Life prediction of l6 steel using strain-life curve and cyclic stress-strain curve by means of low cycle fatigue testing

Sanket Inamdar[1*], Manoj Ukhande[2], Prashant Date[3], Dattaprasad Lomate[1], Shyam Takale[2], RKP Singh[1]

[1]Kalyani Centre for Technology & Innovation, Bharat Forge Ltd., Pune, India -411036
[2]R&D CDFD Engineering, Bharat Forge Ltd., Pune, India-411036
[3]Indian Institute of Technology Powai, Mumbai. India-400076

Email: sanket.inamdar@bharatforge.com

Abstract. L6 Steel is used as die material in closed die hot forging process. This material is having some unique properties. These properties are due to its composition. Strain softening is the noticeable property of this material. Due to this in spite of cracking at high stress this material gets plastically deformed and encounters loss in time as well as money. Studies of these properties are necessary to nurture this material at fullest extent. In this paper, numerous experiments have been carried on L6 material to evaluate cyclic Stress - strain behavior as swell as strain-life behavior of the material. Low cycle fatigue test is carried out on MTS fatigue test machine at fully reverse loading condition R=-1. Also strain softening effect on forging metal forming process is explained in detail. The failed samples during low cycle fatigue test further investigated metallurgically on scanning electron microscopy. Based on this study, life estimation of hot forging die is carried out and it's correlation with actual shop floor data is found out. This work also concludes about effect of pre-treatments like nitro-carburizing and surface coating on L6 steel material, to enhance its fatigue life to certain extent.

1. Introduction

Forging is a metal forming process used to manufacture critical geometry components which are difficult to manufacture by other modes of production. Metal Forming, it is a process that has been constantly revolutionizing and evolving since the concept of fire. In today's era, the markets of automotive, aerospace, defense and industrial products are controlled by the countries which are producing the accurate metal parts using most cost efficient process control [1]. As long as there is no material stronger cheaper, and abundant then metallic material, the world will forever revolve around those, who can control and form it the best. Even though forging is not a new science. It has been constantly getting evolved with the help of super computers and finite element modeling. Recently it has become more popular and inexpensive way of crafting net shaped and near to net shaped metal products with less design time and cost. As technology is progressing, the spectrum of physical size of product being generated is becoming larger with smaller tolerances. In that forging is standing well ahead of all.

Wear of forging dies is a predominant issue and that is uncontrollable. Another unwanted phenomenon is fatigue failure and plastic deformations, occurring frequently in hot forging process. Prediction of die failure due to plastic deformation will be an enormous step for the forging industry [2].

2. Experimentation

2.1 Pre-Processing on Material
The die material selected for present investigations is L6 steel. Cylindrical shaped samples were used for performing thermal fatigue experiments. Sample preparation involved following stages;
   1. Heat treatment of raw material (annealed) with different austenizing temperatures.
   2. Machining to dimension as per ASTM E606, with surface roughness of 0.3 to 0.5 Ra.
   3. Nitriding using ammonia gas nitriding to obtain desired case depth
   Heat treatment was carried out using two different austenizing temperatures followed by triple tempering to obtain final hardness values of 42 HRC; Later these samples were machined to finished dimension as mention above and subject to surface nitriding treatment using ammonia gas nitriding technique.
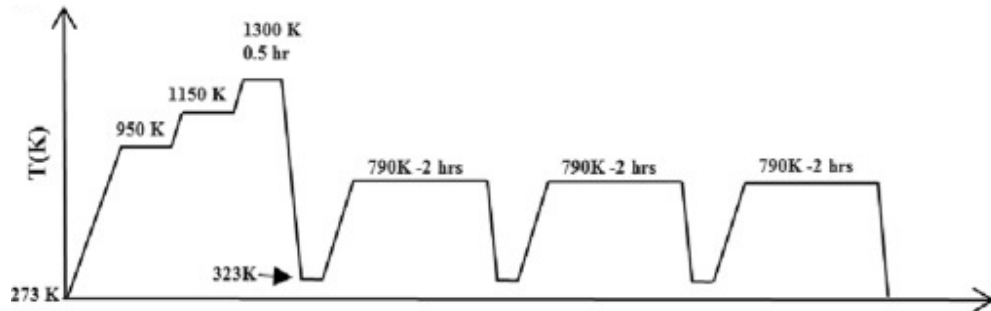

Figure. 1: Heat Treatments and Triple Tempering for 42 HRC.

