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Reliability approach for lifetime prediction of the aluminum extrusion dies

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Abstract

This paper introduces a probabilistic approach for predicting the lifetime of extrusion dies using a structural reliability method known as stress-strength interference. In our investigation, we have integrated the assessment of the die's cycle life by following behavioral and rheological law. The approach relies on estimating the reliability index through a combination of a behavioral model and a reliability analysis of the hot extrusion process. Subsequently, the reliability analysis is conducted using a mechanical model to depict the most likely failure conditions. In this regard, the rheological law of Hansel & Spittel emerges as the most suitable choice, as it incorporates the mechanical properties of the materials employed in the fabrication of hot tools. The proposed mechano-reliability approach enables us to estimate reliability and its sensitivity by adjusting the parameters controlling the input process in die formation. Numerous scenarios involving extrusion dies were considered. The results demonstrate that temperature's impact on the die during the extrusion process is manifested through fatigue and damage parameters, as well as the first equivalent strain, which affect the evolution of the reliability index β and subsequently enhance the number of billets extruded.

1. Introduction

In a world characterized by rapid changes and significant technical advancements, the global aluminum extrusion market has seen considerable growth. In the realm of extruded aluminum manufacturing, particularly related to our research paper, extrusion tools and molds have garnered significant attention due to their role in enhancing efficiency and reducing costs, encompassing material expenses, research expenditures, and manufacturing costs with thermal processing. Our research is dedicated to enhancing the quality of metals and controlling their properties to extend die life.

Die life is primarily determined by the number of billets extruded in relation to profile size requirements, making it a critical concern. Controlling die failure mechanisms, such as thermal fatigue and surface wear, is essential for achieving economically viable tool longevity. Additional load effects may also be caused by fatigue damage [1]. 70% of die-casting die failures are caused by thermal fatigue, one of the several failure modes. [2], stands out.

The user may choose material parameters, especially crack growth statistics, from a menu, which is a handy feature of the program. The kinetics of crack formation can be represented by a variety of models. [1]. Compared to other steels in its class, AISI H13 is a hot work tool steel containing 5% chromium and a higher than average amount of

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vanadium By virtue of its high hardenability, material chemical composition presented in Table.1 [3.4]. It exhibits a combination of desirable properties including toughness, strength, ductility, and thermal conductivity [5,6]. Consequently, H13 tool steel finds extensive applications in casting, extrusion, and forging processes. Its resistance to thermal fatigue cracking, a result of repeated heating and cooling cycles in hot working setups, is attributed to its hot hardness, which is synonymous with hot strength [7].

Table 1. H13 chemical composition

Element	C	Si	Mn	Cr	Mo	V
Wt %	0.39	0.99	0.4	5.23	1.34	0.95

The value of the first effective strain, which is a critical parameter that requires careful evaluation, is closely related to the effect of temperature on die life [8]. The most pronounced die wear occurs near the die bearing, posing a higher risk of die failure due to significant plastic deformation, elevated die temperature, and interface pressure [9]. During the hot extrusion cycle, especially under high-temperature and high-speed conditions, localized heating due to friction at the billet-tool interface results in a temperature increase close to the melting point, accompanied by high tension stress [10]. Improving and controlling scrap production and assessing its impact on product quality is dependent on variables related to extrusion temperature, time, ram speed, pressure, and die geometry [11].

Aluminum alloy 6063 with main chemical composition of 0.47% Si and 0.55% Mg is known to be one of the properties that influences the die's life during the extrusion process. This is due to the metal's quality, particularly when utilizing the secondary melting alloy especially from mixed scrap, which enhances the quality of the coefficient of friction's reduction. This raises the temperature, which in turn shortens the die's lifetime.

Several vital parameters, including equipment conditions, operating conditions, temperatures, pressures, and die quality, significantly influence the extrusion process. Despite diligent efforts by manufacturers, various challenges in the process still lead to product defects [12]. Many defects and wastage are linked to the choice of billet size for extrusion and involve factors such as surface quality, temperature, speed, die geometry, and weld joints. To mitigate these issues, it is imperative to maintain control over all relevant parameters, including extrusion billet size, cutter position, puller speed, die entry angle, conveyor roller surfaces, temperature, and speed [13].

