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Evaluating Die Life in High-Pressure Die Casting: Correlating Temperature Dynamics and Durability through Altair Inspire Cast and SIMSOLID

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A B S T R A C T

This paper explores the efficiency of high-pressure die casting (HPDC) in producing complex geometries while focusing on fatigue patterns and failure points in dies subjected to repeated thermal stress. An energy-based semi-empirical model is proposed to predict fatigue life, integrating mean stress, stress amplitudes, and strain through finite element analysis (FEA). The study includes experimental characterization of die temperature profiles during HPDC, along with statistical correlation studies that connect temperature dynamics to durability metrics. Numerical simulations using Altair's Inspire Cast and SIMSOLID analyze the die's thermal behavior and predict temperature distributions, providing valuable insights into the conditions leading to fatigue failure. Additionally, a fatigue analysis of an AISI H11 tool steel component is presented, revealing a clear relationship between the number of cycles and the accumulation of fatigue damage, highlighting the importance of thorough evaluations in the design process to enhance reliability and performance. Overall, this research aims to contribute to improved understanding and optimization of die life in HPDC applications, ultimately ensuring the safety and efficiency of manufactured components.

1. INTRODUCTION

High-pressure die casting (HPDC) is a pivotal manufacturing process for producing complex metal components with high precision and efficiency. In HPDC, molten metal is injected into a steel mold cavity under high pressure to form desired shapes. This method is preferred in industries such as automotive, aerospace, and consumer electronics due to its productivity and cost-effectiveness. However, a major challenge is the limited lifespan of the die used, which suffers from gradual deterioration due to repeated thermal cycling and mechanical stresses. Understanding and predicting factors affecting die durability are crucial for optimizing the process parameters, improving die design, and extending die lifespan. This research investigates the relationship between die temperature dynamics and durability in HPDC of aluminum alloys. By characterizing die temperature profiles during casting operations and analyzing their correlation with durability metrics, predictive models for die life based on temperature dynamics are developed. Numerical simulations using FEA software, including Altair's Inspire Cast and SIMSOLID, model thermal behavior and predict temperature distributions under different conditions, providing insights into the thermal stresses experienced by dies and their impact on durability. The automotive industry's global focus on reducing weight has increased interest in casting structural aluminum components. High pressure die casting (HPDC) is preferred for this task because it allows us to produce large quantities of parts with complex designs, tight tolerances and consistent surface quality. Over the years, aluminum alloys have been refined to achieve the mechanical properties needed for strong and high-performance components.

High-pressure die casting (HPDC) is a widely utilized manufacturing process for producing complex metal components with high precision and efficiency. In HPDC, molten metal is injected at high pressure into a steel mold cavity to form the desired shape. Casting processes such as low and high pressure die casting is used widely to make the wheels. Forming processes such as forging, extrusion etc. are also being used for making the wheels [1]. This process offers significant advantages in terms of productivity and cost-effectiveness, making it a preferred choice in various industries such as automotive, aerospace, and consumer electronics. However, one critical challenge in HPDC is the limited lifespan of the die cast used in the process. The repeated thermal cycling and mechanical stresses experienced by the dies during casting operations lead to gradual deterioration and eventual failure. Understanding and predicting the factors influencing die durability is crucial for optimizing process parameters, improving die design, and extending the operational lifespan of dies. This research aims to investigate the relationship between die temperature dynamics and die durability in HPDC of aluminum alloys. By characterizing the temperature profiles of the dies during casting operations and analyzing their correlation with durability metrics, this study seeks to develop predictive models for estimating die life based on die temperature dynamics. Furthermore, numerical simulations using finite element analysis (FEA) software, such as Altair's Inspire Cast and SIMSOLID, will be performed to model the thermal behavior of the dies and predict temperature distributions under different operating conditions. These simulations will provide valuable insights into the thermal stresses experienced by the dies during casting operations and their impact on die durability.

