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ANALYSIS OF FAILURE OF FORGING DIES

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Abstract : For choosing the most appropriate process and processing parameters that will lead to long time between failures, analysis of defective surfaces is essential. In order to determine the type and severity of failure and to prevent hot forging die failure, a number of procedures are being developed and applied. Despite all these efforts, losses were still incurred in terms of profitability. However, in order to assess and understand the current research status of hot forging dies in order to solve the problem of failure, no comprehensive review has been carried out. The goal of this study is to communicate an updated perspective of kind of failures such as wear (Abrasive and Adhesive), plastic deformation, fatigue (thermal and mechanical) occurs due to high thermal combats, mechanical strain, whorled loading and corrosion while hot forging process. This study will contribute to better understanding of the directions in which failure analysis has been carried out having an impact on hot forging industry, and thus helps prevents the die failures.

Index Terms – Forging, Fatigue, Transient analysis, Deformation.

1. INTRODUCTION

Forging is a manufacturing process involving the shaping of a metal through hammering, pressing, or rolling. These compressive forces are delivered with a hammer or die. Forging is often categorized according to the temperature at which it is performed cold, warm, or hot forging. A wide range of metals can be forged. Hot forging is one of the most conventional metal forming processes used in the production of critical parts in the manufacturing of automobiles and industrial machine components.

The forging die is a crucial tool in the die forging process, which is a key factor in the production process. The die is considered a consumable accessory, and its failure refers to a loss of its functional use during its specified lifespan. The service life of the die refers to the number of parts produced from the time it is put into use until normal wear and tear leads to its consumption. Premature failure of the die can result in production interruptions, increased costs, decreased competitiveness in the market, and reduced economic benefits for the company. To maximize the performance of the die material, improve its quality and service life, and reduce production costs, is a major concern in the forging industry.

Hammer forging dies and machine forging dies are hot forming dies used in free forging hammers, die forging hammers, and presses. These are typical hot work dies that undergo both mechanical and thermal stress during the working process. The mechanical stress primarily comes from impact and friction, while the thermal stress is caused by alternating heating and cooling. Due to the complex working conditions of forging dies, their failure can also be complex, including wear and cracking of the cavity part, thermal fatigue (thermal cracking), and plastic deformation of the cavity surface. The primary failure modes of forging dies include wear and cracking of the cavity, thermal fatigue, and plastic deformation of the cavity surface. Figure 1.1 illustrates the various failure modes that are prone to occur in different parts of the forging die cavity.

1.1 Need Of The Study

There is a high chance of die failure used for hot forging. Due to this, the quality, cost and time of the production process can be affected. The material used for this study is die steel or D2 steel which is an air hardening, high-carbon, high-chromium tool steel. It has high wear and abrasion resistant properties. It is heat treatable and will offer hardness in the range 55-62 HRC, and is machinable in the annealed condition. D2 steel shows little distortion on correct hardening. The Theoretical die life is 5000 and 7000 cycles but, in the industry, only 55% of the die life is achieved. So, analysis of failure of forging dies is important to increase the life span of the die which in turn increases the profitability.

1.2 Data And Sources Of Data

For this study, the primary data has been collected from Steel and Industrial Forging Ltd (SIFL) which is a public sector undertaking fully owned by Government of Kerala situated in Athani, Thrissur. SIFL has the proven technical capability to forge all types of steel alloys including stainless steel & maraging steel, forgings out of Non-ferrous and special metals viz. Titanium alloys, Aluminium alloys, Nickel alloys, Inconel, Super alloys, etc. With expertise over the years SIFL has now been recognized as a World class manufacturer and Solution provider for Aerospace forgings and finished components. The data collection period is ranging from January 2023 to March 2023.

