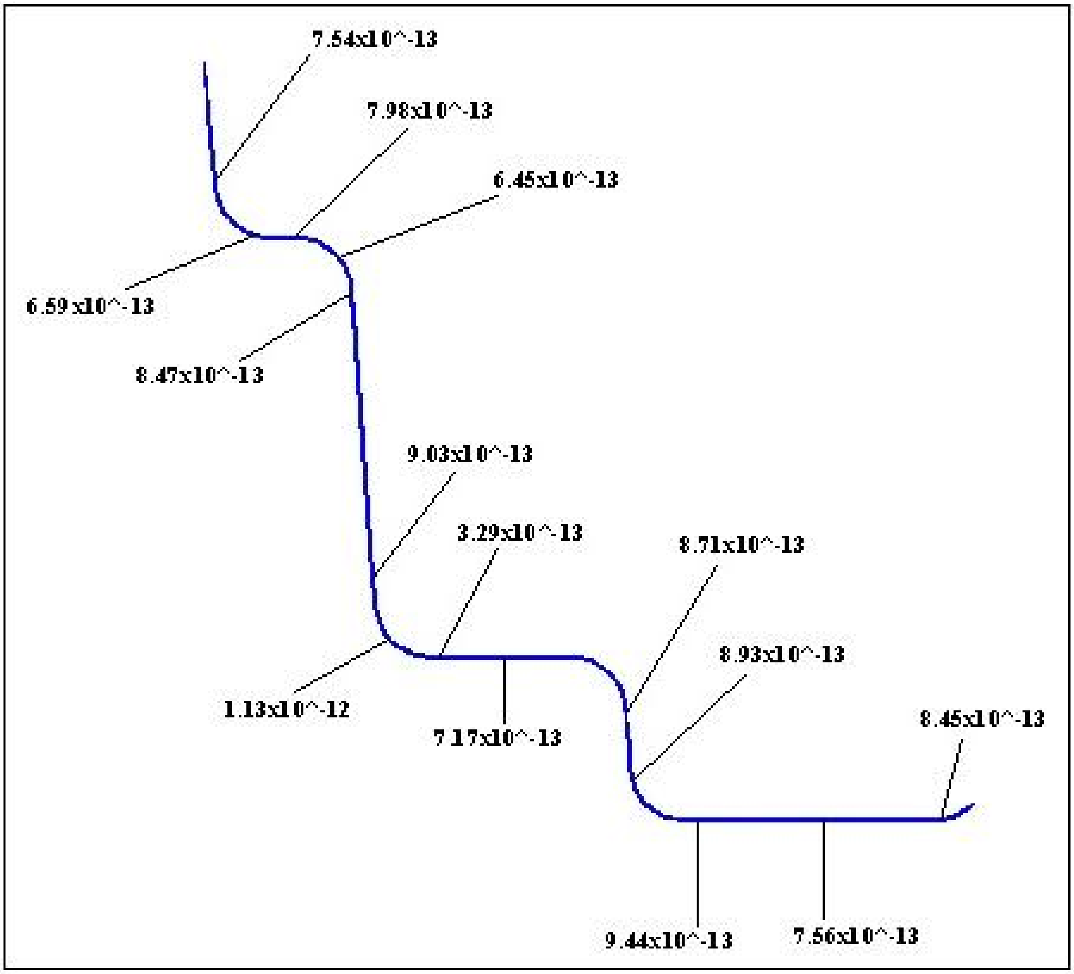


Figure 4.9: Dimensional Wear Coefficients evaluated at different points on the die.

Figure 4.10 shows the variation of dimensional wear coefficient along the radial dimension of the die.

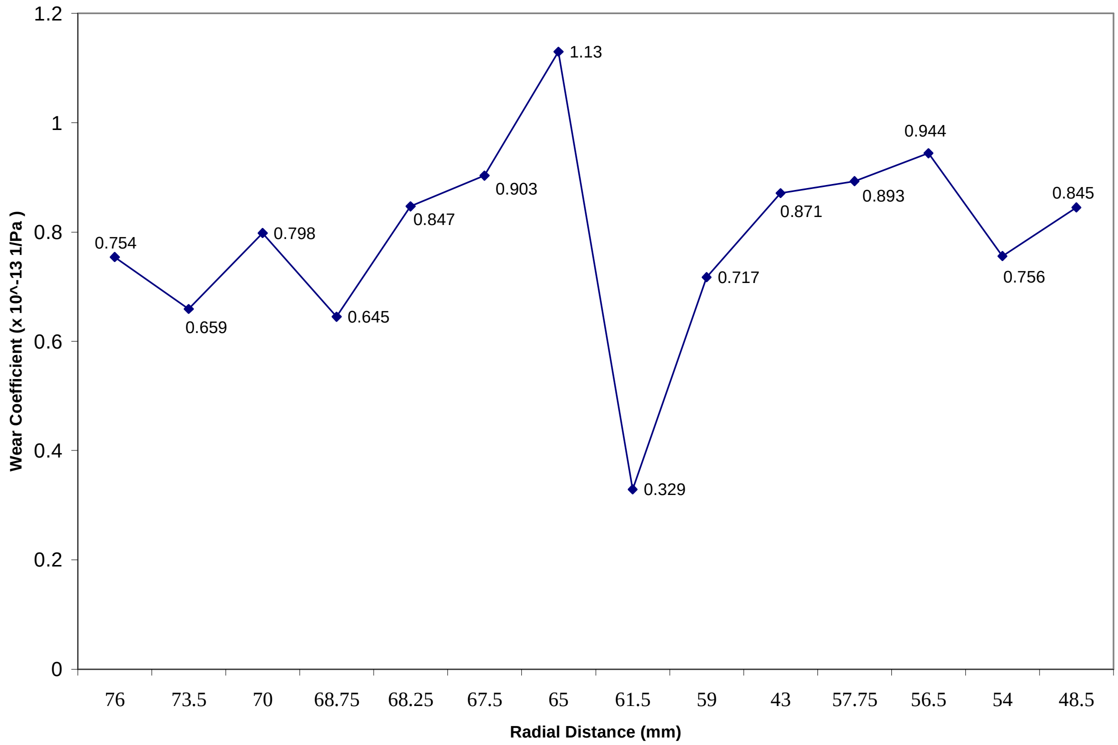


Figure 4.10: Variation of Dimensional Wear Coefficient along the Radial Dimension of the Die

4. 5 PARAMETERS AFFECTING WEAR ANALYSIS

In addition to effect of wear coefficient in wear analysis other parameters like contact time between die and workpiece, and temperature on the surface of the die have great effect on die analysis.

Since wear is result of contact between surfaces, then for wear analysis, it is important to study the time that different points of die are in contact with workpiece. For example some points are in contact from the beginning to the end of operation (100% of operation time), and there are some points that they come to contact during few percentage of operation time. Figure 4.10 shows the process of contact between workpiece and die.