High-pressure die casting (HPDC) stands out as a key process in manufacturing, leveraging high-pressure injection of molten metal at a very high velocity into molds to produce components renowned for their strength, precision, and dimensional accuracy. This method finds extensive application in industries like aerospace and automotive [2-4]. In high-pressure die casting (HPDC) operations, various stages, including chamber filling, solidification, mold manipulation, part extraction, cooling, and die replacement—significantly impact time and cost considerations [5, 6]. High-pressure die casting (HPDC) is a pivotal manufacturing process for producing complex metal components with high precision and efficiency. In HPDC, molten metal is injected into a steel mold cavity under high pressure to create the desired shapes, making it particularly beneficial in industries such as automotive, aerospace, and consumer electronics due to its productivity and cost-effectiveness [7, 8]. The ability to produce large quantities of intricate designs with tight tolerances and consistent surface quality makes HPDC an attractive choice for mass production.

Despite its advantages, HPDC faces significant challenges, particularly the limited lifespan of the die used in the process. Repeated thermal cycling and mechanical stresses lead to gradual deterioration and eventual failure of the dies, which significantly impacts production efficiency and costs [9]. Research indicates that die durability is influenced by several factors, including die material, surface treatment, and cooling system design [10]. Understanding and predicting these factors are crucial for optimizing process parameters, improving die design, and extending the operational lifespan of dies. This research investigates the relationship between die temperature dynamics and durability in HPDC of aluminum alloys. By characterizing die temperature profiles during casting operations and analyzing their correlation with durability metrics, this study aims to develop predictive models for estimating die life based on temperature dynamics. Furthermore, numerical simulations using finite element analysis (FEA) software, such as Altair's Inspire Cast and SIMSOLID, will model the thermal behavior of the dies and predict temperature distributions under various operating conditions. These simulations will provide insights into the thermal stresses experienced by dies and their impact on durability, ultimately contributing to enhanced design strategies.

In addition, the automotive industry's increasing focus on weight reduction has intensified interest in casting structural aluminum components. The continuous refinement of aluminum alloys aims to achieve the mechanical properties necessary for producing strong, high-performance components [11]. Recent advancements in alloy development and processing techniques have further enhanced the potential of HPDC in meeting the demanding requirements of modern engineering applications [12]. High-pressure die casting (HPDC) is a critical manufacturing process utilized across various industries for producing complex metal components with remarkable precision and efficiency. The process involves injecting molten metal, typically aluminum or zinc alloys, into a steel mold cavity at high pressure. This method enables the production of intricate shapes that would be challenging or uneconomical to achieve through traditional manufacturing methods, such as machining or forging (Cortés et al., 2016; Mazzolani et al., 2020). The high-speed injection and solidification of the metal not only enhance productivity but also improve the surface finish and dimensional accuracy of the cast components, making HPDC particularly advantageous for mass production in sectors like automotive, aerospace, and consumer electronics [13]. Understanding and predicting the factors affecting die durability are essential for optimizing process parameters and improving die design. Previous studies have highlighted the importance of temperature management in prolonging life, as excessive thermal gradients can lead to thermal fatigue and cracking [14].

Furthermore, the automotive industry's increasing emphasis on lightweight structural components has intensified interest in the use of advanced aluminum alloys in HPDC. Continuous advancements in alloy development and processing techniques have led to significant improvements in the mechanical properties and performance of die-cast components, thereby expanding their application range [15]. The integration of innovative materials and manufacturing technologies positions HPDC as a vital process in the future of sustainable manufacturing, aligning with global trends toward energy efficiency and reduced environmental impact.

The importance of understanding die temperature dynamics cannot be overstated. Studies have shown that optimizing die temperature can enhance the overall performance and lifespan of the die, thus contributing to increased productivity and reduced manufacturing costs (Zhang et al., 2021). Advanced numerical simulations and modeling techniques, including finite element analysis (FEA), have become invaluable tools for predicting thermal behavior and optimizing die designs. Software such as Altair's Inspire Cast and SIMSOLID allows engineers to simulate various casting scenarios, providing insights into the thermal stresses experienced by the dies and informing strategies to mitigate wear [16].