In light of the aforementioned considerations and recent research on extrusion die behavior and defects, the primary objective of our research paper is to determine the reliability index by considering die material elements and their influencing factors. To achieve this goal, we have developed a model to analyze the behavior of the extrusion process by integrating mechanical reliability and key influencing factors. This has led to the development of a mechanical model that combines the rheological model with the damage model.

In the present work, a model is developed to analyze the behavior of the most essential tool (die) in the aluminum extrusion process by coupling mechanical reliability to obtain different key factors. This leads to the development of a mechanical model coupling the rheological model to the damage model to evaluate the reliability index β and determine the sensitivity of variations in the random values of the input parameters from the aluminum extrusion process. The probabilities of die failure can be predicted using the combined model, which is defined in terms of the reliability index β determined by the reliability simulations in PHIMECASoft® as a limit state function.

2.Failure Mode and Analysis of Extrusion Die

Die failure encompasses various wear factors, predominantly influenced by the material quality and temperatures experienced during extrusion processes. The die is responsible for forming the shape of the extrusion, and it is kept in place by the die holder/ring so that it does not collapse or fracture. The die backer is responsible for providing support for the die. The extrusion load is transferred from the die to the pressure ring, transferring the force to the press platen. This process prevents the bolster from deflecting and ensures the weight is correctly transferred. The complete die set, which includes the die ring and the bolster, is being held in the press by the die slide, it also withstands a high degree of stress based on AISI H13 material used, and its high properties to withstand stress and fatigue. [14,15], as illustrated in Fig 1.

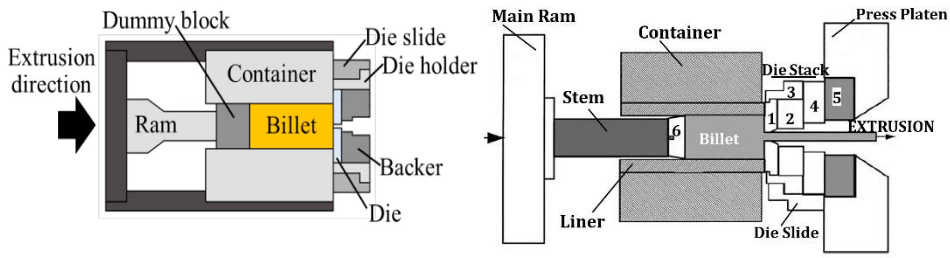


Fig. 1. Extrusion tooling used in hot extrusion. [10, 15],1, solid die; 2, backer; 3, die holder ; 4, bolster; 5, pressure pad; and 6, dummy block

Factors contributing to die wear involve abrupt temperature fluctuations and prolonged exposure to high temperatures, resulting in friction between the aluminum flow and the die's surface.

