PERFORMANCE EVALUATION OF FORGING DIES

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ABSTRACT

Hot working tool steels are frequently used to make forging dies. These are high performance alloy steels, which can withstand substantial mechanical and thermal stresses encountered in forging processes. Producing forging dies is technically a demanding process, at all stages of its evolution and manufacturing. During use the forging dies can fail due to variety of failure modes, such as, wear, cracking and mechanical & thermal fatigue. The objective of this paper is to evaluate in service performance of these forging dies. This performance evaluation will be based on industrial data of time to failure of the forging dies. The time to failure shows a significant variability around its average value. Keeping in view both the average value and dispersion in the die life the nature of their failure rate will be explored and appropriate reliability characterization will be provided. Using the parameters of the fitted reliability models a strategy is outlined to have a comparative evaluation of forging tools produced by two competing die manufactures or die materials and /or heat treatments. Reliability analysis of tool life data is done for a variety of forging dies. Various modes of failure and their underlying damage mechanisms are discussed. Important features of the damage processes are identified, and approaches to minimise the tool damage are highlighted. Major focus of the paper is on the reliable life modelling of these metal-forming tools, and to discuss some possibilities to enhance their life. An interpretation of tool quality in view of Taguchi's loss function is also provided, which can be used as a criterion of tool performance, as well as for comparative evaluation of tools.

Keywords: *Forging, performance evaluation, reliability analysis, life modelling, fatigue, wear, Taguchi.*

الملخص

كثيراً ماتستخدم الأدوات الفولاذية الحرارية في صنع قوالب التشكيل . وهذه الأدوات عبارة عن سبائك عالية الجودة تستطيع تحمل اقسى الضغوط الحرارية والميكانيكية التي تدخل في عملية تشكيل القوالب . و تتطلب عملية تشكيل القوالب عناية فائقة في جميع مراحل التصنيع . وخلال العمل يمكن ان تتعطل هذه الأدوات نتيجة لعدة عوامل مثل التآكل و التشقق و الكلال الحراري والميكانيكي . يهدف هذا البحث إلى تقييم الأداء الخدمي لقوالب التشكيل . وسيعتمد هذا التقييم على المعلومات الصناعية حتى وقت تعطل قوالب التشكيل . وتظهر هذه القوالب حتى وقت تعطلها قيماً متغيرة هامة حول القيمة الوسطية . وسيتم إظهار طبيعة معدل تعطل القوالب والصفات الإعتمادية مع الأخذ بعين الإعتبار القيم الوسطية ووهن القوالب . و بإستخدام عوامل النماذج المعتمدة الصالحة ، سيتم رسم استراتيجية لعمل مقارنة لتقييم أدوات التشكيل المصنوعة بواسطة مصنعين متنافسين لعمل القوالب أو مواد التشكيل أو المعالجة الحرارية. وسيتم إجراء التحاليل الإعتمادية لمعلومات عمر الأدوات للعديد من قوالب التشكيل .كما سيتم مناقشة العديد

من أسباب تعطل وإنهيار هذه القوالب و ميكانيكية هذا التاف. كما سيتم التعريف بأهم الصفات لهذه التلفيات و طرق التقليل منها . التركيز الأساسي في هذا البحث هو حول العمر المعتمد لهذه التشكيلات المعدنية ومناقشة كيفية إطالة هذا العمر . وأيضا سيتم تقدير جودة هذه الأدوات بإستخدام " وظيفة تاف تاجوشي" والتي تستخدم كصفة لمعرفة أداء المعدات وكذلك كأداة للمقارنة التقييمية

1. INTRODUCTION

Forging is an important metal forming process and is usually done as hot working operation, where as if the total deformation is relatively small and materials are ductile with less flow stress, then it could be done as a cold working operation. *Hot -forged parts are of different shapes and geometrical complexity* such as turbine blades, connecting rods, housings, gear blanks, garden hoses, etc. and *cold forged parts* such as nails, screws, rivets and small size finished gears.