2. RESEARCH METHODOLOGY

The methodology section outline the plan and method that how the study is conducted. This includes Universe of the study, sample of the study, Data and Sources of Data, study's variables and analytical framework. The details are as follows;

2.1 Failure Analysis Process

The procedure for failure analysis for a failed hot forging die is actually the same as for traditional machine parts. Of course, a hot forging die failure analysis needs to be done for each failed hot forging die. The methodology for the failure analysis involves the following steps as shown below;

a) Identification
b) Data collection
c) Analysis
d) Evaluation

2.1.1 Identification

The first step is to make macroscopic observations of failed hot forging dies, as in this study. For this, the die with the most demand and the one with highest probability of failure was identified. Forging equipment, die production process, and forging die steel are each examined with regard to the variables that may affect hot forging die failure. *1154 – a type of gear blank (Coded as per the company specifications) was identified to be the die with highest probability of failure*. The die was made of high-grade Cr-Ni-Mo alloyed hot work tool steel. Forging dies commonly employ the 2714 ISO-B die steel. great toughness, ductility in all directions, high-temperature strength, outstanding tempering resistance, great hardenability, and good dimensional stability are all characteristics of this die steel. These properties also apply to the heat treatment and coating processes.

2.1.2 Data Collection

Data collection includes all the information required for the failure analysis. The following data were collected for this study;

a) Forging Die Manufacturing: The initial stage in the creation of a forging part is to manufacture forged dies. There are two major types of forgings: Open and Closed Die Forging. Open die forging shall be carried out between flat dies or dies with a simple shape. This technique is primarily intended to focus on larger pieces. On closed die forging, the metal billet's shape and dimensions are deformed to a suitable extent on both upper and below dies. Precision forgings with precise tolerances are produced by high pressures and closed deformation of the joints. The process is therefore used frequently to create both simple and complex high power precision components when safety considerations are taken into account.

b) Causes of Die Failure: The fundamental causes of die failure have long been studied. Poor design, shoddy assembly, unpredictability of circumstances, improper storage and poor handling during movement are all to blame for the catastrophic failure of dies. They can be avoided through measures that take into account qualitative stages from design to relocation and installation. Production errors are caused by a particular material, the production procedure or process parameters which are not in conformity. The cracking is caused by inadequate heat treatment, additional post machining, finishing processes and poor durability and fatigue. The failure of dies is a result of mistaken selection and direction of machining, insufficient lubrication because of lack of accessibility or time efficient techniques resulting in an uneven and unusual stress pattern. Operational failures are the direct causes for failure of dies. Almost all cases of failure mechanisms are linked with their operation conditions (temperature, mechanical loading, continual heating and cooling and integrity of part to forge). The focus of current study is to explore mechanisms involved in failure due to operational conditions; since these have greatest potential to harm the die surface.