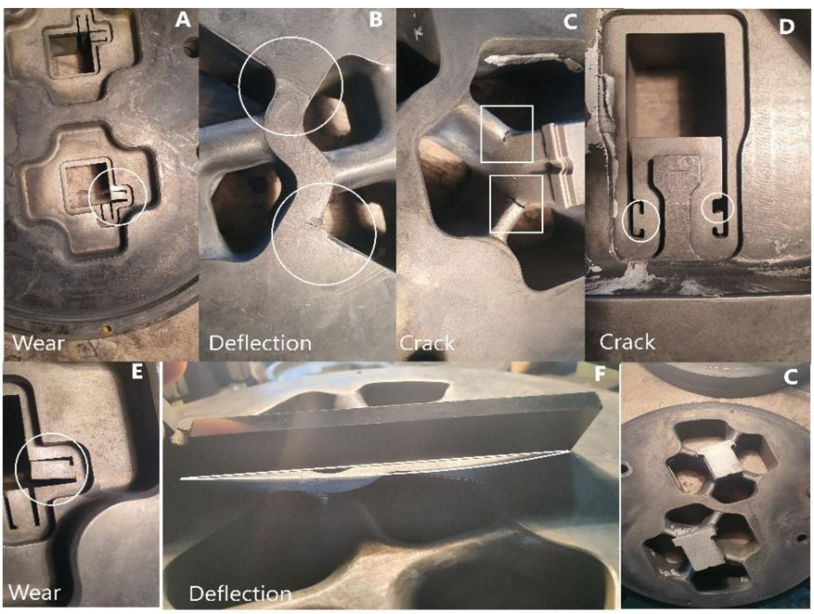


Fig. 2. The most important failures of aluminum extrusion dies

Among the factors mentioned, temperature and extrusion speed are of paramount importance. The speed of extrusion and the temperature increase at the die bearing are directly interrelated [15]. The extrusion die is susceptible to various categories of defects, with the most influential ones being those that are irreparable, including cracking, deflection, friction, and wear. Fig 2 illustrates some of these defects: (C, D) depict cracking in its advanced stages, while (B, F) illustrate deflection, and (A, E) showcase wear. Each of these defects contributes to a damage model in hot extrusion. A statistical examination of the primary types of die failure and their subcategories, as well as a greater understanding of die failure modes and processes, was conducted by AFM ARIF [16]. Indeed, the presence of various irreversible effects like wear, deflection, and cracks in a damaged die underscores the need to establish a reliability index and conduct a statistical analysis. This analytical approach is essential for pinpointing the pivotal factors that impact the cycle life of the die.

3.Model Identification

3.1 Basic Equations

As a general rule, it is important to note that cracks are often found in dies and extruders as a result of metal alloy die manufacturing processes. These cracks are usually about 0.01 mm deep during processes such as surface hardening of the bearing zone [17].

The increase in crack intensity, influenced by various material properties, results in heightened stress levels. This, in turn, accelerates crack growth at a certain rate. When the material is subjected to a specific stress intensity factor K for a given number of extrusions ΔN, the fracture length is accelerated and experiences a notable increase represented by the parameter 'a.' The rate of crack growth acceleration is determined by the changing property of interest within a strain resistance range, [18] expressed as the ratio Δa/ΔN. Consequently, we present the rate of acceleration of crack length, denoted as da/dN.

$$\frac{da}{DN} = C(\Delta K)^m \tag{1}$$

Constants unique to the material and environment under consideration are the factors C and m. In the case of the extrusion die steel.

3.2 Lifetime determination

By substituting the definitions of maximum and minimum stress into the stress range formula, we can derive a valuable alternative definition of the stress range:

$$\Delta K = \alpha \Delta\sigma\sqrt{\pi a} \tag{2}$$

Here, α represents the crack geometry factor. In general cases, the rate of propagation of a given crack under constant amplitude loading depends on several factors, including the duration of the extrusion cycle, the end stresses of the fatigue cycle (σ_max, σ_min), and the length of the crack. In simpler scenarios where the similarity condition is met, the concept of stress intensity factor allows us to consider the two principal components by utilizing the range of stress intensity factor. This is because the extrusion cycle commences with the minimum load (Δσ = σ_max - σ_min) = σ_max.

By substituting Equation 2 into Equation 1 and integrating it, we can determine the total number of extrusions allowed before reaching the end of the fatigue life. The fatigue life (Nf) was determined by the number of cycles until fracture failure [19].

$$Nf = \frac{(a_0)^{1-\frac{m}{2}} - (a_c)^{1-m/2}}{C(\frac{m}{2}-1)\alpha^m \pi^{m/2} {\sigma_{max}}^m} \tag{3}$$

Considering that H13 tool steel belongs to the category of ultrahigh strength steel, it is possible to determine the values of C and m for this type of steel by referring to standard sources. As previously mentioned, heat-treated and surface-hardened H13 steel has preexisting cracks (a0) that fall within a range of 0.05 to 0.1 mm. It is possible to set the geometry factor (alpha) value at 1.12 if the kind of fracture is an edge crack [17].

The equation alpha = f(a/w) is a function of the normalized crack length (a/w) and serves to eliminate surface tensile stresses. Using mode-I stress intensity factor according to its typical definition, while disregarding the finite-size factor f(a/W), and recognizing that the crack becomes unstable (a=ac) when KI = KIC, we can derive the following relationship [7].