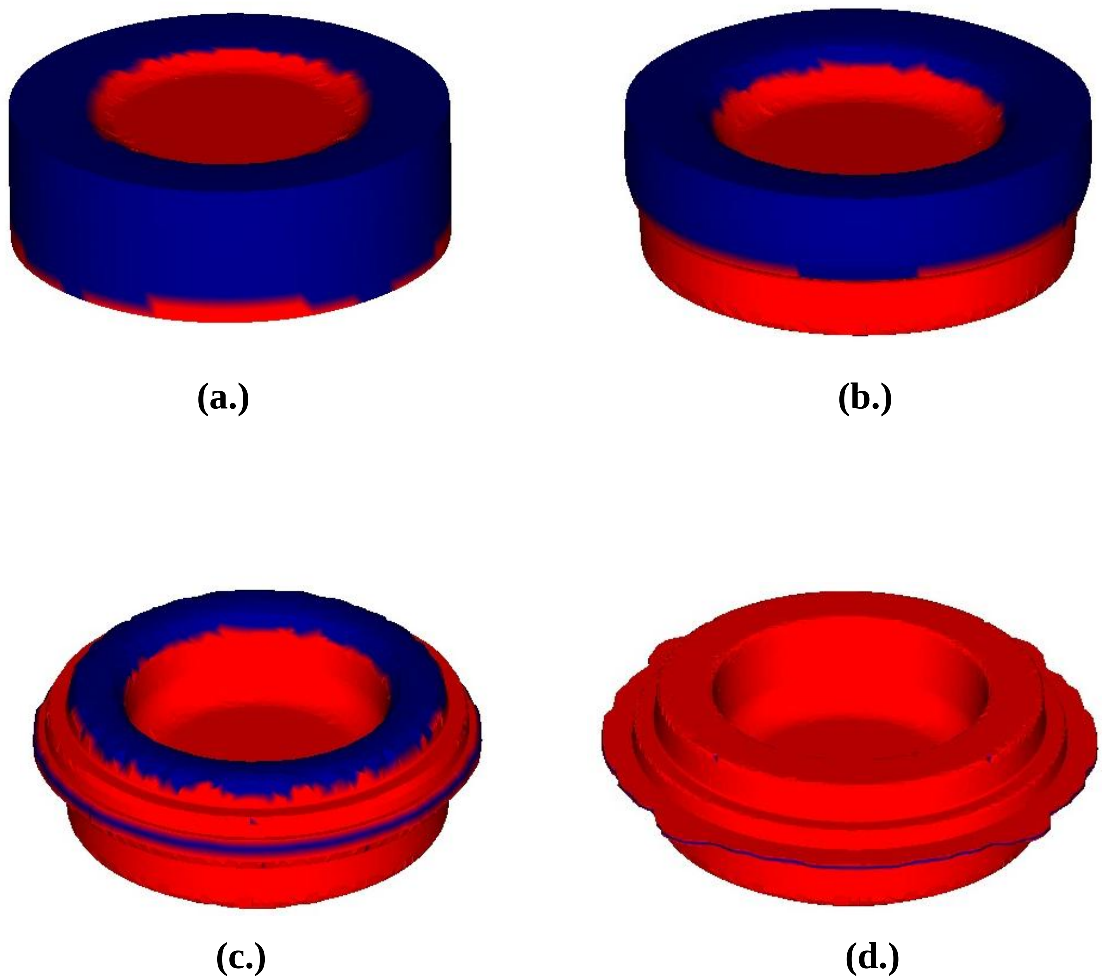


Figure 4.11: Contact between die and workpiece in different stages. Red color shows contact between die and workpiece a) After 20% progress in operation, b) 50%, c) 80%, and d) 100%.

The other important parameter that affects wear is the surface temperature of the die. In hot forging process, a high temperature billet is in contact with the die. Due to temperature differences, there will be rapid change in the temperature of die. This change of temperature is cause of two main factors: friction on the contact interface and heat transfer from hot workpiece to the die. Friction can be reduced by using proper lubrication after each cycle. By making the operation time as small as possible, the heat transfer can be reduced so much. By increasing the temperature of die, the wear coefficient increases and the hardness of die decreases by increasing of temperature. Then amount of wear may increase sharply by raising temperature on the surface of die. The final surface temperature of the die can be obtained from the simulation of hot forging process. In this case study, there is not any change in the temperature of the die. Since the initial temperature of die is 200°C, there is no increase in the die temperature. That could be due to small operation time. Therefore, the hardness of die and wear coefficient do not change during the process. Hence, assuming constant dimensional wear coefficient is a good approximation for this analysis.

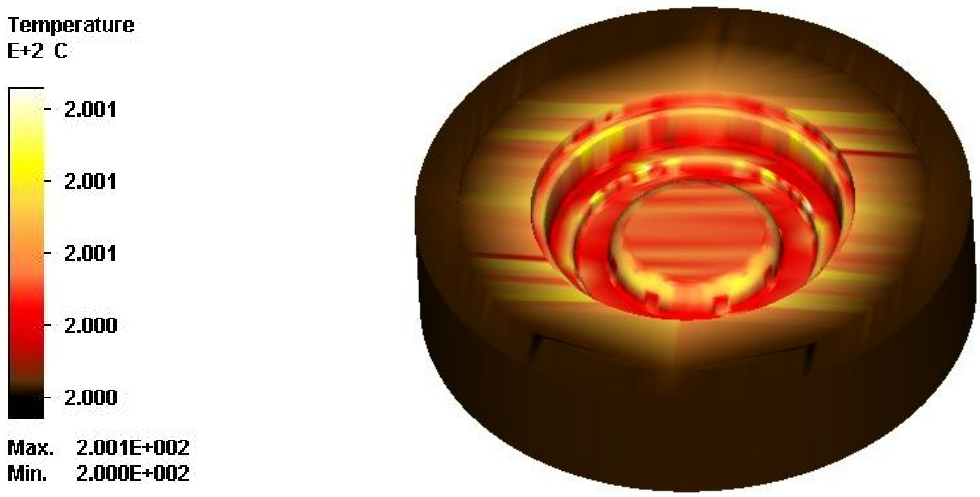


Figure 4.12 Temperature distribution of the die at the end of process time.

CHAPTER 5: Results and Discussion

5.1 DISCUSSION OF RESULTS

In this thesis the wear analysis has been done on the hot forging die. This die was provided by ESSEN Forge Company located at Ludhiana, Punjab. The hot forging die is used for manufacturing Hubs used in agricultural equipments.

The Die wear option of MSC.Superforge is used for calculating the depth of wear. In this software, Finite Volume method is used for the analysis of the forging operation. The forging equipment used is a Hammer of capacity 1000 Kg. The worn die measurement was taken on a Coordinate Measuring Machine. The depth of wear obtained from this measurement is compared with that obtained from the simulation results from the software. By using the Archard's Model of Abrasive Wear, the wear coefficient is calculated. Then, the simulation is done by heating the die at different temperatures, and the relation between the wear coefficient and temperature of the die is established.

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. Therefore, some evaluation is 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 calculations, the wear coefficients have been evaluated for different points. The wear coefficient obtained at the end is 7.92×10^{-13}.

The difference between the results of worn die measurement and the result obtained from simulation are because of the reason that Airlift Hammers are operated manually and energy supplied during each blow is not same necessarily.

Figure 5.1 shows the different points on the die where the depth of wear is calculated. Wear Depth at these points are shown in Table 5.1 at different temperatures. It has been observed that at 200°C, the depth of wear is minimum.

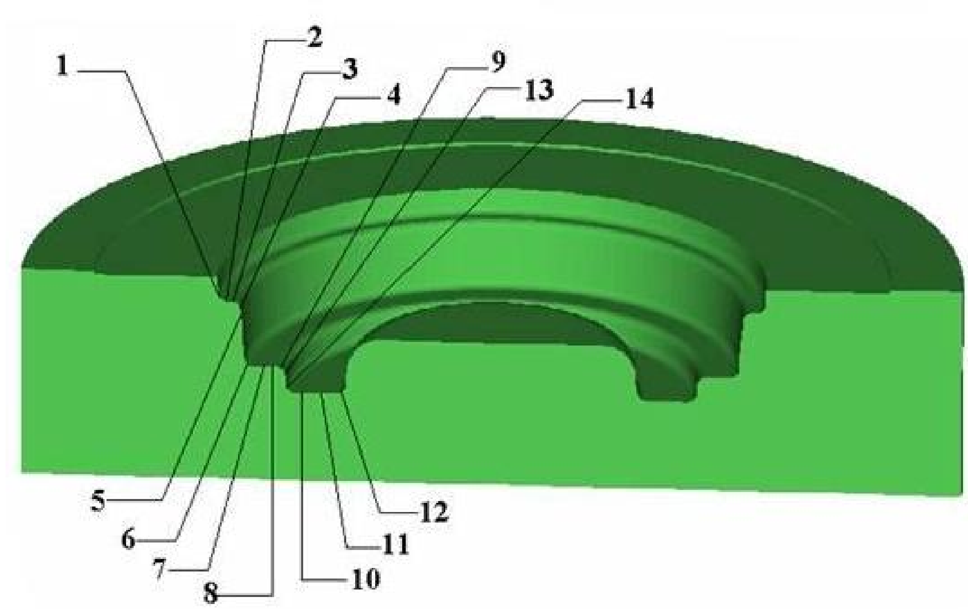


Figure 5.1: Points on the die where depth of wear is taken into account.