Forging tools (dies) are subjected to sever pressures, which are determined by the effect of state of stress (as expressed by the yield criterion), friction, and in-homogeneity of deformation. The tools and dies must be made of appropriate materials to accommodate these pressures, and need to be designed with configuration, which provide the maximum resistance to plastic yielding. The tool and die materials are selected and manufactured with greater care. In general, they should meet the following requirements:

- High cold strength
- High hot strength
- High wear resistance
- High mechanical fatigue resistance
- Good thermal fatigue resistance
- Good brittle fracture resistance

Because of the high costs of these metal-forming tools an important goal is to either, (a) *decrease the cost* or (b) *increase the die life*. In general all tools are subjected to failure. Tool failure need to be either avoided or delayed. The most rational strategy for tooling economics in metal forming is to delay this failure as far as possible, or enhance the tool life as much as possible. Unfortunately the ability to predict or forecast the tool life for bulk metal forming tools is still a difficult job [1,2]. In almost all types of metal forming processes including forging tools show a considerable scatter in their life, some times the life varies by several orders of magnitude [3]. This scatter further adds the difficulty in life prediction modelling. The statistical or probabilistic approach in modelling the life of bulk metal forming tools provides a promising approach, which is the main framework of this paper.

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2. CAUSES OF DIE FAILURE AND FAILURE MODES

Failure of tools and dies in forging generally results from one or more of the following causes:

- improper design
- incorrect material selection and inherent material defects
- incorrect tool manufacturing
- improper heat treatment and finishing operations
- overheating and heat *checking* (Cracking caused by temperature cycling)
- excessive wear
- overloading
- misuse and
- mishandling

The proper design of dies is as important as the proper selection of materials. In order to withstand the forces in metal forming processes, a die must have proper cross section and clearances. Sharp corners, radii and fillets as well as sudden changes in cross section, act as stress raisers and can have detrimental effects on die life. Dies may be made in segments and pre-stressed during assembly for improved strength. The proper handling, installation, assembly and aligning of dies are important. Overloading of tools and dies can cause premature failure.

Even if they are manufactured properly, dies are subjected to stresses and temperature during their use, which can cause wear and hence shape changes. Die wear is important because when dies shape changes, the parts in turn have improper dimensions. Thus the economics of the manufacturing operation is adversely affected by the wear characteristic of die material. Greater abrasion resistance (at room temperature for cold working dies, and at elevated temperatures for hot working dies) is highly desirable. For greater abrasion resistance the die surface should be as hard as possible. In addition to hardness, there is an opposing demand on the die material that it should minimise the susceptibility to cracking by providing a relative tough surface without initial cracks. This high fracture toughness is simultaneously desirable with the demand of high hardness.

During use, dies may also undergo heat *checking* from thermal cycling. To reduce *heat checking,* (which has the appearance of parched land) and eventual dies breakage in hot working operations, dies are usually preheated to temperatures of about 150^0C to 250^0C (300^0F to 500^0F). Cracked or worn dies may be repaired by welding and metal deposition techniques, including lasers. Dies may be designed and constructed with inserts that can be replaced when worn or cracked. The proper design and placement of these inserts is important, because otherwise they can crack.

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Due to high speeds, at which tools operate in closed die forging, the tool failure due to fatigue is quite common. In closed die forging, about 25% of all tools failed by mechanical crack initiation, 3% by thermal crack initiation and about 5% by plastic deformation, the most prominent cause of failure however is wear [4-6]. A typical tool wear growth pattern in forging is shown in Figures 1& 2 [7].

2.1. Wear Failures

Wear also constitutes a major cause of die failure. It is observed that the wear is more pronounced at locations of high stress concentration, resulting in wearing the die cavity unevenly. Die material should have a wear resistant surface, hence a proper surface treatment is essential to create such a surface, and tool material should be adaptable to this treatment without a greater sacrifice of toughness.

Several mechanisms have been suggested for the wear of drop forging dies but the main one is micro-machining of the die surface by scale particles embedded in the forging stock [4-6].

Assuming an abrasive wear mechanism die wears may be related to the properties of the stock and die material as follows:

$$W = K\left(Y_s/Y_d\right)(\Delta_o)(A)S \tag{1}$$

where Y_s is the yield strength of the stock at the forging temperature, Y_d is the yield strength of the die material at its surface operating temperature, Δ_o is the total amount of scale formed on the stock, A is the adhesion index, S is sliding distance and K is a constant. If sliding distance S, is assumed as proportional to the number of forgings produced N, then $W = \alpha N$, where $\alpha = \varphi(Y_s/Y_d, \Delta_o, A)$. Figures 1 and 2 reasonably reflect this relationship.