(A) Heat Treatment,   (B) Triple Tempering.

2.2 The governing equations used for heating and cooling are as below
I. Heat transfer equation,

$$\nabla(-k\nabla T)=Q-(\rho C_p u.\nabla T)$$

Where, k – Thermal Conductivity,

   Q – Heat source,
   ρ – Density,
   C_p – Specific heat capacity at constant pressure &
   T – Temperature
II. Induction heating with high frequency

$$Q_v=\sqrt{3}\ V\ I\ cos\emptyset$$

   Where, Q_v – Power per unit volume of heat source,
      V – Voltage,
      I – Current,

      φ – Power factor,

2.3 Boundary Conditions
1. Heating

   I = 220 A for (0+it) < t < (5+it) where, t = Time
      V = 320 V for 0 < t < 5 t = 0 – 4200 seconds
         φ = 85 – 90 % i = 0:1:300
         f = 12 kHz where, f = Frequency [5]

2.4 Low Cycle Fatigue Test on MTS:
Low cycle fatigue testing is carried out in Kalyani Centre for Technology and Innovation, to generate strain life curves for L6 Steel Material at various conditions. These conditions are as follows.

1. Plain sample without any surface treatment at room temperature (23 C)
2. Plain sample without any surface treatment at elevated temperature (350 C)
3. Nitrided sample at room temperature (23 C)
4. Nitrided sample at elevated temperature (350 C)

Elevated temperature is taken 350 C as this temperature is measured immediately after forging of a component. Nitriding parameters are same as of sample S2C1. Parameters specified for tests are as follows. The specimen, used for this test is dumbbell shaped threaded sample, as shown in figure 2

Table 1. Parameters used for Low cycle fatigue testing

Sr. No	Parameter	Room Temperature	Elevated Temperature
1	Frequency	3Hz	3Hz
2	No. of cycles	20000	20000
3	Strain	0.001-0.1	0.001-0.1

Figure 2.: Specimen for Low Cycle Fatigue Test

This specimen is loaded on MTS machine and strain value is provided to software of this machine. With extensometer attached to gauge length of the sample we can control and measure strain in specimen. If sample completes 20000 axial cycles then sample is removed and next sample is mounted on machine with increase in strain rate. Loaded sample on machine is shown in figure 5.16.

Figure 3. Specimen for Low Cycle Fatigue Test mounted on MTS

3. Results and Discussion

3.1 Tensile Test results and analysis
Tensile test has been carried out to find out material properties and also to analyze deformation of the material. Following figure 3.4 shows stress strain curve for die steel material. By this curve we can say that yield point of this material is 1000 MPa and UTS is around 1250 MPa. This curve helps to differentiate between plastic phase and elastic phase.
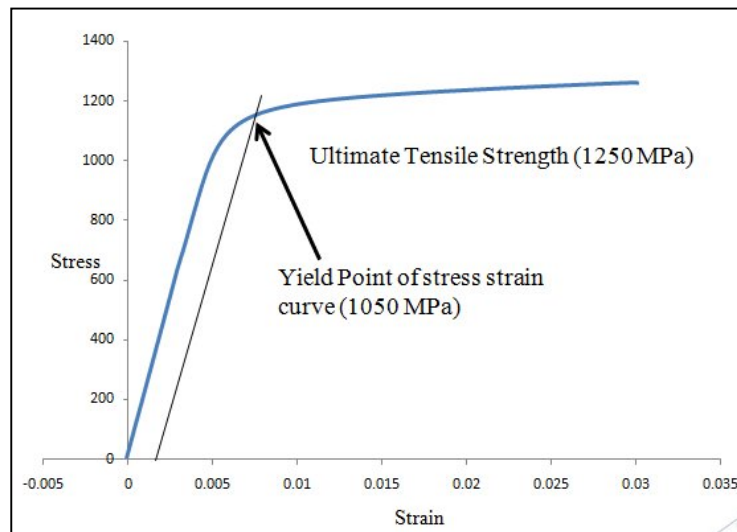
Figure 4: Stress – Strain Curve for Die steel material