In addition, the sustainability of the HPDC process is gaining attention in the context of global efforts to reduce environmental impact. The ability to recycle aluminum and other materials used in HPDC contributes to a more sustainable manufacturing paradigm. The efficient use of resources, combined with the potential for reduced energy consumption during production, aligns with the principles of green manufacturing [17]. The rapid injection and solidification not only enhance productivity but also significantly improves the surface finish and dimensional accuracy of the cast components, making HPDC particularly advantageous for mass production in sectors such as automotive, aerospace, and consumer electronics [18, 19]. The efficiency and cost-effectiveness of HPDC have led to its widespread adoption in industries where high-quality components are essential. For instance, in the automotive sector, the need for lightweight and structurally robust parts has driven the increased use of aluminum alloys, which offer favorable mechanical properties while contributing to weight reduction strategies aimed at improving fuel efficiency and lowering emissions [20].

Recent advancements in aluminum alloy development and processing techniques have further enhanced the performance of die-cast components, broadening their applicability in modern engineering [21]. Despite its numerous advantages, HPDC is not without its challenges. A significant concern is the limited lifespan of the dies used in the casting process. The repeated thermal cycling and mechanical stresses that dies endure during casting operations can lead to gradual deterioration and eventual failure, impacting production efficiency and escalating costs [22]. Research indicates that die durability is influenced by a multitude of factors, including die material, surface treatment, cooling system design, and particularly, temperature management [23]. Understanding and predicting these factors is crucial for optimizing process parameters, enhancing die design, and ultimately extending the operational lifespan of dies.

Furthermore, as the automotive industry continues to prioritize lightweight structural components, the importance of HPDC in this context cannot be overstated. The drive for innovation in alloy composition and processing techniques has resulted in aluminum alloys that meet the demanding mechanical property requirements for high-performance applications [24]. The integration of these advanced materials and manufacturing technologies positions HPDC as a vital process in the future of sustainable manufacturing, aligning with global trends toward energy efficiency and reduced environmental impact.

The critical role of die temperature dynamics in this process highlights the need for thorough investigation. Optimizing die temperature has been shown to enhance the performance and longevity of dies, ultimately contributing to increased productivity and reduced manufacturing costs [25]. Advanced numerical simulations and modeling techniques, including finite element analysis, are invaluable tools for predicting thermal behavior and optimizing die designs, allowing for a deeper understanding of the thermal stresses and their implications for wear [26]. Additionally, the sustainability of the HPDC process is gaining traction, particularly concerning global efforts to minimize environmental impact. The ability to recycle aluminum and other materials used in HPDC contributes to a more sustainable manufacturing paradigm, aligning with the principles of green manufacturing [27].

In comprehensive study, Smith and Jones delve into the complex phenomena of thermal fatigue that occur during die casting processes. They identify key mechanisms contributing to thermal fatigue, such as rapid temperature fluctuations, thermal gradients, and the resultant material stresses that can lead to microstructural changes and crack formation in the dies. The authors review various mitigation strategies, including optimized cooling systems, the use of advanced die materials with improved thermal properties, and surface treatments that enhance wear resistance. By implementing these strategies, manufacturers can significantly extend die life and improve the reliability of the casting process. The findings emphasize the critical role of thermal management in maintaining die integrity and reducing downtime in production [28]. Thompson and Lee present an innovative computational model that accurately simulates the thermal behavior of dies throughout the die casting process. Their model accounts for various factors influencing temperature distribution, including the heat transfer characteristics of the molten metal, the thermal conductivity of the die material, and the cooling mechanisms employed. The authors demonstrate how different casting parameters, such as injection speed and cooling rates, affect thermal gradients within the die, ultimately impacting its durability and lifespan. Through detailed simulations, the study provides valuable insights into optimizing die design and process conditions, thus facilitating better control over die performance and enhancing overall production efficiency [29]. In this pivotal paper, Nguyen and Zhao conduct a thorough life cycle assessment (LCA) of high-pressure die casting (HPDC) processes, evaluating their environmental impacts from raw material extraction to end-of-life disposal. The authors analyze various stages of the HPDC process, including energy consumption, emissions, and resource utilization, to identify key areas for improvement. They discuss potential strategies for reducing the carbon footprint of die casting operations, such as optimizing energy efficiency, incorporating recycled materials, and implementing cleaner production technologies. The results of this assessment highlight the importance of sustainability in manufacturing practices and provide a framework for future research aimed at enhancing the environmental performance of HPDC, aligning with global sustainability goals [30].