2.2. Fatigue due to Crack Growth

Fatigue failure is considered to be another major cause of tools and dies failure in metal forming [8]. In most cases, the fatigue failure is located at a change in section size at a sharp corner or at stamp marks. Various aspects of the operating conditions of these dies suggest a potential for failure resulting from the growth of cracks on the bearing surface(s). First, during normal operations, the dies are subjected to large, cyclic stresses. Second, the cavities in both dies create regions of high stress concentration especially at raceways and at intricate barrages, where cracks can initiate and grow resulting in catastrophic failure. Third, in order to produce profiles of well-controlled shape and dimensions, the dies are made of high strength, hardened material for example H-12 or H-13 steel. As such they must be prone to fatigue fracture particularly when subjected to heat treatment. Die material and heat treatment should produce minimum initial cracks and provide greatest fracture toughness to resist die breakage under fatigue crack growth.

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3. FORGING DIE LIFE MODELLING

The fact that the tool life in general is typically stochastic in nature and hence governed by the laws of probability has been well appreciated in literature [9,10]. In literature mostly the cutting tools have been studied in a probabilistic framework. There is a lack of probabilistic treatment for tools used in metal forming, in particularly for forging [11]. In this work probabilistic tool life modelling concepts used in machining systems, are extended to the forming process specifically in forging, in order to predict the die life. The reliability R (t) of a die is defined as the probability that its life T will be greater than a time t (i. e; R (t) = P {T>t}), and for the Weibull model it is given by the following function:

$$R(t) = \exp\left(-\left(\frac{t}{\eta} \right)^{\beta} \right) \qquad \eta, \beta > 0 \tag{2}$$

The knowledge of the die life is useful not only in predicting the number of dies required to suffice a production order but also to compare the different dies on the basis of their quality, shape and complexity, nature of heat treatment, and reconditioning or manufacturing. Using this model a comparison of the quality of the dies supplied by the different suppliers can be made as well as dies could be designed to withstand a defined number of stress cycles. Kendall and Sheikh [12] and Sheikh [13] have demonstrated that Weibull reliability model is an appropriate model to be used in the reliable life prediction of cutting tools, because of a number of reasons, some of which are mentioned below and they are quite applicable for forging and extrusion dies as well.

- Monotonically increasing failure rate of the tools or dies is best characterised by the power law type Weibull failure rate model.
- It is the life model obtained as an outcome of extreme value phenomenon of tool damage, which is quite relevant to the die failure phenomenon in metal forming (i.e. extreme damage due to crack propagation or/ and wear reaching a critical level).
- The Weibull model as compared to other probability models is the most conservative reliable life prediction model.
- The Weibull model is quite versatile and has necessary flexibility and the ability to be expressed in a closed form to accommodate a number of shapes of distributions by varying its parameters.
- Adequate computerised means of estimating the Weibull model's parameters are available; the statistical estimates can be easily obtained with relatively small data. This becomes extremely important in case of expensive testing procedures, or when one has to rely on actual field test data.

Therefore Weibull model will be hypothesised to characterise the life of a variety of forging tools. The reliability of forging dies will be evaluated using the real life industrial data from literature [7]. The die life data will be used to determine empirical probability distribution,

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which will be plotted either on the Weibull probability paper, or after suitable transformation on a linear paper, and the validity of the Weibull distribution as a suitable model will be established. On a Weibull probability paper a straight line fit will validate the model, whereas when transformed data is plotted on a linear paper the validity can also be checked by regression [14]. Further the shape and scale parameters of the Weibull model will be estimated. This Weibull analysis of the reliability data will provide invaluable information useful for comparative evaluation, prediction and planning purposes.

3.1. Weibull Analysis of Die Life Data

For each die the time to failure (life) data, ($t_1<t_2< \cdots <t_i<\cdots<t_N$) , is analysed to determine empirical distribution function $F(t_i) = i/(N+1) = 1 - R(t_i)$ and is assumed to be Weibull distributed $R(t_i) = \exp\ [-(t_i/\eta)^{\beta}]$ which can be expressed as:

$$\ln\{\ln\{1/R(t_i)\}\} = \beta \ln t_i - \beta \ln \eta \tag{3}$$

Which is a straight line of the form $Y_i = mX_i + C$; where $Y_i = \ln\ln(1/R(t_i))$, $X_i = \ln t_i$, $m = \beta$, and $C = -\beta\ln\eta$. A straight line fit to (X_i, Y_i) data by regression will determine (a) suitability of the model if high value of r^2 is observed, and (b) parameter β and η from the regression coefficient.