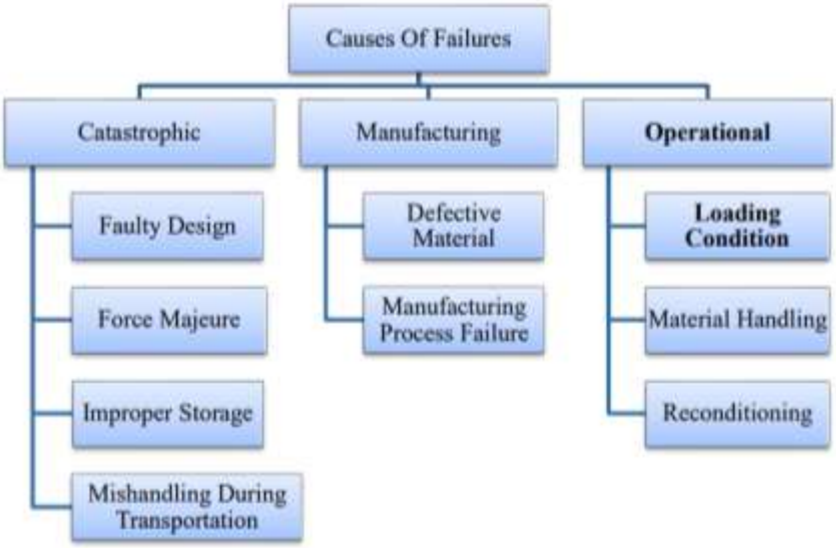


Figure 2.1 Causes of Die Failure

c) **Mechanisms of Die Failure:** Die deterioration during hot working is primarily caused by three factors: intense thermal loads, intense mechanical loads that are cyclically variable, and intense friction and erosion. The three main damage mechanisms have been identified: abrasive wear, thermomechanical fatigue and plastic deformation. Usually, they act simultaneously even at early stages of the die life. The damage is located at the die surface and subsurface, which means that a local characterization approach is needed. Dies fail for various reasons, including:

- Abrasive wear to out-of-tolerance conditions;
- Heat checking and spalling/accelerated wear out;
- Thermal softening and subsequent deformation of dies;
- Excessive "benching" (hand grinding/polishing);
- Catastrophic failure (broken dies); and,
- Inaccurate dies that miss target dimensions.

d) **Die Material:** Cr-Ni-Mo alloyed die steel based on grade 1.2714 (Die Steel 2714 ISO-B) with optimized composition to achieve full quenching and tempering with dimensions up to 800 mm reference diameter, improved high temperature strength properties, and increased wear resistance compared to the standard. Alloy steel 18CrNiMo7- 6 is a grade consisting of the addition of chromium, nickel, molybdenum and coal with a range characteristic for all carburizing grades 1.6587 materials, unlike other simple steel grades, can be used for much larger sizes and loads. This grade of steel is used for heavy-duty parts and components subjected to high pressures and highly variable speed of operation. Materials and derivatives are used for the production of special bearings, bolts, gears, shafts, or rack-and-pinions. They are related grades of steel according to UNI standards, having slightly narrowed content of Chromium, Nickel and Molybdenum.

Table 2.1 Physical properties of Die Steel 2714 ISO-B

Thermal expansion coefficient (10–6/K)	20–100 °C 12.2	20–250 °C 13.1	20–500 °C 14.2
Thermal conductivity (W/mK)	20 °C 36.0	250 °C 37.5	500 °C 34.5
Young's modulus (GPa)	20 °C 215	250 °C 198	500 °C 175

e) **Failure of the Dies:** Also die and tool design determine the structure of the product and therefore, the design team precisely undertakes die design principles to ensure the product is developed impeccably. Before beginning the production process, a progressive die is prepared with exact geometrical specification in advance. The die design produced below refers to the design of the gear blank – 1154 (Die Steel 2714 ISO-B).

f) **Production Parameters**: The closed die hot forging process is most suitable for generating complex shaped work parts with reasonable profile accuracy. The process is quite complex from the analysis point of view as there exist several parameters, that can influence the process. These parameters in broader terms can be classified into two categories: design and process parameters. The design parameters include the preform shape design and die design. The preform shape design is primarily dependent upon the number of stages involved. The die design includes parameters such as flash thickness, flash width, draft angle, corner and fillet radius, input billet geometry etc. The process parameters include input temperature of billet and die, interface friction, speed of deformation etc.