Table 5.1: DEPTH OF WEAR AT DIFFERENT TEMPERATURES

Point No.	DEPTH OF WEAR AT DIFFERENT TEMPERATURES				
	0°C	**100°C**	**200°C**	**300°C**	**400°C**
1	2.09×10^{-4}	1.83×10^{-4}	1.26×10^{-4}	2.61×10^{-4}	2.55×10^{-4}
2	1.98×10^{-3}	3.12×10^{-4}	1.91×10^{-4}	2.51×10^{-4}	2.86×10^{-4}
3	3.65×10^{-3}	1.57×10^{-3}	1.34×10^{-3}	2.62×10^{-3}	3.23×10^{-3}
4	4.98×10^{-3}	4.61×10^{-3}	3.97×10^{-3}	4.46×10^{-3}	5.91×10^{-3}
5	4.13×10^{-3}	2.67×10^{-3}	2.03×10^{-3}	3.39×10^{-3}	4.21×10^{-3}
6	5.84×10^{-4}	5.31×10^{-4}	3.11×10^{-4}	6.81×10^{-4}	8.47×10^{-4}
7	3.41×10^{-4}	4.04×10^{-4}	1.85×10^{-4}	6.75×10^{-4}	7.11×10^{-4}
8	2.41×10^{-3}	1.05×10^{-3}	4.01×10^{-4}	1.43×10^{-3}	2.32×10^{-3}
9	2.67×10^{-3}	2.59×10^{-3}	1.13×10^{-3}	2.15×10^{-3}	2.24×10^{-3}
10	7.01×10^{-4}	6.90×10^{-4}	2.32×10^{-4}	5.35×10^{-4}	5.46×10^{-4}
11	5.89×10^{-4}	5.34×10^{-4}	3.82×10^{-4}	6.04×10^{-4}	6.11×10^{-4}
12	5.85×10^{-4}	5.94×10^{-4}	2.45×10^{-4}	5.19×10^{-4}	5.78×10^{-4}
13	2.18×10^{-3}	1.29×10^{-3}	9.21×10^{-4}	1.37×10^{-3}	1.82×10^{-3}
14	4.03×10^{-4}	3.03×10^{-3}	1.98×10^{-4}	4.33×10^{-4}	4.85×10^{-4}