4. RELIABILITY OF FORGING DIES

Figure 3 to 8 uses the industrial data from reference [7] and illustrate die life distribution for various forging processes. For example Figure 3 & 4 represent data of 36 & 43 forging dies respectively of H11 and H12 steel for forging a commercial rod in high production forging facilities. Figure 5 represents data of 32 dies (6F3) used in forging of housing type part used in automobile industry. Figure 6, 7 & 8 represent die life distribution in forging of brass and aluminium alloys. Table.1 represents the average life $\overline{T}$ and scatter parameter β of each die.

Table 1. Average life $\overline{T}$ and Scatter parameter β of various forging dies.

	Figure 13	Figure 14	Figure 15	Figure 16	Figure 17	Figure 18
Die Material	H11	H12	6F3	H12	H12	G6
Hardness	1139	1345	1025 Steel	56Cu-40Zn-2Pb	Copper Alloy	Al 2014
β	2.23	2.9	1.45	1.29	0.45	1.29
η	28000	30500	38000	29500	19000	17000
$\overline{T}$	24000	30000	32000	23000	11000	12000
COV	1.45	1.34	1.68	1.78	3.2	1.78

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4.1. Effect of Weight per Piece (of Similar Shape) on Die Life

Figure 9 illustrate the effect of weight per piece on forging die life. The following two observations can be made; (a) as weight per piece (W) increases average die life decreases, (b) the scatter in die life decreases as W/piece increases which means β increases or COV decreases. For the average life $\overline{T}$, the trend line is $ln\ \overline{T} = \alpha_0 - \alpha_1 W$, where W is the weight per piece of similar shapes.

4.2. Effect of Die Material

In forging H12 dies usually perform better than the several other die materials as reflected in Table 1 and Figures 3-8.

5. EFFECT OF TOOL LIFE SCATTER ON THE QUALITY LOSS FUNCTION

Reliability of a die is a manifestation of a set of performance characteristics embedded in its design, material selection, manufacturing and heat treatment. Reliability R(t) of a die deteriorate with respect to time which could be viewed as a degradation of its embedded quality. The quality is related to the loss to the society caused by a product during its life cycle [15]. The loss to the society caused is composed of the costs incurred in the production process as well as the costs encountered during use by the customer. In the case of tools and dies the loss is which occurred in the production process, and the corresponding cost transmitted to the consumer of the product in terms of high price. A truly high quality tool or die will have a minimal loss to the manufacturer or consumer. Taguchi quantitatively expressed this fact with a quadratic loss function [15]. Taguchi's loss function recognises the customer's (manufacturer in this case) desire to have dies that are more consistent in their performance and help to produce a low cost product. The Taguchi's strategy is to enhance quality by determining conditions, which provides a robust design [14, 15] to encourage uniform tools, and reduces cost of product at the point of consumption. When the life of a tool is measure of its quality, then we would like to have a higher-the-better situation.

The loss function for *higher-a-better characteristics* is shown in Figure 10 and the *expected loss* E[L(t)] is given by k/t^2 and in terms of average $\overline{T}$ and standard deviation σ of life is given by [15]:

$$E[L(t)] = k(1/\overline{T})\{1 + 3(\sigma/\overline{T})^2\} \tag{4}$$

The ratio $\sigma/\overline{T}$ is related to the Weibull shape parameter β as illustrated in Figure 4. As $\sigma/\overline{T}$ decreases β increases and an approximate relationship between these two quantities is

$\sigma/\overline{T} \cong 1/\beta$. Using this approximation equation (5) can be written as

$$E[L(t)] = k(1/\overline{T})\{1 + 3(1/\beta)^2\} \tag{5}$$

Thus expected loss E [L (t)] is minimum when both $\overline{T}$ and β are highest. The reliable life of tool to meet a target reliability is given by

$$t_p = (\overline{T} / \Gamma(1+1/\beta)) \ln\{-R(t_p)\}^{1/\beta} \tag{6}$$

Thus for a specified reliability level $R(t_p) = R^*$ (target reliability), tool A is better than tool B if

$$\overline{T}_A / \overline{T}_B > \{\Gamma(1+1/\beta_A) / \Gamma(1+1/\beta_B)\} \{\ln(-R^*)\}^{(1/\beta_A - 1/\beta_B)} \tag{7}$$