- Temperature: In general, increasing the hot forging temperature (which is far above the recrystallization temperature of the material) reduces the flow stress, the strain hardening coefficient and hence the resistance of the material to deform. It is expected that, the forging load requirement would go down. Preheated dies are generally used in the hot forging process to avoid chilling effect at die and billet interface which hinders the metal flow at surfaces. The heated dies also facilitate die filling and reduce forging pressures. Typically, the die is heated in the range of 450º C, based on complexity of workpiece and then quenched to the forging temperature 300- 350º C. The billet (workpiece) is heated to a temperature of 1200º C.
- Hammer Load: During hot forging (hammer method), the metal workpiece (billet) goes into a die (the tool used to cut and shape metals) and then receives repeated blows from a hammer. These strikes gradually shape the metal workpiece according to the die's shape. In hammer forging, the metal's surface changes shape, but the centre remains relatively untouched. Hammer load is imparted by a very short contact time and very rapid rate of increase of force with time (impact loading). For the present work, the 16T hammer was used along with its parameters including blow energy, rated weight of falling parts, maximum operating stroke of RAM and width of die blocks, distance between the guides and minimum height of guides.
- Frequency of hammering: In the forging process, multiple blows are required at each stage (for each die). The present work requires about 20-25 blows which takes up to 6 minutes to complete.
- Die support: It is very important that the die is properly supported underneath by a perfectly flat backing surface with sufficient hardness. Proper backing is especially important in hammer forging because there is usually no side support in this case. When dies of greatly different dimensions are used on the same press or hammer, it is essential to remove any cavities in the backing block or plate when switching from a small to a large die. The lower die is fixed at die holder of the furnace and the upper die is fixed at the hammer (pneumatic hammer).

2.1.3 Analysis

The structural deformation of the forging die during the industrial process was analysed using ANSYS software. ANSYS is a general purpose, finite element modelling package for numerically solving a wide variety of mechanical problems. These problems include static/dynamic, structural analysis, heat transfer, and fluid problems, as well as acoustic and electromagnetic problems. It is a powerful tool that is used to simulate various metal manufacturing processes, such as metal cutting, forging, rolling, welding, hemming, flanging, electromagnetic forming, bending and stamping. Input Parameters for simulation are a) 3D model of the Die and Work piece b) Mechanical and Thermal properties of Die and Work piece c) Force applied on the upper die.

2.1.3.1 3D model of the Die and Work piece

3D modelling of the die was done by using SOLID WORKS. This software allows designers and engineers to bring better products to the market faster.

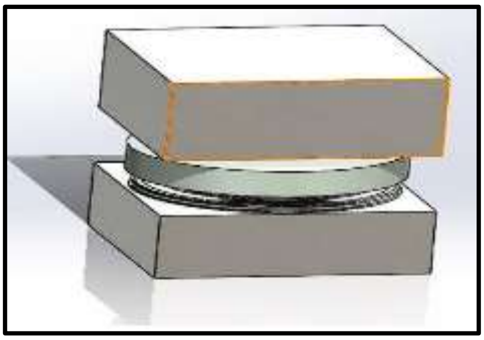


Figure 2.2 Assembly of top and bottom dies

Figure 2.3 Lower die

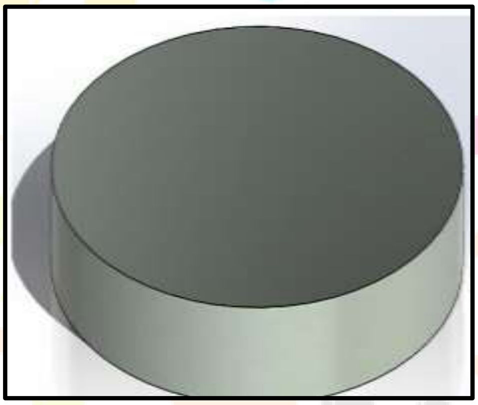


Figure 2.4 Blank

2.1.3.2 Mechanical and thermal Properties of Die

Table 2.1 Physical properties of Die

Thermal expansion coefficient (10–6/K)	20–100 °C 12.2	20–250 °C 13.1	20–500 °C 14.2
Thermal conductivity (W/mK)	20 °C 36.0	250 °C 37.5	500 °C 34.5
Young's modulus (GPa)	20 °C 215	250 °C 198	500 °C 175

Table 2.2 Heat Treatment properties

Heat Treatment	
Stress relieving	Temperature: ~ 650ºC in the annealed state Duration: 1 hour per 50 mm wall thickness Cooling: furnace
Soft annealing	Temperature: 700ºC Duration: 1 hour per 25 mm wall thickness Cooling: furnace
Hardening	Temperature: ~ 880ºC Duration: 1 hour per mm wall thickness
Quenching hardness	Max. 58 HRC: in water/ oil, protective atmosphere/oil, oil, hot bath or vacuum
Tampering	Temperature: tampering curve Duration: 1 hour per 25 mm wall thickness Cooling: air
Working hardness	300-440 HB : depending on application