$$a_c = \frac{1}{\pi}\left(\frac{K_{IC}}{\alpha\sigma_{max}}\right)^2 \tag{4}$$

The behavior of the production system is governed by a mathematical law that describes the required deformations needed to shape a billet into a profile with the desired dimensions and shape. In the context of extrusion, the most suitable choice is the rheological law developed by Hansel & Spittel. The Hansel-Spittel model was selected due to its strong support for establishing a simple connection between variables such as strain, strain rate, and temperature. This enables the modelling of flow stress by considering the strain's dependence in accordance with the rheological law parameters [20,21]. It has been integrated into many alloys [22,23,]. The modeling of behavior characterized by Hansel & Spittel's law has been seamlessly integrated into FORG shaping calculation codes.

$$\sigma_{max} = Ae^{m_1 T} T^{m_9} \varepsilon^{m_2} e^{m_4/\varepsilon} (1+\varepsilon)^{m_5 T} e^{m_7 \varepsilon} \dot{\varepsilon}^{m_3} \dot{\varepsilon}^{m_8 T} \tag{5}$$

Most referenced material has null values for parameters m_5 to m_9. Thus, it is possible therefore simplify the equation like this (equation 6).

$$\sigma_{max} = Ae^{m_1 T} \varepsilon^{m_2} e^{m_4/\varepsilon} \dot{\varepsilon}^{m_3} \tag{6}$$

In the given context, A represents the material's cohesion, T denotes the die temperature, and m_1 signifies the material's sensitivity to temperature. Additionally, m_2 and m_4 dictate the material's sensitivity to tension, while m_3 is contingent upon the material's sensitivity to the strain rate. Equation (3) is employed to substitute the term a_c.

$$Nf = \frac{(a_0)^{1-\frac{m}{2}} - \left(\frac{1}{\pi}\left(\frac{K_{IC}}{\alpha(Ae^{m_1 T}\varepsilon^{m_2} e^{m_4/\varepsilon}\dot{\varepsilon}^{m_3})}\right)^2\right)^{1-m/2}}{C(\frac{m}{2}-1)\alpha^m \pi^{m/2} {\sigma_{max}}^m} \tag{7}$$

The reliable geometric mechanical model is derived from the following equation (Equation 8). By combining the material model based on Hansel-Spittel with the mechanical model for lifespan analysis, we have developed a comprehensive mechanistic model for conducting reliability analyses.

$$Nf = \frac{(a_0)^{1-\frac{m}{2}} - \left(\frac{1}{\pi}\left(\frac{K_{IC}}{\alpha(Ae^{m_1T}\varepsilon^{m_2}e^{m_4/\varepsilon}\dot{\varepsilon}^{m_3})}\right)^2\right)^{1-m/2}}{C(\frac{m}{2}-1)\alpha^m\pi^{m/2}(Ae^{m_1T}\varepsilon^{m_2}e^{m_4/\varepsilon}\dot{\varepsilon}^{m_3})^m} \quad (8)$$

Lemaître and Chaboche are modelled the damage expressed as a function of n/Nf is: (Equation 9) [21, 24].

$$D = 1 - \left[1 - \left(\frac{n}{Nf}\right)^{\frac{1}{1-\alpha}}\right]^{\frac{1}{\beta+1}} \quad (9)$$

Where α is given by:

$$\alpha(\sigma_{max}, \bar{\sigma}) = 1 - a\left(\frac{\sigma_{max} - \sigma_I(\bar{\sigma})}{\sigma_u - \sigma_{max}}\right) \quad (10)$$

Equation 11, which describes a model correlating the Hansel–Spittel model, is thus the method by which the reliability engineering mechanical model is obtained [23]. (Equation 6) presents the mechanical model for reliability evaluations by combining it with the Lemaître–Chaboche model (equation 9) [21, 24].

$$D = 1 - \left[1 - \left(n/\frac{(a_0)^{1-\frac{m}{2}} - \left(\frac{1}{\pi}\left(\frac{K_{IC}}{\alpha(Ae^{m_1T}\varepsilon^{m_2}e^{m_4/\varepsilon}\dot{\varepsilon}^{m_3})}\right)^2\right)^{1-m/2}}{C(\frac{m}{2}-1)\alpha^m\pi^{m/2}(Ae^{m_1T}\varepsilon^{m_2}e^{m_4/\varepsilon}\dot{\varepsilon}^{m_3})^m}\right)^{1/1-1-a\left(\frac{\sigma_{max}-\sigma_I(\bar{\sigma})}{\sigma_u-\sigma_{max}}\right)}\right]^{1/\beta+1} \quad (11)$$

And then we construct failure steps from (equation 11) using the reliability statement with limit state functions to achieve the reliability index of the extrusion dies.