Two special cases are as follows:

(i) If scatter in both tools is the same ($\beta_A = \beta_B$), then the tool A is better than tool B if

$$\overline{T}_A / \overline{T}_B > 1 \tag{8}$$

(ii) If the average life of both tools is same ($\overline{T}_A = \overline{T}_B$), but the scatter is not the same ($\beta_A \neq \beta_B$), then the tool A is better than tool B if

$$1 > \{\Gamma(1+1/\beta_A) / \Gamma(1+1/\beta_B)\} \{\ln(-R^*)\}^{(1/\beta_A - 1/\beta_B)} \tag{9}$$

These equations provide a rationale of comparative evaluation of tools supplied by two or more suppliers. The role of scatter parameter β is significant in determining the tool quality, and every effort should be made to maximise it, in addition to enhancing the average tool life $\overline{T}$.

6. STRATEGIES TO ENHANCE THE DIE LIFE

Some critical aspects of forging and extrusion dies to minimise the failure rate by increasing the average life $\overline{T}$ and decreasing the scatter ($\sigma/\overline{T}$) or increasing the parameter β are [1-8, 11].

6.1. Proper Selection of Die Material

A variety of high quality materials are used for hot forging depending upon actual applications. Die materials must possess adequate strength to accommodate the stresses developed during the forming operation. Desirable properties for tooling materials to withstand the high mechanical and thermal stresses encountered include:

- High toughness and resistance to softening/hot hardness.
- High resistance to abrasive wear at elevated temperature.
- Adequate strength at high temperature.

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- Resistance to distortion and cracking from tensile stresses developed during heat treatment, as well as from temperature changes during metal forming particularly during extrusion which can initiate hot cracking.
- Acceptable resistance to thermal fatigue cracking.
- High thermal conductivity to continuously remove heat from the area of contact with the hot billet.

Resistance to softening is an important requirement for tooling materials operating at high temperatures. When tool and alloy steels are used, this resistance is controlled primarily by the addition of tungsten, molybdenum, and vanadium alloying elements. Selections of the optimum grade for a given application are generally a compromise between toughness and wear resistance, although other factors may be more important in certain situations. Because most tools and dies operate under highly stressed conditions, toughness must be adequate to prevent brittle fracture. It is usually better for tool or die to wear out than to break in service prematurely. Thus in a new application, it is best to select a grade that will have adequate toughness. A typical aluminium extrusion die is made of H-12 or H-13 (classified by AISI), with hardness 48-60 R_C (nitrided) and a typical fracture toughness of 80 MPa $\sqrt{m}$ at room temperature. H-13 steels are perceived to provide good blend of desirable properties (characteristics) against the three modes of die failure, and to render a good die life.

6.2. Proper Manufacturing and Heat Treatment

- Machining process must not alter the surface microstructure or surface finish and must not produce excessive residual stresses that will promote heat treatment problems or service failures.
- Heat treatment operations must produce the desired microstructures, hardness, toughness and hardenability at the surface and the interior.
- Grinding and finishing operations must not impair the surface integrity of the component.

6.3. Proper Handling and Care in Operation of Dies

- Tool and die set up alignment must be precise to avoid irregular, excessive stresses that will accelerate wear or cause cracking.
- Tool and die operation overloading must be avoided to ensure achievement of the desired component life.

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7. DISCUSSION AND CONCLUDING REMARKS

- In this paper it has been demonstrated that the reliable life of forging and extrusion dies can be modelled by Weibull model. The scale parameter of the model is related to the average die life $\overline{T}$, and the shape parameter β has an inverse relationship with its coefficient of variation $COV= \sigma/\overline{T}$.
- Generally for most of the tools scatter parameter $\beta > 1$, which reflect a time dependent deterioration (ageing) of dies. The wear-out processes causing this ageing of the tools are *fatigue*, and *wear* for forging dies. In limited cases (such as forging of copper alloy; Figure 8) $\beta < 1$, which reflect wide scatter in tool life and poor tool quality.
- Using the proposed reliability model comparative evaluation of dies can be done on more rationale basis.
- Die quality can be enhanced if both average life $\overline{T}$, and the shape parameter β are increased, by proper design and selection of tool material, manufacturing processes, heat treatment, as well as care and skill during handling and use of dies.
- For tool reliability enhancement in addition to proper material selection and manufacturing the most important is the heat treatment regime. Heat treatment of these tools and dies involve hardening and tempering. The heat treatment processes need to be done to achieve a compromise between having a hard (wear resistant) surface as well as a tool with high fracture toughness. These contradicting objectives are greatly influence by selection of tempering temperature Figure 11) and shows a considerable scatter in the response Figure 12. The more care, understanding and precautions taken the greater the rewards are.