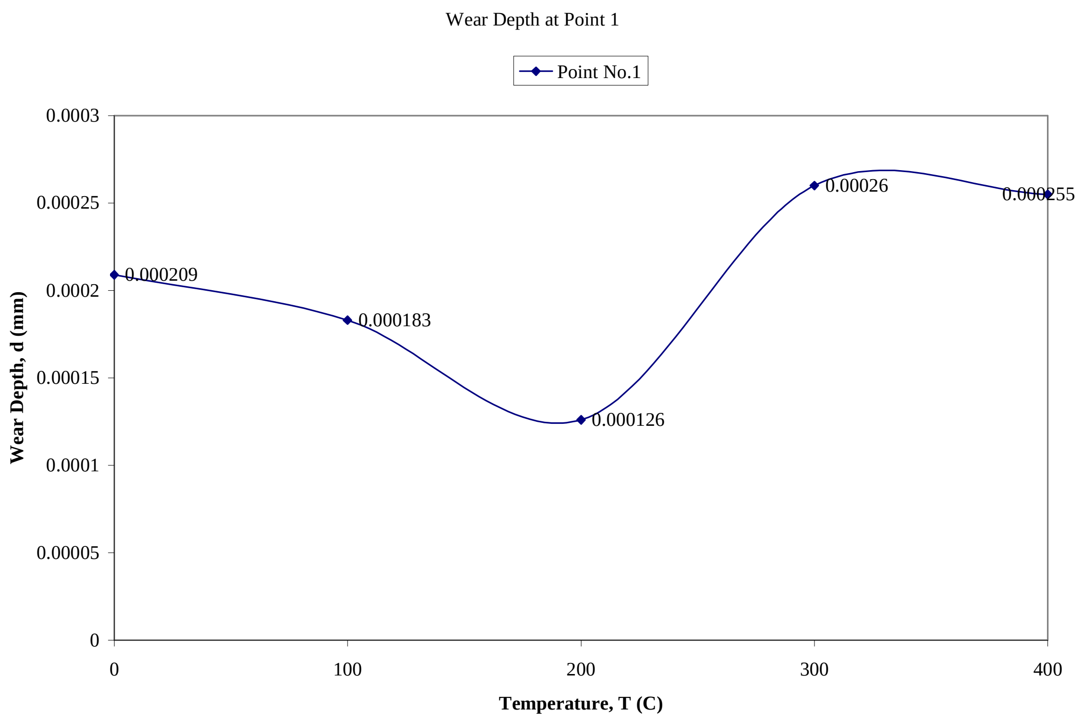


Figure 5.2: Variation of wear depth (d) w.r.t temperature (T) at Point 1

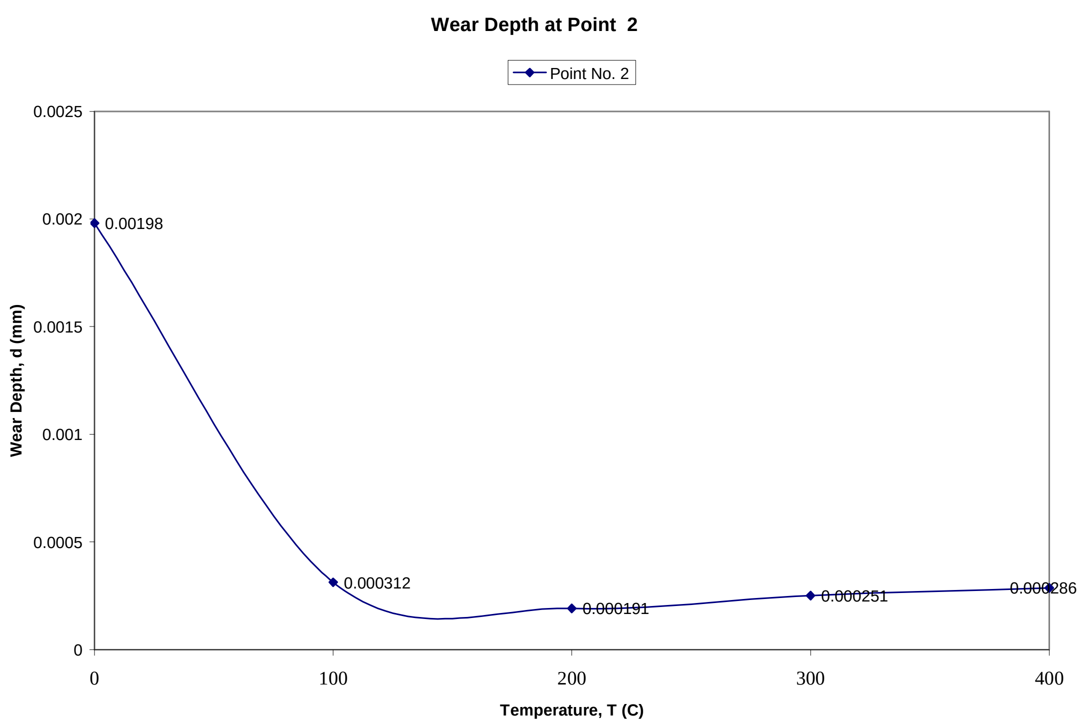


Figure 5.3: Variation of wear depth (d) w.r.t. temperature (T) at Point 2

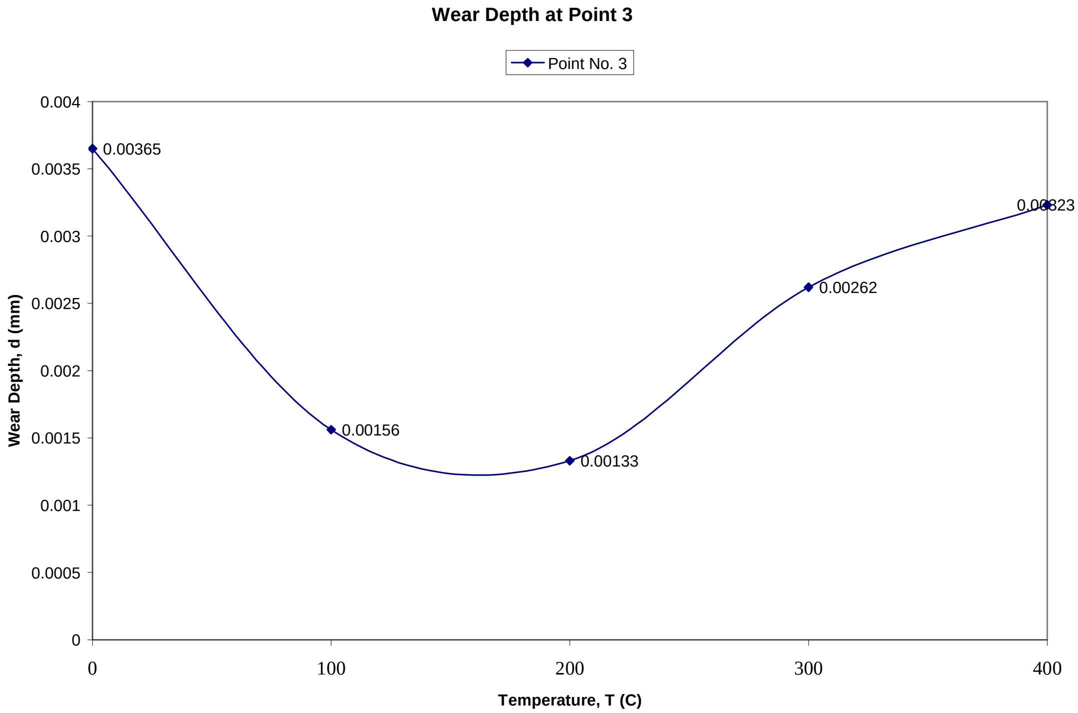


Figure 5.4: Variation of wear depth (d) w.r.t temperature (T) at Point 3

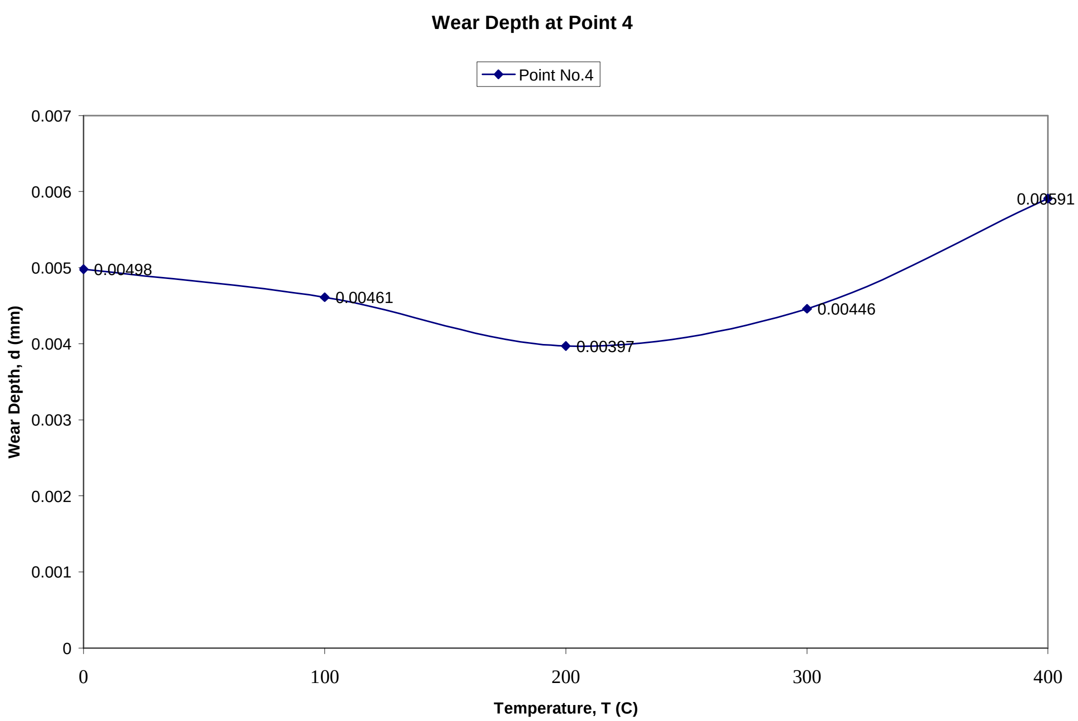


Figure 5.5: Variation of wear depth (d) w.r.t temperature (T) at Point 4

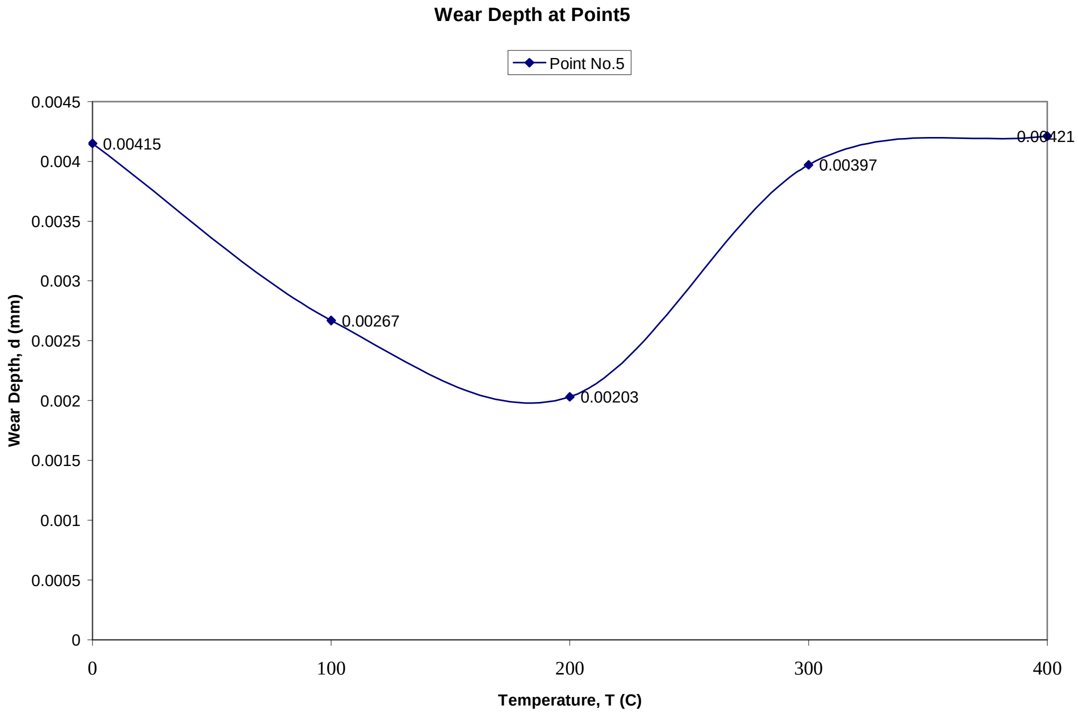


Figure 5.6: Variation of wear depth (d) w.r.t temperature (T) at Point 5

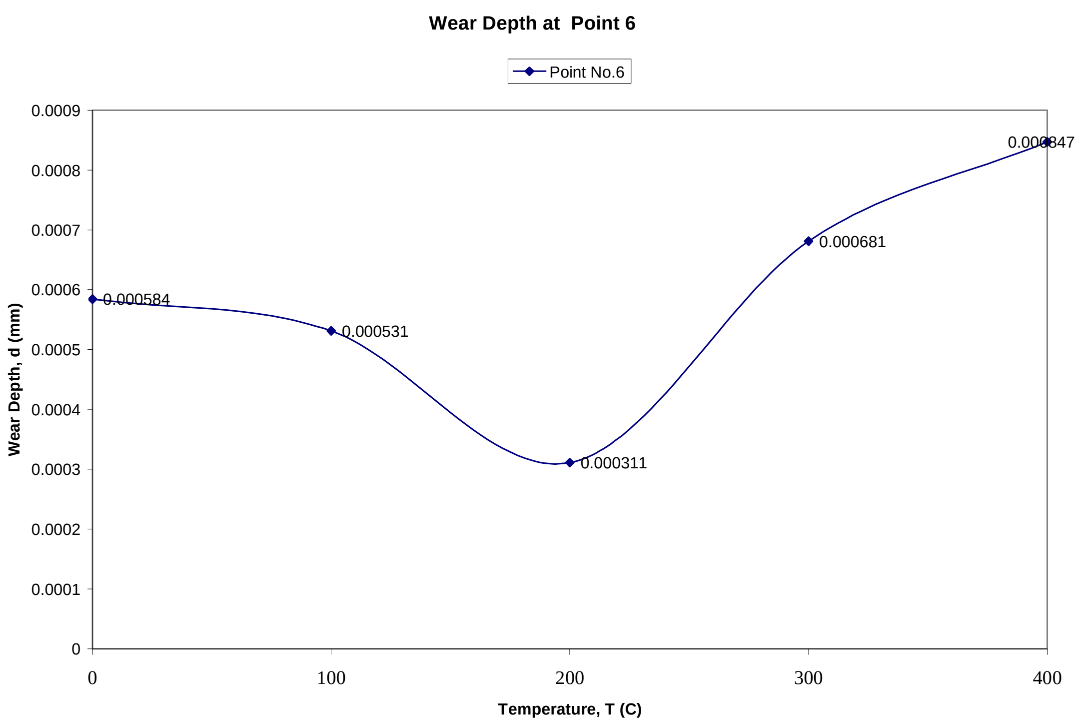