4. Die Reliability Assessment

When delving into the realm of reliability within mechanics, it is essential to first establish the context in which the proposed approach operates. Reliability encompasses both well-established methods, such as the implementation of statistical techniques for manufacturing control, and emerging methods that focus on failure and risk assessment. The latter approach stems from a relatively new philosophy that must be contextualized.

Our interest lies in methods primarily developed in the context of material and structural modeling. These methods allow mechanics to draw upon the wealth of knowledge derived from fields like probability theory and the experiences gained in the domain of aluminum extrusion die manufacturing.

Embracing a probabilistic approach, reliability methods in mechanics enable us to calculate the reliability index and sensitivity to failure. The success of the dimensioning process is validated by confirming an equality function, which relates the number of extruded billets (determining die lifetime, Nf) to critical damage (Dc) and the acting damage (D) as time-independent output variables. This approach allows us to describe the structural state through a single global random variable known as the margin, representing the elementary resistance-solicitation case.

The limit state function, denoted as G(Xi), quantifies the lifetime limit, presented as the variation between the number of billets extruded into the die and the required number for satisfactory performance (Equation 12).

$$G(X_i) = D_c - D(X_i) \tag{12}$$

according to the literature [26,27,28,29], Dc is defined by: $0.2 \leq D_c \leq 0.5$

The reliability index β is employed to describe the probability of failure, which is defined as the shortest distance in the middle of the origin and the domain of failure in the equivalent Gaussian space u_i.

$$\beta = minimise\sqrt{\sum_i u_i^2} \;\; subjected\ to G(X_i) \leq 0 \tag{13}$$

Ensuring the reliability of structures is a fundamental criterion when it comes to making choices in terms of design and maintenance. For each dimensioning rule, a failure scenario is described by means of a performance function $G(X_i) = R(X_i) - S(X_i)$

(X_i)being the basic random variables,$R(X_i)$the resistance and$S(X_i)$ the stres). $G(x_i) > 0$ indicates the state of safety $G(x_i) \leq 0$ while reflects the state of failure.

The objective is to evaluate a probability of failure, Pf that of being in a situation of failure. Within the framework of the first-order approximation, the calculation of Pf is equivalent to the evaluation of an indicator called the reliability index β, the probability of failure of the system can be expressed as:

$$P_f = p_r[G(X) \leq 0] = \Phi(-\beta) \tag{14}$$

The reliability software PHIMECASoft® can be applied to calculate the reliability index β and failure probability, where Φ(.) is the cumulative Gaussian probability function in the die environment and Pr[.] is the probability function, there are four primary factors that contribute to determining the reliability index. These factors include material rheological parameters, die temperature, fatigue damage parameters, and strain, all of which are expressed as random variables.

Table 2. Random elements and their associated variables for fatigue and damage

Type of var.	Symbol	Description	Probability distribution model	Mean value	Coefficient of variation (%)	Source
Fatigue param.	a_0	Constant material	Normal	0.01018	11.78	[17]
	β	Coefficient of the damage model	Determinist		2.94	[30]
	K_{IC}	fracture toughness	Normal	83.6	5.98	[17]
	C	Paris constants	Normal	3.13×10^{-7}	12.65	[31]
Damage param.	Dc	Critical damage	Normal	0.4	16.03	[26,27]

The uncertainties associated with the die are linked to various states, including geometry, loading, manufacturing, and service conditions. The results obtained are presented in Tables 2 and 3, which separately list the random variables and their corresponding variables. Table.2 contains the fatigue and damage parameters, while Table.3 presents the rheological law parameters for the selected random variables during the initial extrusion phase (as per Equation 11).