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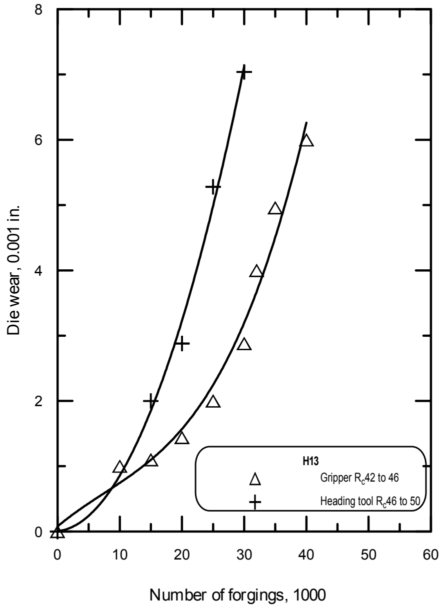

Figure 1 Tool wear of Heading Tool (H13) and Gripper (H13) in a bolt manufacturing process. [7]

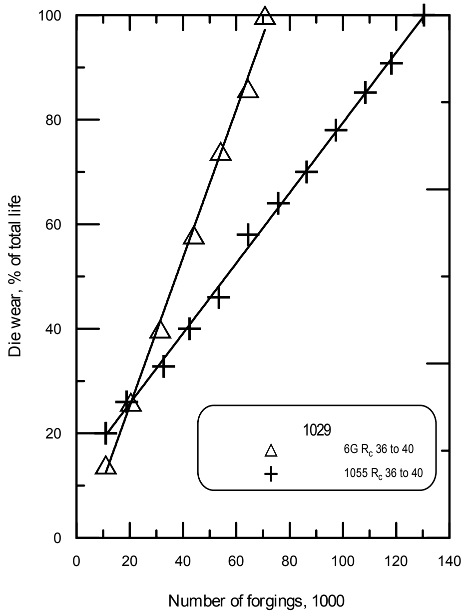

Figure 2 Wear of a forging tool (1055) in manufacturing an 8" diameter pipe with flange from 1029 steel.[7]

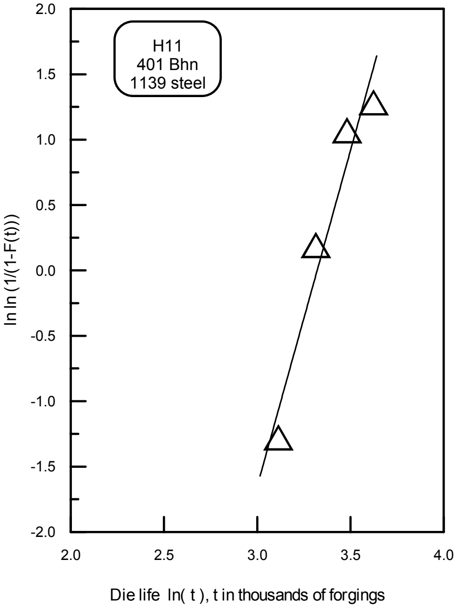

Figure 3 Weibull distribution of die life made of H11 steel in forging a connecting rod of 1139 steel.

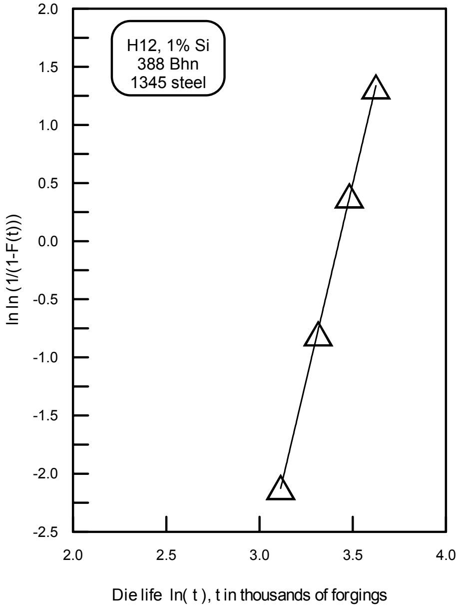

Figure 4 Weibull distribution of die life made of H12 steel in forging a connecting rod of 1345 steel.