Table 2.3 High temperature yield strength

Quenched and tampered state	0.2 % yield strength Mpa at temperature			
	450ºC	500ºC	550ºC	600ºC
~1570 Mpa	910	750	470	230
~1370 Mpa	830	605	410	215
~1180 Mpa	630	480	305	165

2.1.3.3 Mechanical and thermal properties of workpiece

Table 2.4 Mechanical Properties of workpiece

Characteristic Property	
Brinell Hardness	180-190
Elastic (Young's, Tensile) Modulus	190 Gpa
Elongation at Break	13-18%
Fatigue strength	220-370 Mpa
Poisson's ratio	0.29
Reduction in area	40-51%
Shear modulus	72 Gpa
Shear strength	380-410 Gpa
Tensile strength(ultimate) UTS	620-680 Mpa
Tensile strength (proof) Yield	330-580 Mpa

Table 2.5 Thermal Properties of workpiece

Characteristic Property	
Latent heat of fusion	250 J/g
Maximum temperature (mechanical)	400 ºC
Melting completion (liquids)	1460 ºC
Melting onset (solids)	1420oC
Specific heat capacity	470 J/kg-K
Thermal conductivity	51 W/m-K
Thermal expansion	12 µm/m-K

2.1.3.4 Hammer Force applied on the die

The hammer force to be applied on the upper die was calculated as follows. The calculated load conditions (force) is given as the input for transient loads and the lower die is the only fixed support in this case.
The force applied is assumed and verified as the hammer load in Transient Structural Simulation.

- F – Force
- S – Distance = 1.5 m
- P – Momentum
- m – Mass = 4.6875 Kg
- t – Time
- v – Average Velocity
- F = P/ t
- P = mv = 16000*v
- v= distance/t = 1.5/t
- S = 1/2 at2
- F = ma
- 1.5=1/2 x (16000/4.6875) t 2
- T = 0.0296sec =0.03sec
- v= 1.5/0.03 = 50m/sec
- P = 16000*50 = 800000 Kgm/sec
- F = 800000/0.03 = 26666667N

2.1.3.5 Evaluation

Simulation Using ANSYS Software: The industrial forging process was analysed using Ansys software. Simulation of the forged part is done on the ANSYS software for finding bend or deflection in the stem of component where improper machining is happened. ANSYS allows to simulate the process by 2 methods: Explicit Dynamics and Transient Structure. Explicit dynamics is a time integration method used to perform dynamic simulations when speed is important. It accounts for quickly changing conditions or discontinuous events, such as free falls, high-speed impacts, and applied loads. The Ansys explicit dynamics suite enables to capture the physics of short-duration events for products that undergo highly nonlinear, transient dynamic forces. Transient structural analysis (Implicit Dynamics) is the process of calculating and determining the effects of loads and internal forces that are a function of time on a structure or an object. It is used to determine the dynamic response of a structure under the action of any general time-dependent loads. Use implicit dynamics when solving for dynamic finite element analysis (FEA) problems that involve mild nonlinearity and when large timesteps can be used. This includes: Static equilibriums, slow, linear, and mildly nonlinear processes, large time increments.

3. RESULTS AND DISCUSSIONS

Transient analysis is a technique to determine the response of a structure to arbitrary time-varying loads such as an explosion. The transient dynamic analysis is used in the design of Structures subjected to shock loads, such as automobile doors and bumpers, building frames, and suspension systems. Structures subjected to time-varying loads, such as bridges, earth moving equipment, and other machine components. Household and office equipment subjected to "bumps and bruises," such as cellular phones, laptop computers, and vacuum cleaners. From the failure analysis of hot forging dies using transient structural suite in ANSYS software, the following results were obtained.