Table 3. Random elements and their associated variables of the rheological law

Type of var.	Symbol	Description	Probability distribution model	Mean value	Coefficient of variation (%)	Source
Rheological law Param.	A	Material coherence	Determinist	2821.246	1	baseFPD1. 3FORGE®
	m_1	Sensitivity of material to temperature	Determinist	0.0029	1	baseFPD1. 3FORGE®
	m_2	Sensitivity of material to stress	Determinist	-0.10727	1	baseFPD1. 3FORGE®
	m_3	Sensitivity of material according to strain rate	Determinist	0.13444	1	baseFPD1. 3FORGE®
	m_4	Sensitivity of material to strain	Determinist	-0.0462	1	baseFPD1. 3FORGE®
	ε	Equivalent strain resulting from the first extrusion cycle	Normal	0.04	10	baseFPD1. 3FORGE®
	T	Die temperature	Normal	485	9.27	[32]

5. Variable Sensitivities

Variable sensitivities are crucial in understanding the impact of random variables on die cycle life. In Fig 3, we can observe the variable sensitivity α^2 for an accepted reliability index value of 3.7273, with the number of extruded billets increased to 1157. There are five primary elements considered in regulating die cycle life: die temperature (T), die material rheological characteristics, equivalent plastic strain after one extrusion cycle, critical damage (Dc), and fatigue damage associated variables.

Among these factors, critical damage (Dc) stands out as the most significant, contributing to 79% of all global factors influencing die life. Paris constants, accounting for less than 7%, follows in importance. Equivalent plastic strain represents 4% of the impact, with the remaining percentage attributed to all other factors. This analysis underscores the critical role of Dc in die life determination, with other factors playing a comparatively lesser role.

The reliability assessment proceeds in two main steps:

- 1. Comparison of Time-Based Life Prediction Models: Initially, the assessment centers on comparing time-based life prediction models and evaluating the parameters within the applied model. This step aims to determine how sensitive the model is to uncertainties associated with the die.
- 2. Analysis of Parameter Sensitivity in the Mechanical Model: In the second step, the assessment delves into the sensitivity of the parameters within the mechanical model, taking into account both the data of the random variables and deterministic factors.

These steps collectively provide insights into the reliability of the die and its susceptibility to various uncertainties and factors.

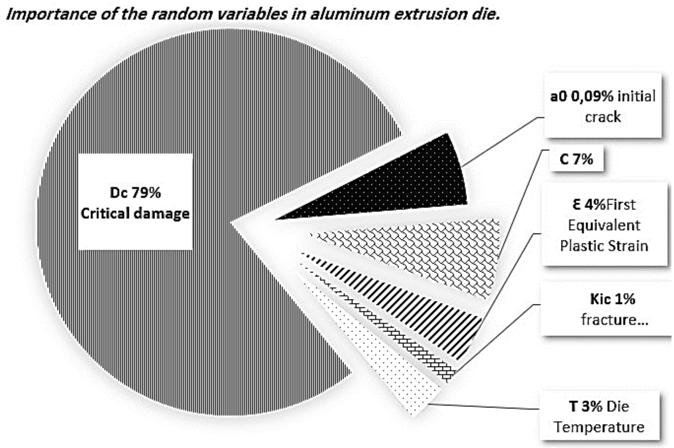
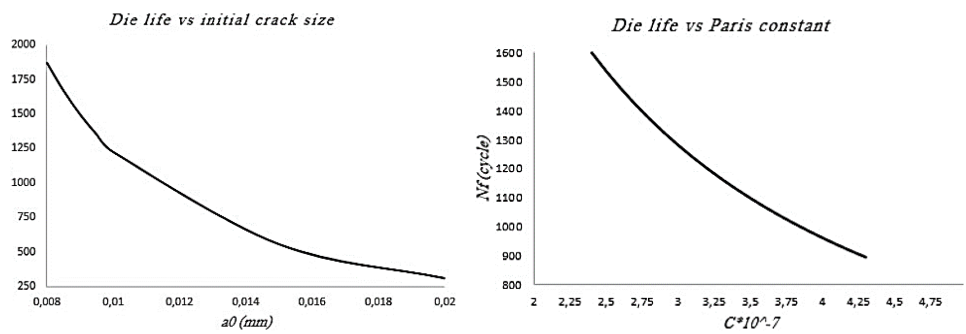


Fig. 3. The significance of the variables in a hot aluminum extrusion die (random variables and parameters founded on Table 2).