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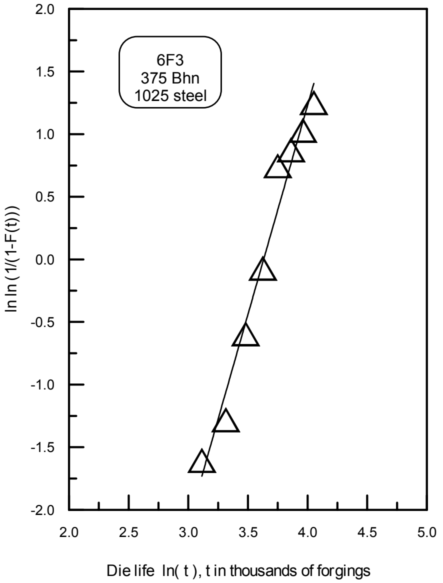

Figure 5 Weibull distribution of die life made of 6F3 in forging a flange type part of 1025 steel.

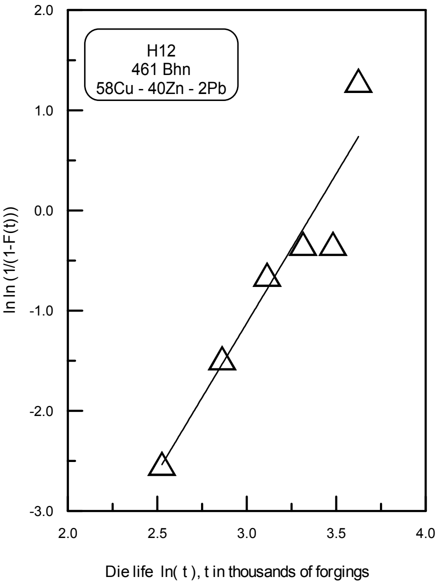

Figure 6 Weibull distribution of die life made of H12 steel in forging a small part of normal complexity from a 58Cu - 40Zn - 2Pb.

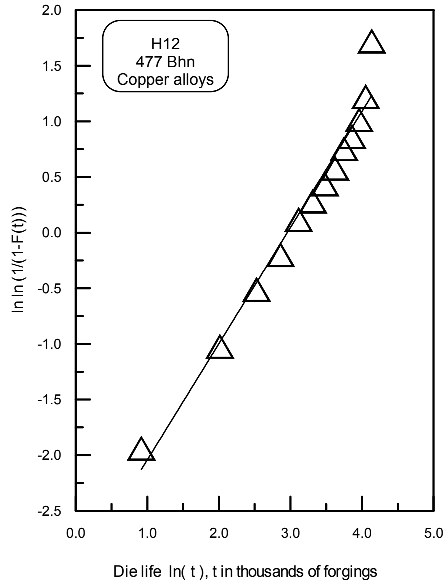

Figure 7 Weibull distribution of die life made of H12 steel in forging a small part of normal complexity from a copper alloy.

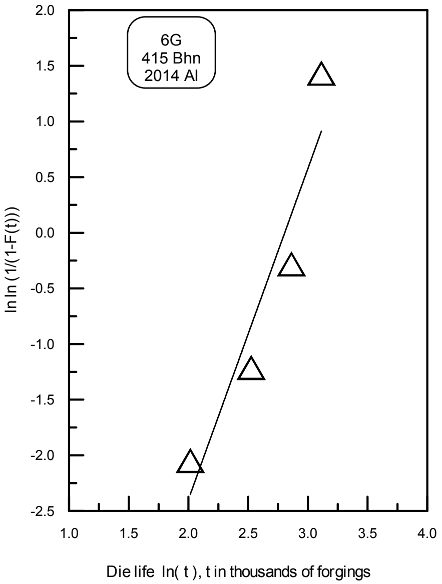

Figure 8 Weibull distribution of die life made of 6G in forging a small part of normal complexity from a 2014 A alloy.