2. EXPLORATION

This study explores the workflow for setting up the HPDC process using Altair Inspire Cast, analyzing results, and predicting die life with Altair SIMSOLID. The goal is to predict die behavior under actual conditions through simulation-driven design environment. Altair Inspire Cast allows users to rapidly set up the casting process using predefined templates and with a five-step workflow. The model, as shown in Figure 1, shows the process setup which involves defining the cavity part, runner system, additional components, and HPDC curve for phase change, followed by running the simulation.

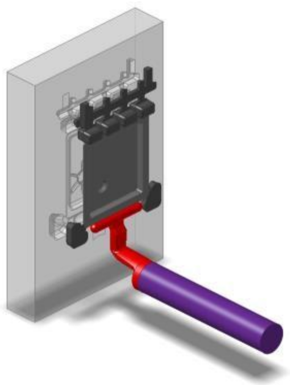

Fig. 1. HPDC Setup using Inspire Cast.

Figure 1 illustrates the model setup within Altair Inspire Cast GUI. A cycling approach is employed to simulate the realistic casting conditions over 50 cycles, achieving equilibrium for the mold temperature. This approach helps in identifying realistic conditions for mold temperature, as shown in Figure 2, which depicts that when using a static temperature of 150°C for mold for starting cycle, it reaches to a temperature of 349.95°C after a certain number of cycles and reached equilibrium.

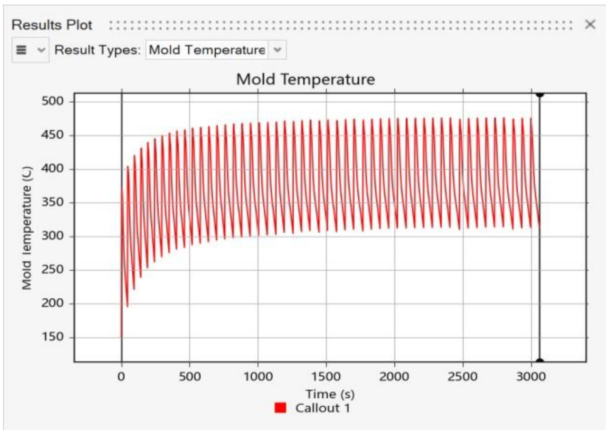

Fig. 2. Mold Temperature plot.

Figure 2 depicts the cycling plot between mold temperature and time for 50 cycles, the Mold equilibrium condition is shown in figure 3, at the initial time step for the specific cycle representing the mold starting temperature at 349.95 deg C, which helps in capturing the material filling in the cavity same as the realistic conditions for all the parts being manufactured.

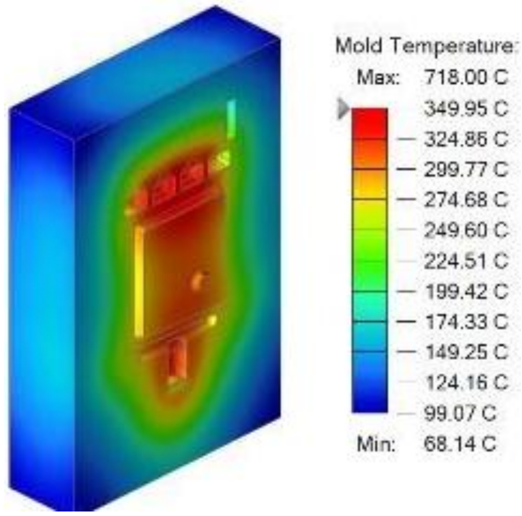

Fig. 3. Mold Temperature.

Using HyperView, temperature plots on all the nodes of the mold component can be exported to .csv file using the Query tool, as shown in figure 4 that can be used for mapping the mold temperature over the structural deck. This .csv data includes nodal ID, coordinates, and results contour, aiding in die life prediction.