From Stress – Strain Curve it is concluded that, if stresses in die are above yield point (1050 MPa), plastic deformation is prone to happen in die. So maintaining die stresses below 1050 MPa leads to only elastic deformation of the die. This elastic deformation cannot be controlled as this is prone to happen in the die. Limiting this die deflection to a certain limit is also important. Maximum deflection of the die in above case is 0.89 mm, maximum strain in die is 0.007 and maximum stresses are around 1145 MPa. Stresses up to yield point i.e. 1000 MPa is consider as elastic stresses so equivalent strain to 1000 MPa is 0.005. Considering these values are limiting values for elastic deformation. And above that can be considered as plastic deformation. Now to analyze the case for front axle beam die up to 1000 MPa it is elastic deformation and for next 145 MPa stress leads to Plastic deformation. Till yield point there is very less plastic strain present in the material. Similarly strain values till 0.005 are considered as elastic strain while next 0.002 strain will cause plastic deformation, hence 0.002 is considered as plastic strain. This plastic strain leads to plastic deformation. In front axle beam die. Elastic and plastic combined deflection is 0.89 mm. By stress strain curve 0.83 mm is elastic deformation while 0.06mm deformation is plastic deformation.

Table 2. Actual Stresses and Strains Present in Specimen by Low cycle fatigue testing

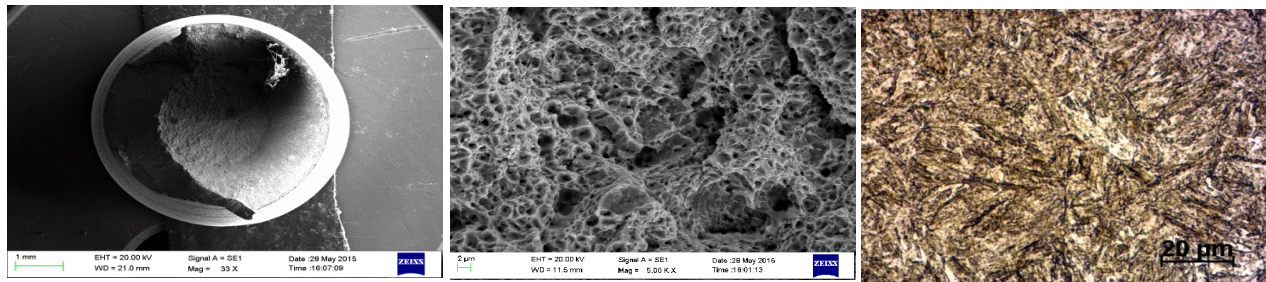| Strain	Elastic strain	Plastic Strain
0.002	0.00198	0.00002
0.003	0.00295	0.00005
0.004	0.00385	0.00015
0.0051	0.0041	0.001
0.0062	0.0042	0.002
0.0075	0.0041	0.0034