Fig.4 illustrates the sensitivity values for die life are evaluated with respect to a range of geometrical parameters, including fracture toughness, initial crack size, maximum stress, and material-specific constants, following the previously described method. Die temperature remains a critical variable in extrusion, as it can be significantly affected during the extrusion process. To minimize uncertainties in the work described, meticulous care should be exercised when selecting material parameters and the mechanical model that governs die life. It is noteworthy that, for a reliability index (β) value of 3.72, there is a noteworthy observation regarding the cycle life number. This observation underscores the significance of managing die temperature and the careful selection of material parameters and mechanical models to ensure desired reliability levels in the extrusion process.

The impact of temperature on the die during the extrusion process is depicted in Fig 5. These figures are correlated with the value of the reliability index and the cycle life achieved under specific conditions. In this analysis, a 15% variation in fatigue parameters and a 10% variation in damage parameters were considered.



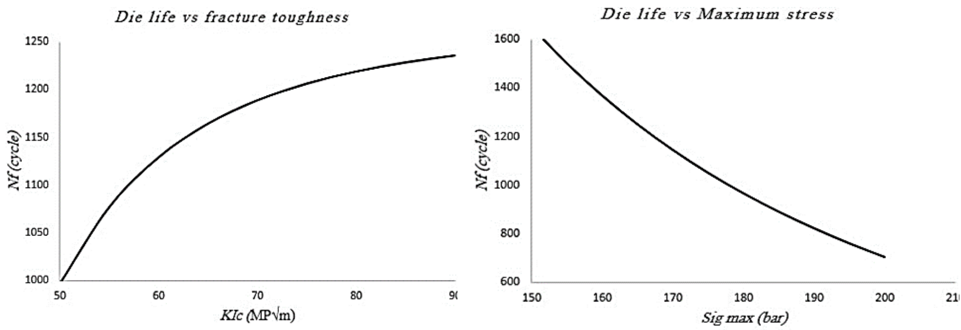


Fig. 4. Variation of die life against geometrical parameters

Additionally, the first equivalent strain was increased from 0.06 by a coefficient variation of 10% in the die temperature, which was maintained at 511°C. These findings provide valuable insights into how changes in temperature, fatigue parameters, and damage parameters can affect the reliability index and cycle life of the die during extrusion.

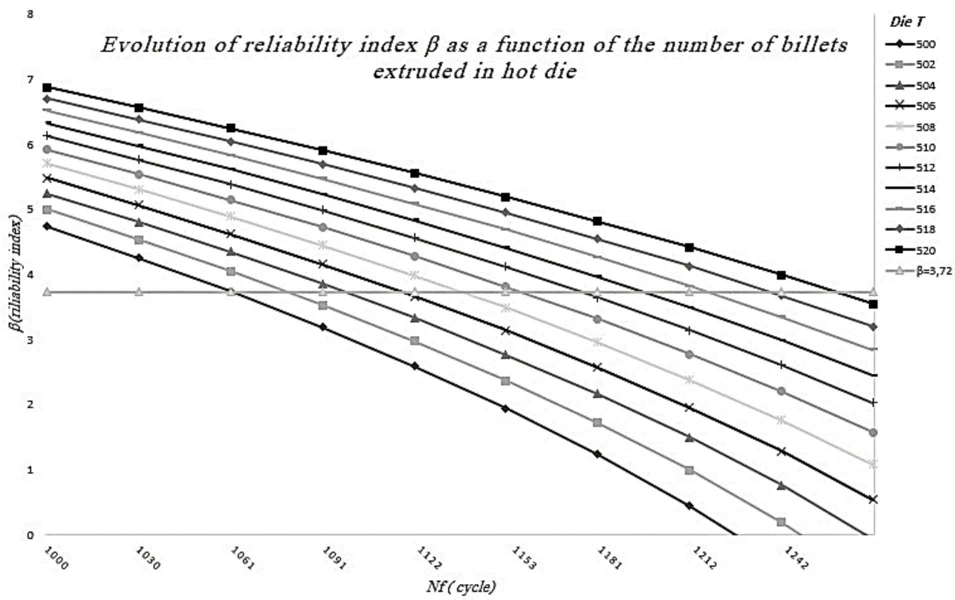


Fig. 5. Evolution of reliability index β as a function of the number of billets extruded in hot die

The analysis presented in Fig 6 demonstrates the evolution of the reliability index (β) at a level of 3.72. It's noteworthy that under these conditions, the cycle number of extruded billets increases to 1157 pushes when the die temperature is maintained at 511.11°C. This result represents a favorable average of the key parameters, indicating improved die performance and a longer operational lifespan for extrusion processes at this temperature.