Figure 5.7: Variation of wear depth (d) w.r.t temperature (T) at Point 6

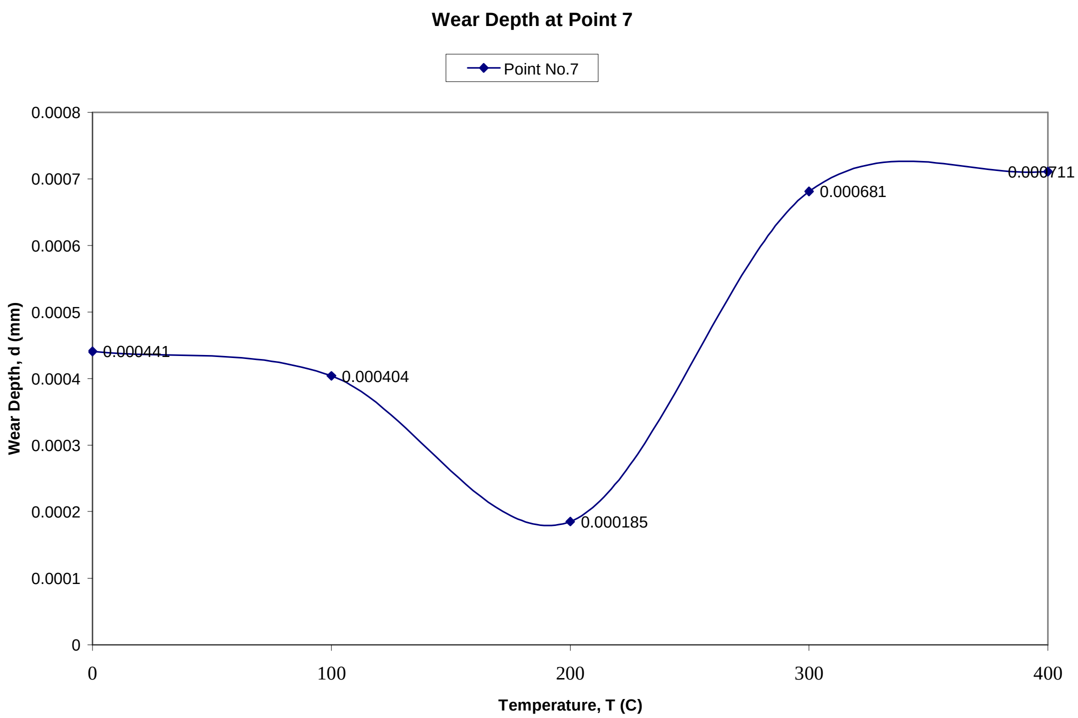


Figure 5.8: Variation of wear depth (d) w.r.t temperature (T) at Point 7

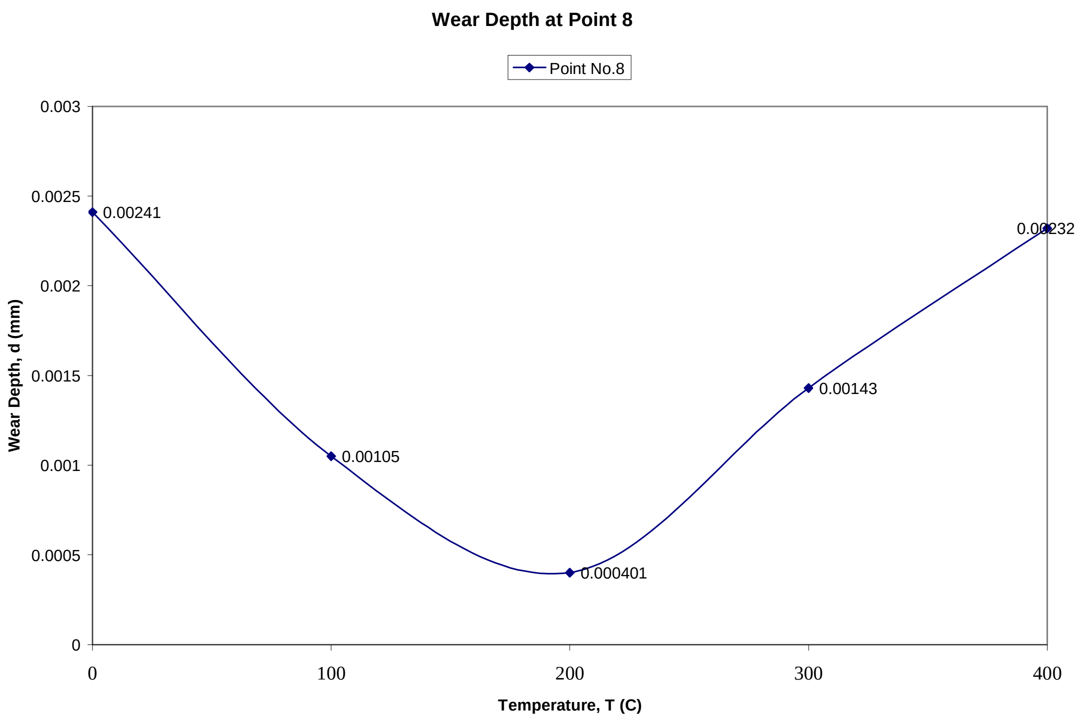


Figure 5.9: Variation of wear depth (d) w.r.t temperature (T) at Point 8

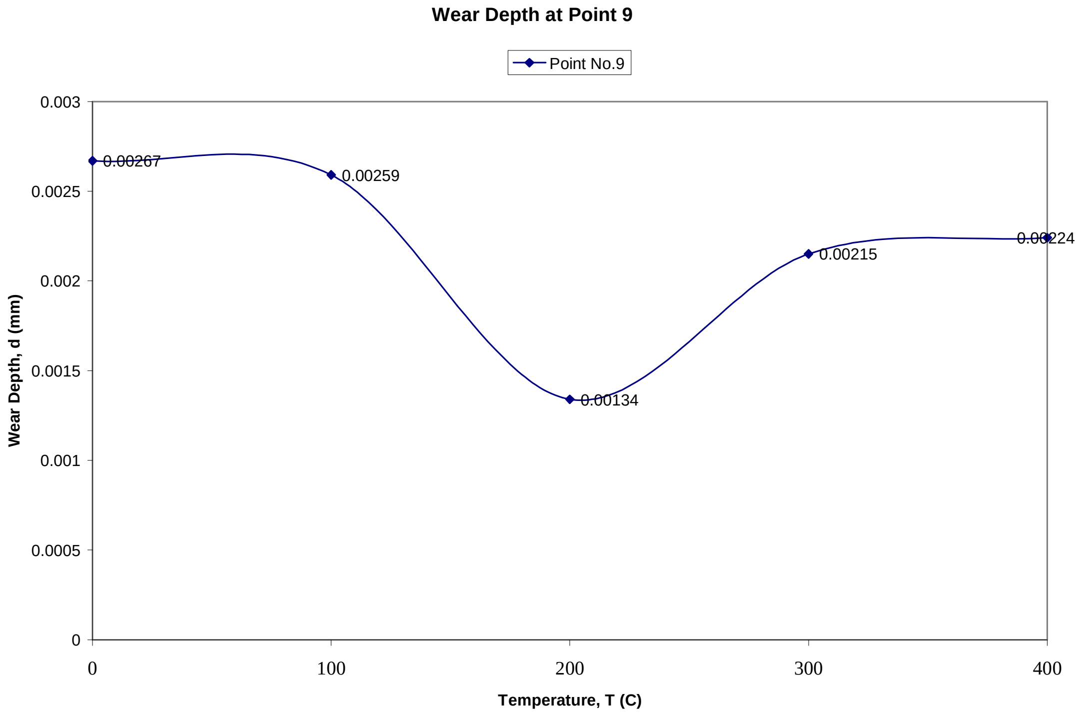


Figure 5.10: Variation of wear depth (d) w.r.t temperature (T) at Point 9

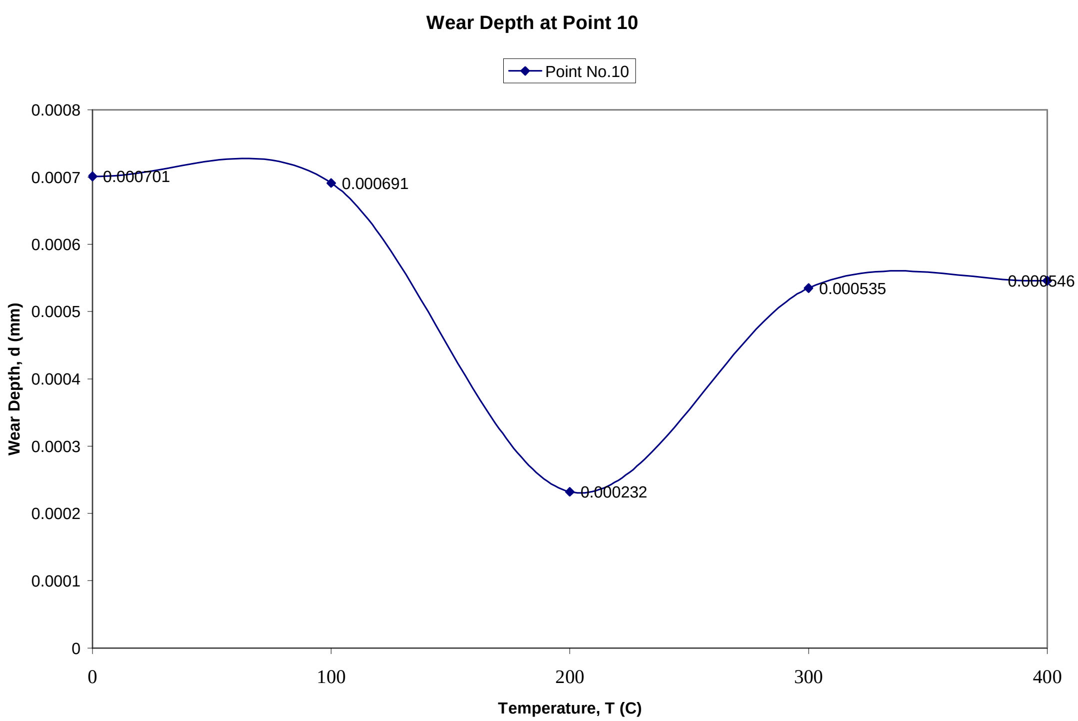


Figure 5.11: Variation of wear depth (d) w.r.t temperature (T) at Point 10

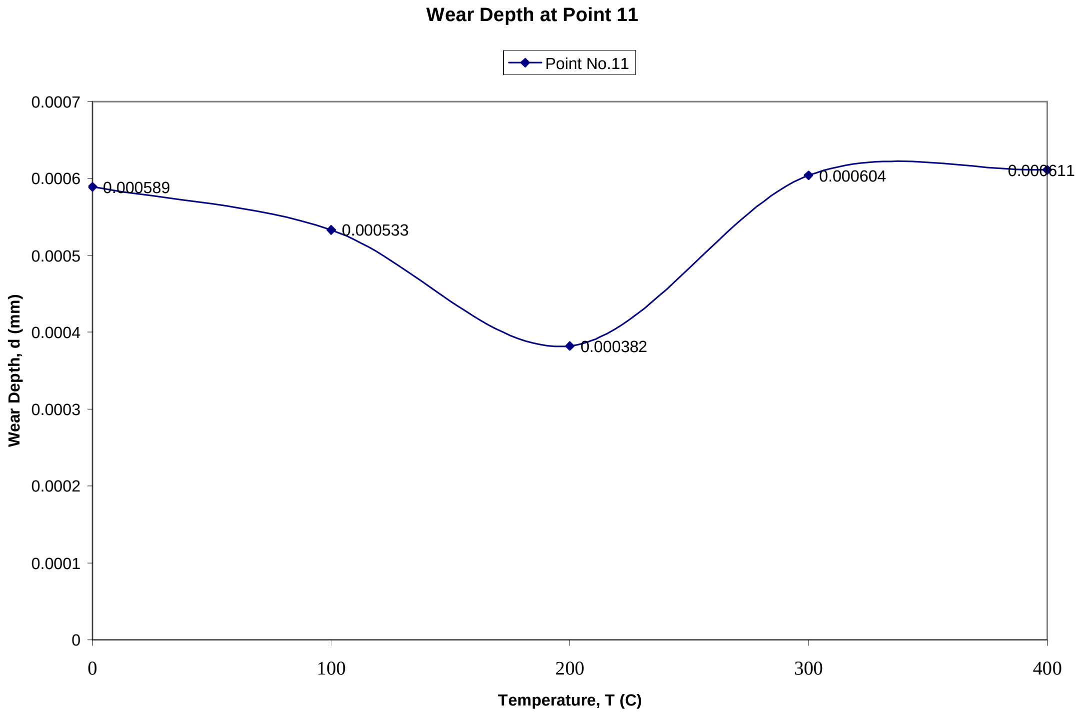


Figure 5.12: Variation of wear depth (d) w.r.t temperature (T) at Point 11