3.1 Total Deformation

From the analysis, the deformation, contact status and contact stresses are plotted and are shown below. The maximum total deformation of 0.352 mm is observed as shown below.

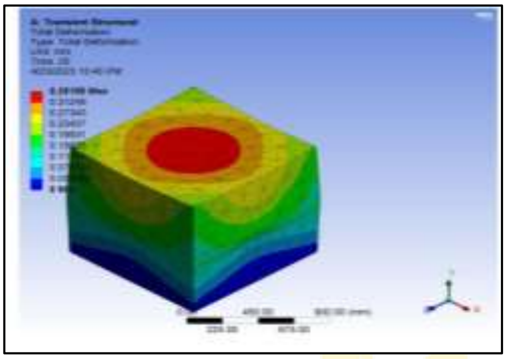


Figure 3.1 Total Deformation-Die Assembly

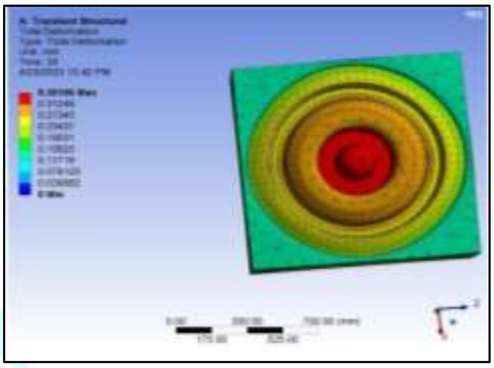


Figure 3.2 Total Deformation-Upper Die

3.2 Directional Velocity

From the analysis results, the maximum Directional velocity in the X direction was found to be 0.0087 mm/s and minimum velocity was found to be -0.0087 mm/s.

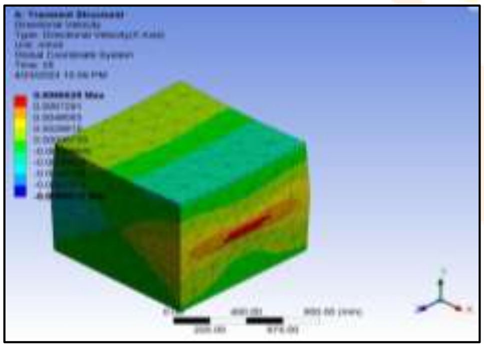


Figure 3.3 Directional velocity-Die Assembly

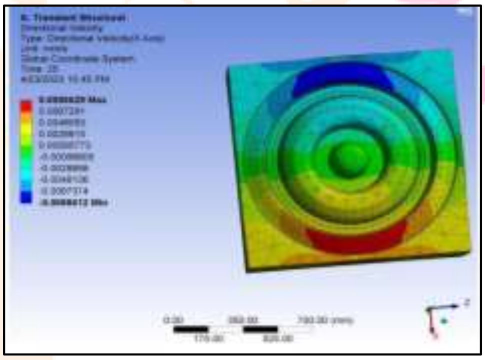


Figure 3.4 Directional Velocity-Upper Die

3.3 Equivalent Stress

From the failure analysis results, it is seen that the maximum contact stress observed is 319 MPa which is less than the yield strength of the material, i.e 550 MPa. The minimum equivalent stress was found to be 0.55 MPa. The highest values of the effective stress are inside the forging and such values are expected because the stress in the material depends on the strain rate because the visco-plastic behaviour of the material is present