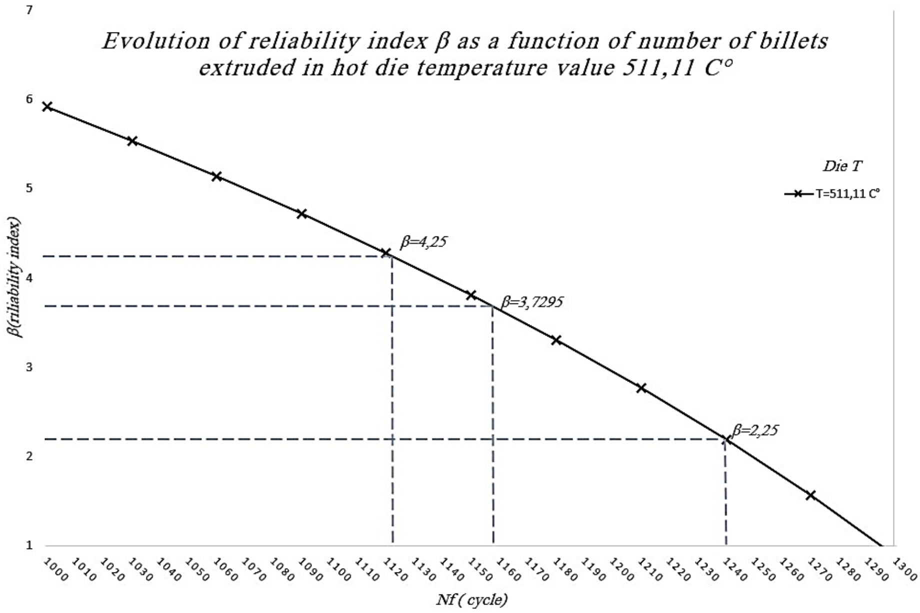


Fig. 6. Evolution of reliability index β as a function of the number of billets extruded in hot die temperature value T=511.11°C

6. Conclusions

A mechanical engineering model that aims to prolong the life of extrusion dies has been successfully constructed using the probabilistic methodology provided, based on the Paris and rheological laws. By considering various geometrical and material characteristics, this model has allowed us to improve the die reliability significantly. However, several factors affect an extrusion die's reliability index, with temperature and equivalent strain notably significant in producing damage areas, particularly fatigue crack propagation. Considering the model's parameter uncertainties is crucial for an in-depth reliability evaluation. The complete analysis shown in Figs. 5 and 6 shows that temperature, first equivalent strain, and model parameters have a more significant impact on die safety than differences in other components and geometric precision. The developed mechanical model offers quantitative instructions that relate important extrusion factors to cycles before the necessity for die replacement or maintenance, as indicated by the limited stat. Die material fatigue parameters, rheological law parameters, and other damage parameters are mapped to estimate longevity. By combining simulations with the reliability index, we believe it will be possible to predict operating limits, giving die designers an essential direction for extending the life of extrusion dies.

The study examined the probabilistic behavior of solid and hollow die failures in commercial aluminum extrusion based on its material, The aluminum extrusion industry has benefited from the data-driven insights that have been gained to boost productivity and competitiveness. These results imply that careful parameter management and adjustment in accordance with service and operational conditions can lead to optimal die life. This strategy will reduce possible sources of failure and damage while improving the extrusion processes' reliability and productivity. The extrusion process and die mechanics including thermal alignment, process control, extrusion metallurgy, quenching, and more have been covered from an operational and best practices perspective.

To sum up, a mechanical engineering model that aims to prolong the life of extrusion dies has been effectively constructed using the probabilistic methodology that has been described. The key focus is demonstrating tangible ways the predictive model facilitates actively modifying and improving the parameters in the mechanical model and probabilistic study using PHIMECASoft®. The model accounts for several geometrical and material characteristics, allowing us to improve significantly die reliability. In practical terms, these findings suggest that achieving optimal die performance and longevity can be achieved by carefully managing and adjusting parameters in accordance with service and operational conditions. This approach will help enhance the reliability and efficiency of extrusion processes to minimize potential sources of damage and failure.

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