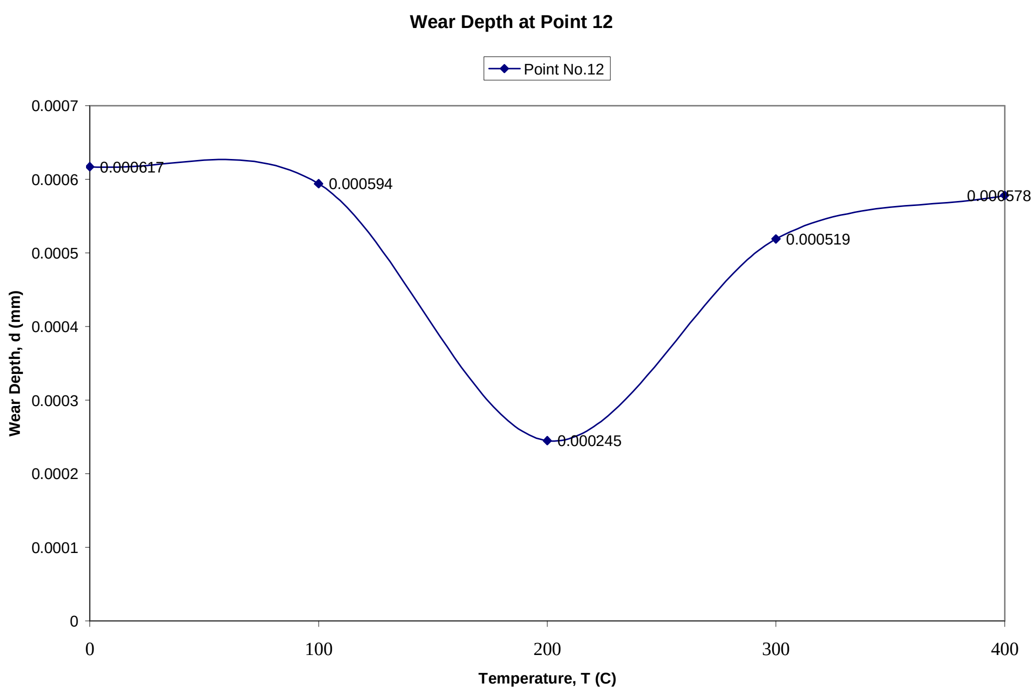


Figure 5.13: Variation of wear depth (d) w.r.t temperature (T) at Point 12

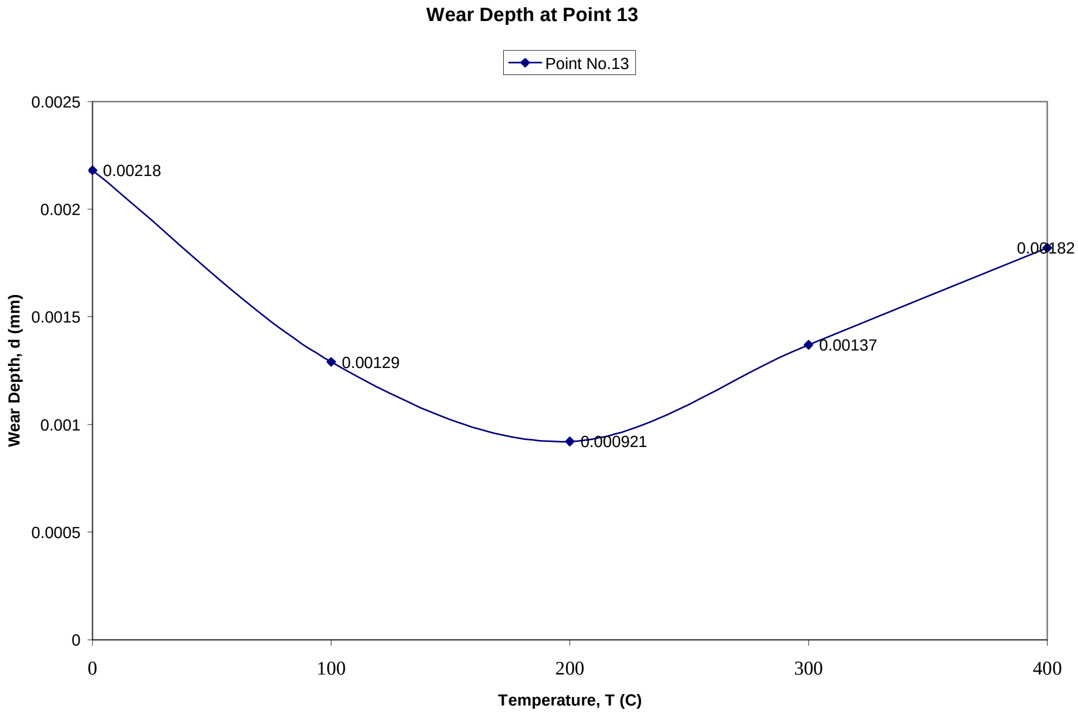


Figure 5.14: Variation of wear depth (d) w.r.t temperature (T) at Point 13

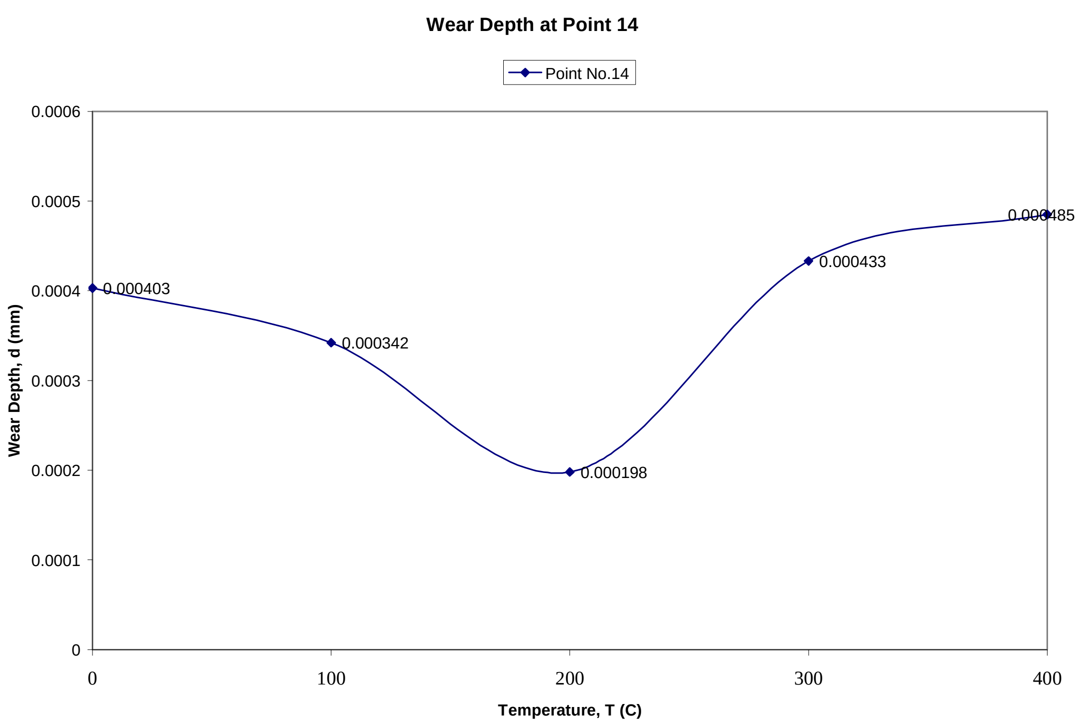


Figure 5.15: Variation of wear depth (d) w.r.t temperature (T) at Point 14

From the graphs it can be seen that the wear depth is minimum at the die temperature of 200°C. It is observed that it increases as the temperature of the die is increased above 200°C and also, if the die is heated to temperatures below 200°C.

The wear depth increases at temperatures above 200°C because as the die is heated to temperatures above 200°C, its hardness is decreased due to which the die material softens. Due to the rapid blows of hammer, the softened die material gets deformed. At temperatures below 200°C, the die material becomes brittle and due to large temperature difference between the workpiece material (heated at 1100°C) and the die material, the die gets worn out. Thermal shocks are produced in the die as the impact force is applied by hammer. The upper layer of the surface of the die starts wearing out due to thermal shocks and this phenomenon is repeated subsequently if the forging is continued at low temperatures.