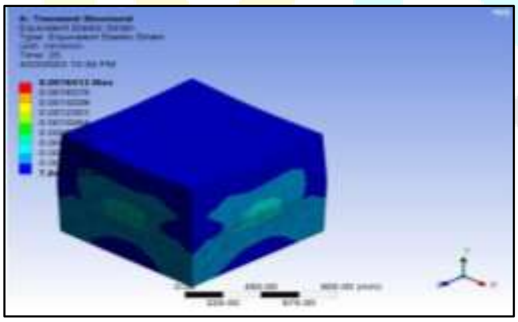


Figure 3.5 Equivalent stress- Die Assembly

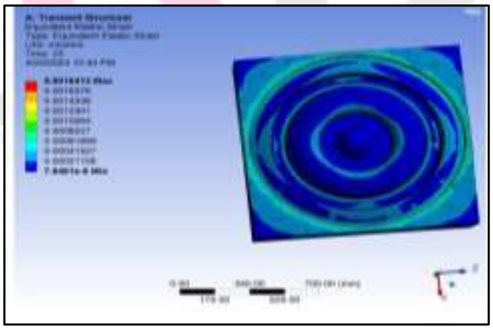
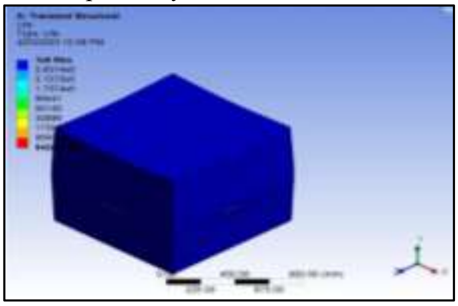


Figure 3.6 Equivalent stress- Upper Die

3.4 Equivalent Elastic Strain

Equivalent elastic strain is a concept used in materials science and mechanics to quantify the amount of strain a material undergoes under an applied load. It is a is a straightforward variable to report strain results over a body. From the analysis, the maximum and minimum equivalent elastic strain was observed as 0.00184 mm/mm and 7.84 $*10^{-6}$ mm/mm respectively.



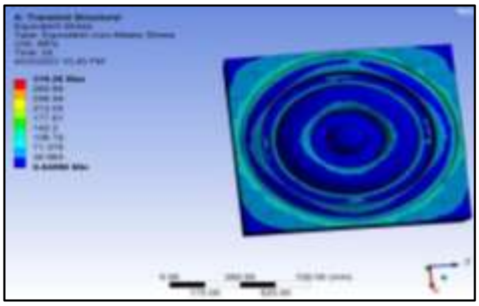


Figure 3.7 Equivalent elastic strain- Die Assembly   Figure 3.8 Equivalent elastic strain- Upper Die

3.5 Fatigue Life

Fatigue, or metal fatigue, is the failure of a component as a result of cyclic stress. The failure occurs in three stages: crack initiation, crack propagation, and catastrophic overload failure. The duration of each of these three steps depends on many aspects including fundamental raw material characteristics, magnitude and orientation of applied stresses, etc. The maximum fatigue life was found to be $1*10^6$.

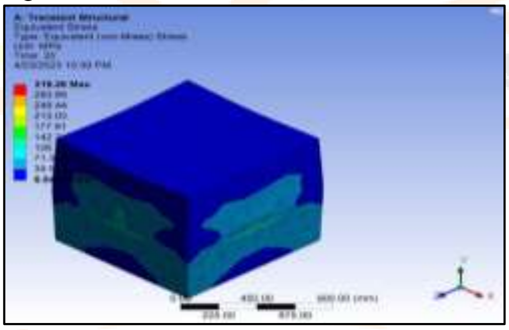


Figure 3.9 Fatigue Life

3.6 Safety Factor

A safety factor is most commonly expressed as the ratio between a measure of the maximal load not leading to the specified type of failure and a corresponding measure of the maximal load that is expected to be applied. The maximum and minimum safety factor was observed as 15 and 0.27 respectively.

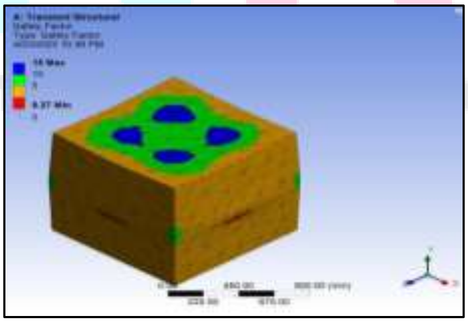


Figure 3.10 Safety Factor

3.7 Most wear prone area

The most wear prone areas of the hot forging die assembly is as shown below.