Figure 5: Failed Specimen of die material, SEM images and Microstructure
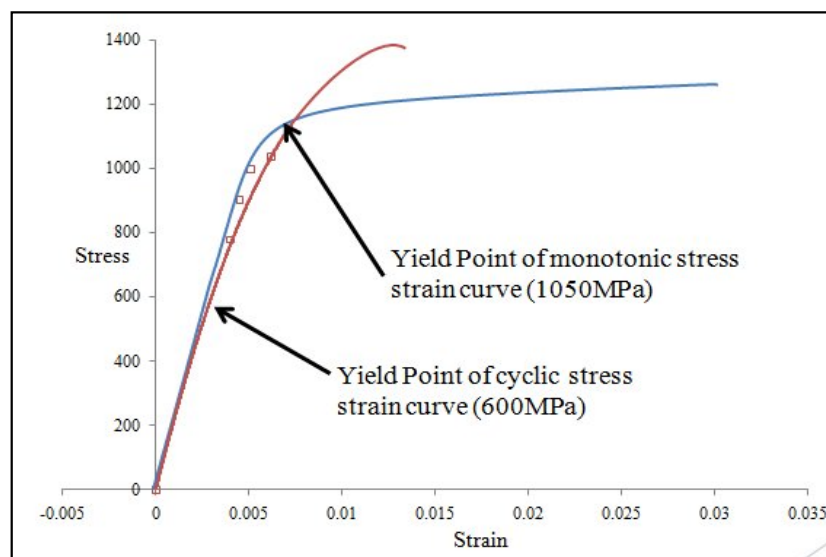

Figure 6. Cyclic Stress – Strain Curve for Die steel material

3.2 Cyclic Testing results and Analysis

To analyze actual deformation in hot forging dies it is important to observe this process from start. Because, any forming process is a cyclic process. And to analyze this process we need to generate cyclic stress-strain curve and give it as an input to analysis software so that results from that analysis will be more accurate.

For doing the same low cycle fatigue testing of die material was conducted and stress strain curves from the same is generated. By observing this stress strain curve, we can say that die material is softening at high stress zone. So to conclude this test we can consider it is a property of special steel like die material to get strain softened. Also its yield point reduces and it is almost 60-62 % of original yield point.
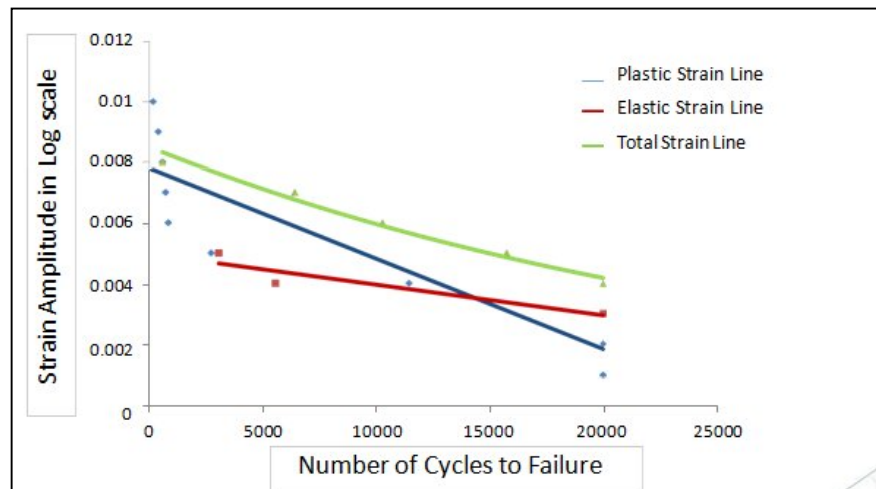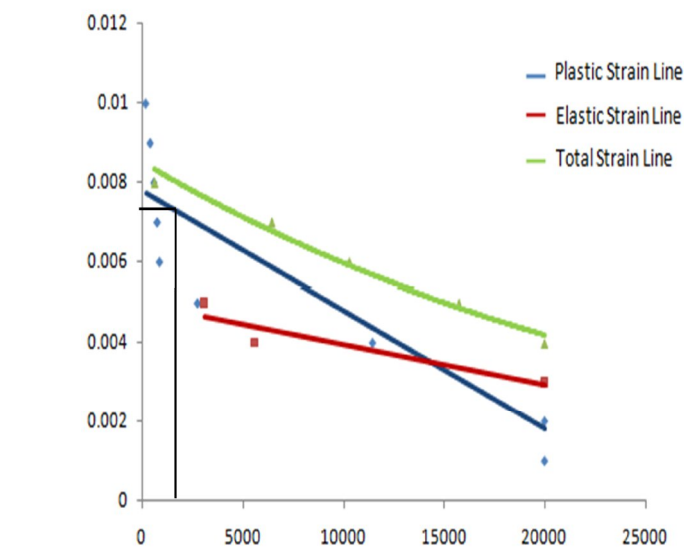
Figure 7. Strain life curve of Material