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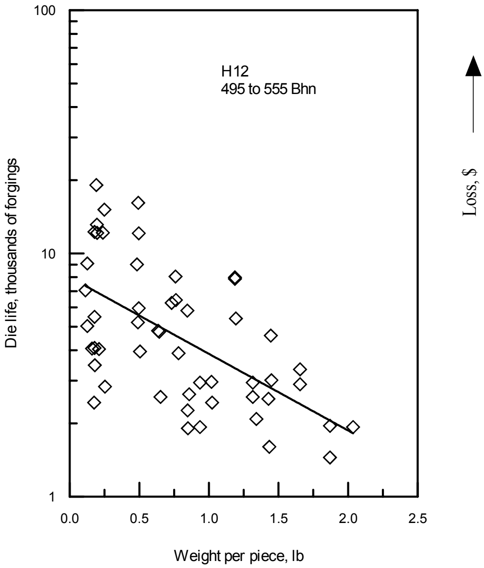

Figure 9 Effect of weight per piece of forging of a gas compressor blade on die life, each data point represent about 100 or more dies for specific design. Material of blades is 403 stainless steel.

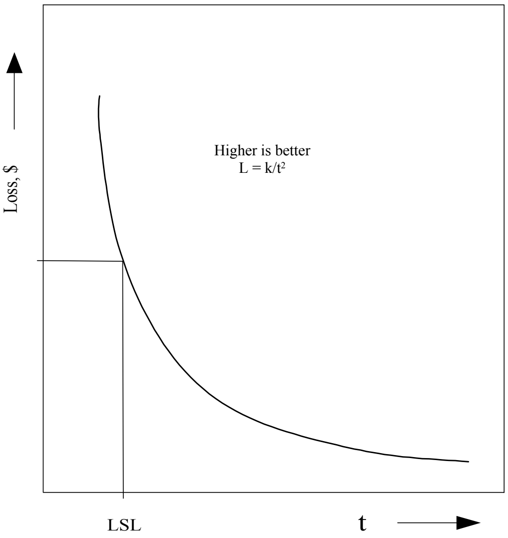

Figure 10 Taguchi's loss function for larger-the-better performance.

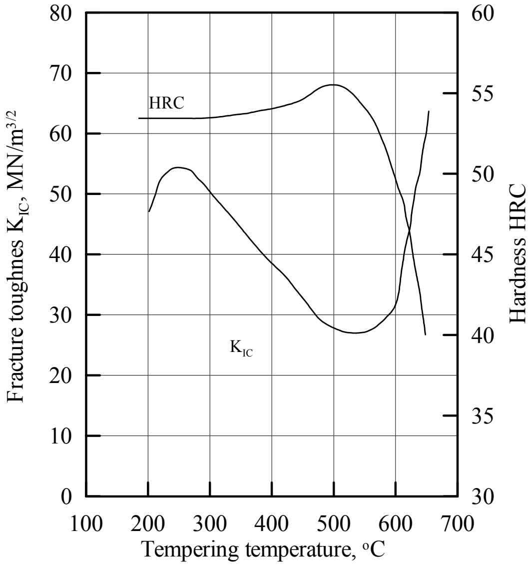

Figure 11 Effect of tempering on hardness (wear resistance) and fracture toughness (fatigue resistance) [10].

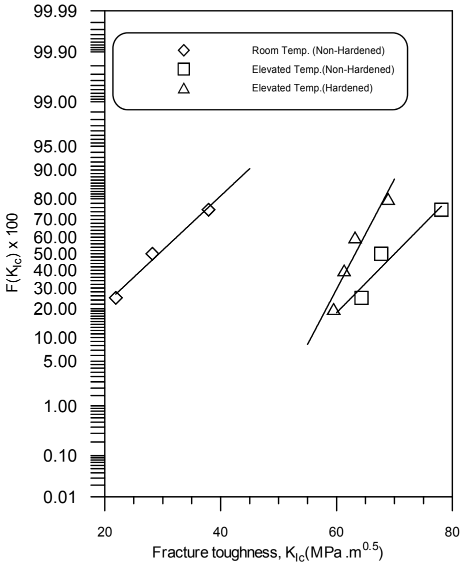

Figure 12 Distribution of fracture toughness of H13 steel.

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