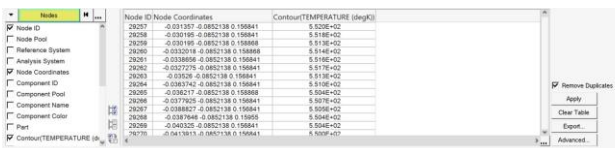

Fig. 4. HyperView Temperature plots.

3. INSPIRE CAST

The study begins by configuring the high-pressure die casting (HPDC) process using Altair Inspire Cast, a software tool designed for rapid and efficient casting setup that can be effectively used in early concept design stage. This configuration follows a structured five-step workflow, starting with the designation of the cavity part. This step involves creating a precise digital model of the component to be cast, capturing its exact shape and dimensions along with its internal structures. Next, the runner system is defined, which entails setting up the pathways—gates, runners, and channels—through which the molten metal will flow into the mold. Proper configuration of these elements is crucial for ensuring smooth metal flow and complete mold filling. The following step involves assigning additional components such as overflows, shot sleeves, molds and cooling channels, which are vital for managing the molten metal's flow and solidification while ensuring effective casting. The process continues with the definition of the HPDC curve either using the phase change approach while defining the multiple velocities or using the short sleeves inputs which define the curve based on time and velocity or displacement of piston and velocity, these reflect the thermal dynamics and phase changes relevant to the casting process. Finally, the simulation run is executed to visualize the entire casting process, providing valuable insights into metal flow dynamics, solidification patterns, and mold filling behavior. This simulation helps in identifying and address the potential issues for both filling, solidification and demolding conditions before the actual production cycle begins, ensuring a more efficient and reliable casting process.

3.1 Cycling approach

To accurately replicate the conditions encountered during continuous production runs, the study employs a cycling approach. This method involves running simulations for 50 cycles to achieve thermal equilibrium in the mold. By simulating multiple cycles, this approach captures the thermal stresses and temperature fluctuations that occur in real-world casting operations. It provides a realistic representation of how the die behaves under prolonged and repeated thermal cycles, offering insights into the thermal fatigue and stress conditions that the die will experience during actual production. This method ensures that the simulation results more closely mirror the real-world performance and durability of the die.

4. HPDC PROCESS ANALYSIS

4.1 Thermal behavior characterization

Data Analysis and Mapping: The thermal behavior of the mold is characterized by using data obtained from Inspire Cast simulations. This analysis involves a detailed examination of temperature distributions across the mold surface to identify areas of concern, such as hot spots where temperatures are significantly higher than the surrounding regions. By mapping these temperature distributions in SIMSOLID, potential risks related to thermal stress and failure can be assessed. Identifying and understanding these thermal patterns is essential for evaluating the die's performance and longevity under varying thermal conditions.

4.2 Temperature profile measurement

Advanced Thermal Monitoring: To gain a comprehensive understanding of die performance, advanced thermal monitoring techniques are employed to measure and record temperature profiles throughout the HPDC process. Techniques such as thermal imaging and thermocouples are utilized to capture real-time temperature data. Thermal imaging provides visual insights into the temperature distribution and variations on the die's surface, while thermocouples offer precise, quantitative temperature measurements at specific points. This real-time data is crucial for analyzing how the die reacts to thermal cycles and stresses, thereby informing adjustments to improve die design and process efficiency.

5. SIMSOLID

In this research, SIMSOLID is employed to carry out comprehensive finite element analysis (FEA) of the die's thermal and structural behavior. The analysis starts by modeling the thermal behavior of the die, with SIMSOLID simulating temperature distributions and heat flux under various operational conditions. This simulation offers valuable insights into how different regions of the die heat up and cool down throughout the casting process, highlighting temperature gradients and patterns of heat dissipation. Additionally, the software performs a heat transfer analysis to evaluate the efficiency of heat conduction through the die, pinpointing potential hotspots and areas at risk of excessive heat accumulation. A significant advantage of SIMSOLID is its ability to facilitate rapid analysis of complex geometries without the necessity for traditional meshing techniques, which greatly reduces both setup time and computational resources. The software's capabilities allowed the designers to create a safer and more reliable product, ultimately contributing to the overall satisfaction and safety of customers who rely on such products [31].