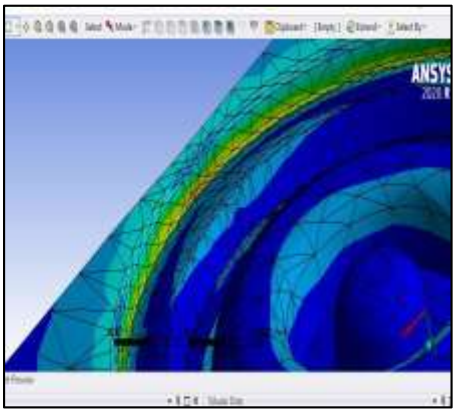


Figure 3.11 Most prone area

3.8 ENDURANCE STRENGTH

Endurance strength refers to the maximum load on a material without considerable signs of fatigue or even defects and the endurance limit (Se) of a material is defined as the stress below which a material can endure an infinite number of repeated load cycles without exhibiting failure. Endurance limit is a material property, while the mechanical blows and associated vibration and its frequency has to be within the safe ranges of endurance limit.

Endurance strength = 0.5 * tensile strength

The tensile strength of material DIN 1.2714 is 1270 MPa. So, in the present scenario, the tensile strength is less than 1400 MPa.

a) Before Hammering

Tensile strength (s) = $\frac{Pressure\ (P)}{Cross\ section\ Area\ (a)}$

P = 26666667 N
a = no. of elements * element size
a = 20160 * 44.25 = 892080 mm^2
s = 26666667 * 892080 = 23.788 *10^9 GPa
Endurance strength = 0.5 * 23.788 * 10^9 = 11.894 *10^9 GPa

b) After Hammering

Total deformation = 0.35156 mm
New area = 20160 * (44.25 + 0.35156) = 899167.4496 mm^2
s = 26666667 * 899167.5 = 23.977*10^9 GPa
Endurance strength = 0.5 * 23.977 *10^9 = 11.988 * 10^9 GPa

c) Change in endurance strength = endurance strength after hammering –endurance strength before hammering

Change in endurance strength = 94.5 * 10^6 GPa

From the analysis, it was observed that:

- Hammer load can be reduced either by reducing the weight of hammer or by reducing the distance from which the hammer hits the die.
- The reduction of hammering load reduces the deformation/ crack experienced by the die which in turn increases the Die Life. Moreover, it will lead to an increase in the number of blows which requires more production time.
- From the equivalent stress- strain results, the damage points on the die was analyzed.
- The change in endurance strength of the die is calculated as 94.5 *106 GPa which is higher than the tensile strength of the material. Therefore, the high endurance strength is a cause of die failure.
- During the process, the outer surface of the die experiences more defect as the amount of material near the rind layer of the forging die is less. And this defect can be reduced by increasing the thickness of the outer layer of hot forging dies.

4. CONCLUSION

This study quickly summarizes the contributing factors, causes, and characteristics of hot forging die failures. The failure of a hot forging die is complicated by a variety of influencing factors, including die material, die design, die production, and forging processes. Numerical techniques and process simulations can be used to analyse the effects of the hot forging on the forging die properties and the forging process itself, as demonstrated in this project. The 3D model of the die was generated by using SOLID WORKS and was subjected to transient structure analysis in ANSYS software to identify the change in nature of the die due to the applied load. The basic failure mechanism actively participating during the hot forging process was analysed using the simulation methods. And analysis was done on the behaviour of the die material during the forging process. The transient structure analysis also revealed the parameters crucial for extending die life. The fatigue life and a factor of safety was also identified for the selected hot forging die assembly.

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