So SEM and Micro structural analysis of this material is carried out. This shows ductile failure of the material. This is mainly due to low resistance from dislocations inside the material at high stresses. Following are the results for analysis of the die with cyclic stress strain curve.

Sr. No.	Actual number of Parts produced	Predicted number of parts	Correlation %
1	480	590	77%
2	870	990	76%
3	1500	7650	20%

Figure 8: Life prediction with strain life curve

4. Conclusions

Metal forming is a cyclic process, so analysis of this process by monotonic stress-Strain curve fails to give accurate values of deformation. So to do accurate analysis instead of using monotonic stress strain curve, cyclic stress-strain curve is used. These values we get from are very nearer to actual shop floor values. Brittle material like die steel fails ductile while loaded in cyclic manner. It concludes that, Strain Softening is prone to happen in the material. Strain softening is occurring due to carbon rejection in BCT phase tempered martensite transforms in to Soft martensite. This reduces yield point of the material from 1050 MPa to 600MPa. So to analyze the deformation, cyclic stress strain curve is useful rather than using monotonic stress strain curve.

Referances:-
[1]   Bannantine, Julie A., Comer, Jess J, Handrock, James L. "Fundamentals of Metal Fatigue Analysis". Prentice Hall. Englewood Cliffs N.J. 1990.
[2]   Bay, N., P. Skov-Hansen, J. Gronbaek, P. Brondsted. "Fatigue in Cold Forging Dies: Tool Life Analysis." Journal of Materials Processing Technology. Vol. 95. 1999: 40-48.
[3]   Bayer, Raymond G., "Wear Analysis for Engineers.", New York: HNB Publishing, 2002.
[4]   Berger, Paul D. & Maurer, Robert E., "Experimental Design: With Applications in Management, Engineering, and the Sciences.", Duxbury Thomson Learning, 2002.
[5]   Caddell, Robert M., & William F. Hosford. Metal "Forming: Mechanics and Metallurgy.", PTR Prentice Hall Inc. Englewood Cliffs, N.J. 1993.
[6]   Castro, J.T.P., M.A. Meggiolaro. "Statistical Evaluation of Strain-Life Fatigue Crack Initiation Predictions.", International Journal of Fatigue. Vol. 26. (2004). 463-476.
[7]   Collins, Jack A., "Failure of Materials in Mechanical Design: Analysis, Prediction, Prevention", Wiley-Inter science Publication 1993.
[8]   Dean, T.A., D.J. Jeong, D.J. Kim, J.H. Kim, B.M. Kim. "Effects of Surface Treatments and Lubricants for Warm Forging Die Life.",Journal of Materials Processing Technology. Vol. 113. 2001: 544-550.
[9]   Dobychin, M.N., I.V. Kragelsky, V.S. Kombalov., "Friction & Wear: Calculation Methods." Pergamon Press. USSR. 1982.
[10]   Engel, U., Falk, B., & Geiger, M., "Estimation of Tool Life in Bulk Metal Forming Based on Different Failure Concepts.", Journal of Materials Processing Technology. Vol. 80-81. 1998: 602-607.
[11]   Farahmand, Bahram.,"Fatigue and Fracture Mechanics of High Risk Parts.", Chapman & Hall International Thomson Publishing. 1997.
[12]   Fatemi, Ali, Fuchs, Henry O., Stephens, Ralph I., & Stephens, Robert R., "Metal Fatigue in Engineering.", 2nd edition, John Wiley & Sons. 2001.