5.1 Thermal analysis

SIMSOLID conducts comprehensive simulations to analyze the thermal behavior of dies, calculating temperature distributions and heat flux under various operational conditions. This analysis is essential for understanding how different die regions heat and cool during casting cycles, highlighting hotspots that are susceptible to thermal fatigue. Additionally, the software performs a detailed heat transfer assessment to identify areas where excessive heat may build up, enabling adjustments to cooling channel designs for better thermal management. Following the thermal analysis, SIMSOLID evaluates the thermal stresses resulting from temperature fluctuations and their impact on the die's structural integrity, as well as assessing mechanical stresses caused by the high pressure of injected molten metal.

This combined stress analysis helps pinpoint critical stress points, allowing engineers to focus on areas that need reinforcement or redesign to enhance the die's durability. By optimizing both thermal and mechanical performance, SIMSOLID ultimately contributes to longer-lasting die and improved manufacturing efficiency. The insights gained from these simulations also facilitate proactive maintenance strategies, reducing downtime and costs associated with die failure.

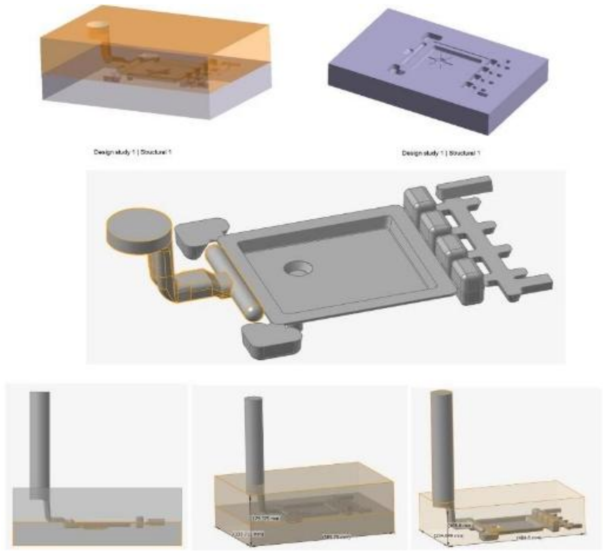

Fig. 5. Structural Design of Die.

The above figure 5 depicts a 3D model of a die or mold. To assess its performance and predict its lifespan, Simsolid was used to conduct structural analysis and failure analysis. By analyzing stress distribution, fatigue, contact pressures, and material properties, you can gain valuable insights into the die's behavior and identify potential areas for improvement.

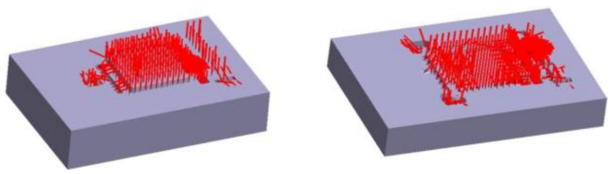

Fig. 6. Pressure mapping.

We applied varying pressures at different locations on the die as shown in figure 6, based on the data received from Inspire Cast. Specifically, the pressures applied were 2 MPa, 78 MPa, 80 MPa, 65 MPa, 50 MPa, and 58 MPa at their respective positions. In the initial step, the die was imported into SIMSOLID, where contacts were defined as bonded. The material selected for the analysis was steel, with its properties outlined below. Subsequently, the pressure was applied to the die, sourced from Inspire Cast. This pressure data was manually mapped onto the die according to the respective values obtained.

5.2 Material

H11, which is equivalent to 882, is a hot work toolsteel containing 5% chromium. It is specifically engineered for applications that demand exceptional toughness along with decent red hardness. This steel offers an added layer of safety for tools exposed to significant hammer impacts and is particularly effective for tools featuring deep recesses or sharp edges.