The simulation has been performed at different die temperatures of 0°C, 100° C, 200°C, 300°C and 400°C, and the wear depth is calculated at fourteen points considered on the die. The wear coefficient for die material is then evaluated for different temperatures. Figure 5.16 shows the variation of the Dimensional Wear Coefficient w.r.t the temperature. The Best fit between the Wear Coefficient and the temperature has been obtained using *cftool* of *MATLAB* software. The fit of the curve obtained in MATLAB is characterized by the goodness of fit parameters. These parameters include sum of squares of error (SSE) and root mean square error (RMSE). Low values of these parameters indicate good fit. Their values obtained in this case are:

SSE: 2.603×10^{-29}

RMSE: Negligible

The Best fit in this case was obtained using 4th degree polynomial where as other distributions such as Weibull and Gaussian failed. The equation, thus obtained is given as:

$$\mathbf{k\ (T) = p1 \times T^{4} + p2 \times T^{3} + p3 \times T^{2} + p4 \times T + p5}$$

where, Coefficients:

p1 =	-2.016	p3 =	5.494	p5 =	7.92
p2 =	-0.7379	p4 =	5.584		

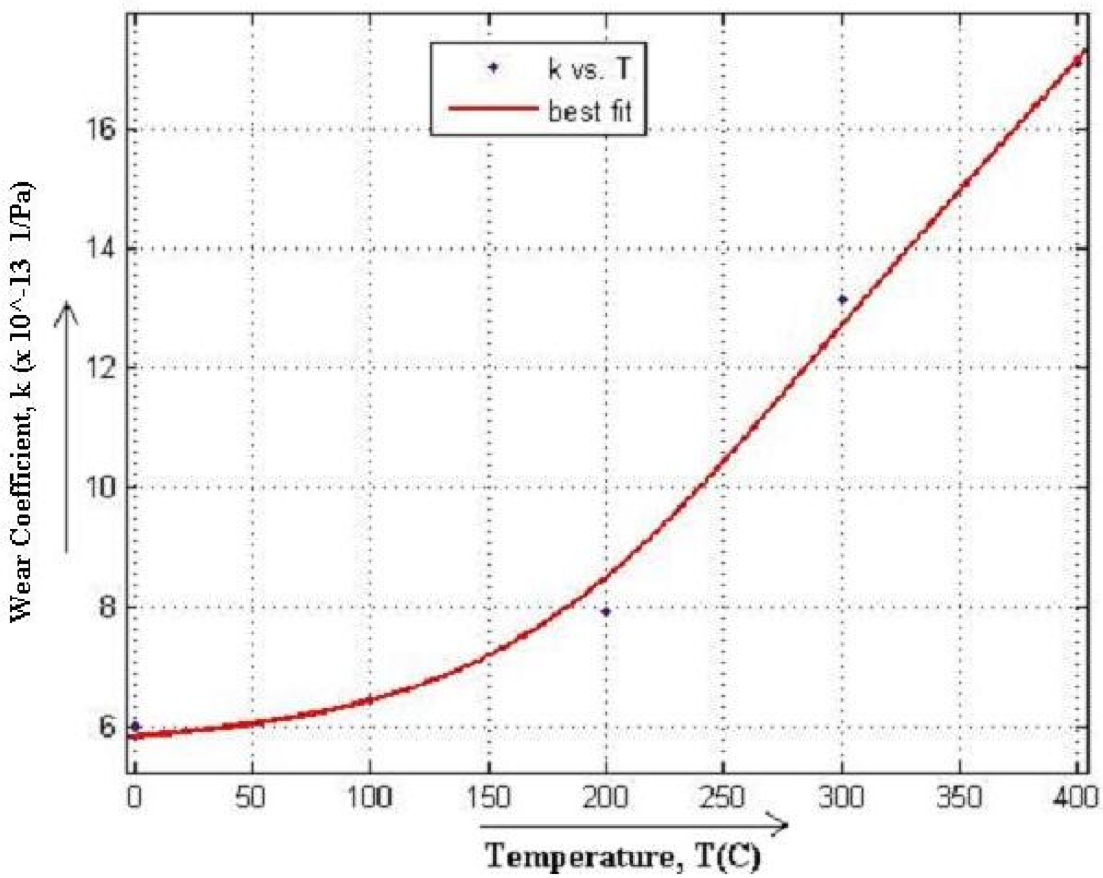


Figure 5.16: Variation of the Dimensional Wear Coefficient w.r.t the temperature

It has been observed that the die wear coefficient increases with the increase of temperature. Upto 200°C there has been a meager increase in the die wear coefficient and above 200°C the wear coefficient increases sharply. This is because the hardness of the die decreases sharply when the die is heated to higher temperatures above 200°C and when the die is heated to low temperatures, the change in the hardness is not appreciable. The wear coefficient being inversely proportional to the hardness follows the same trend. Therefore, it is concluded that die should be pre heated to a suitable temperature before forging. In this case study, the pre heating temperature is 200°C and it has been observed that the depth of wear is minimum at 200°C.

Table 5.2: Wear Coefficients at various Temperatures

S. No.	**Temperature, T (°C)**	**Wear Coefficient, k (Pa^{-1})**
1	0	5.98×10^{-13}
2	100	6.45×10^{-13}
3	200	7.92×10^{-13}
4	300	13.14×10^{-13}
5	400	17.12×10^{-13}

5.2 FUTURE SCOPE OF THE STUDY

- This study can be performed on different die materials and workpiece materials.
- Simulation of forging process could be done using different forging softwares like DEFORM, QFORM etc.
- Different Forging Machines of higher capacity could be used like Hydraulic Presses, Mechanical Presses.
- This analysis could also be done in warm forging and cold forging.

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APPENDIX A: MATERIAL PROPERTIES

MATERIAL PROPERTIES OF TOOL STEEL AISI_H13

Close Analog: ASTM A681, X40CrMoV5-1, BS 4659 H13.

Applications: Hot work applications, pressure die casting tools, extrusion tools, forging dies, hot shear blades, stamping dies, plastic molds.

Physical Properties:

Density: 7.80 g/cm^3

Hardness: 43-47 HRC

Mechanical Properties (at room temperature):

Tensile Strength (Ultimate): 1990 MPa

Tensile Strength (Yield): 1650 MPa

Bulk Modulus: 140 GPa

Young’s Modulus: 210 Gpa

Shear Modulus: 81 GPa

Poisson’s Ratio: 0.3

Thermal Properties:

Specific Heat Capacity: 460 Joules/ (kg-K)

Thermal Conductivity: 24.6 Watt/ (m-K)

Composition (%):

Carbon	Chromium	Silicon	Vanadium	Molybdenum	Iron
0.32-0.4	5.13-5.25	1.00	1.00	1.33-1.40	>=90.95

MATERIAL PROPERTIES OF AISI_1018 MILD STEEL

Close Analog: ASTM A108, DIN 1.0453, BS 970 080A17.

Applications: Hot rolling, Used as Forged material in automotive industry for e.g. discs, hubs etc.

Physical Properties:

Density: 7.87 g/cm^3

Hardness: 78 HRB

Mechanical Properties (at room temperature):

Tensile Strength (Ultimate): 475 MPa

Tensile Strength (Yield): 275 MPa

Bulk Modulus: 140 GPa

Young's Modulus: 205 Gpa

Shear Modulus: 80 GPa

Poisson's Ratio: 0.29

Thermal Properties:

Specific Heat Capacity: 486 Joules/ (kg-K)

Thermal Conductivity: 49.8 Watt/ (m-K)

Composition (%):

Carbon	Manganese	Sulphur	Phosphorus	Iron
0.14-0.2	0.6-0.9	<=0.05	<=0.04	98.81-99.26