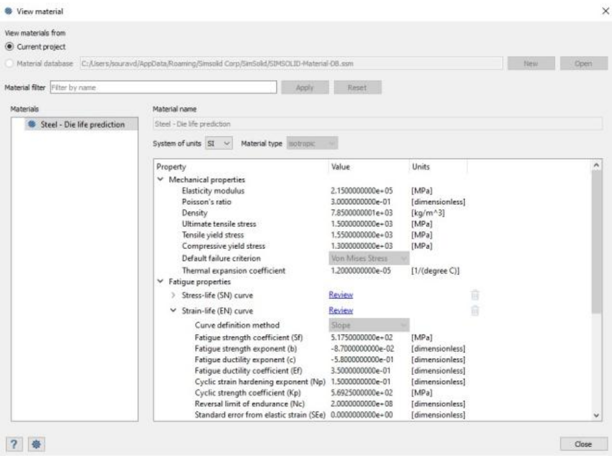

Fig. 7. AISI H11 Tool Steel Material Property of Steel used for Die life prediction.

Mechanical properties: The above figure 7 shows the material " AISI H11 Tool Steel " exhibits the following mechanical properties: an elasticity modulus of 215,000 MPa, a Poisson's ratio of 0.3, a density of 7.85 g/cm^3, an ultimate tensile stress of 1,500 MPa, a tensile yield stress of 1,550 MPa, a compressive yield stress of 1,300 MPa, and a default failure criterion of Von Mises stress. Additionally, the material has a thermal expansion coefficient of 1.2 x 10^-5 /°C. The fatigue strength coefficient (Sf) is 517.5 MPa, the fatigue strength exponent (b) is -0.087, the fatigue ductility exponent (c) is -0.58, the fatigue ductility coefficient (Ef) is 0.35, the cyclic strain hardening exponent (Np) is 0.15, the cyclic strength coefficient (Kp) is 569.25 MPa, the reversal limit of endurance (Nc) is 2 x 10^8, and the standard error from elastic strain (SEe) is 0.

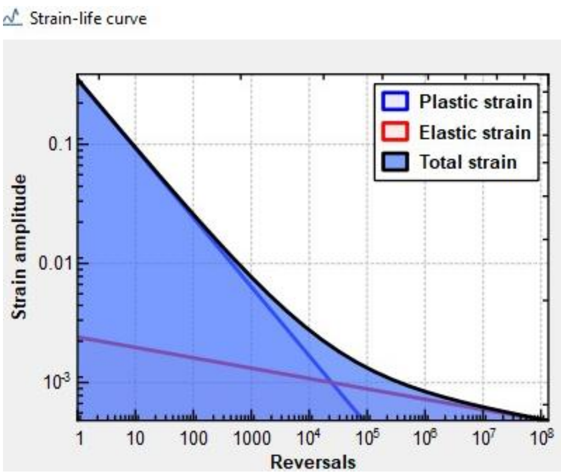

Fig. 8. EN curve.

The above figure 8 shows the Strain-Life (E-N) Approach. The E-N Approach uses plastic-elastic strain results to perform strain-life analysis and is a plot that illustrates the relationship between the strain amplitude and the number of cycles to failure for a material under cyclic loading conditions. The curve is typically divided into three regions: high-cycle fatigue, low cycle fatigue, and the fatigue limit. The high-cycle fatigue region is characterized by low strain amplitudes and many cycles to failure, while the low-cycle fatigue region is characterized by high strain amplitudes and a small number of cycles to failure. The fatigue limit is the point at which the curve becomes horizontal and represents the maximum strain amplitude that a material can withstand without failing under an infinite number of cycles. The figure also shows the components of the total strain, which is the sum of the elastic strain and the plastic strain.

5.3 Last time step

Figure 9 indicates the molten metal is being poured into a mold through a hole indicated by the orange arrow. The top and bottom surfaces of the mold will shape the cast part. The process involves pouring molten metal into a cavity to create a specific shape. We applied varying pressures at different locations on the die as earlier mentioned in figure 6, informed by the data obtained from Inspire Cast. Specifically, the pressures were distributed as follows: 2 MPa, 78 MPa, 80 MPa, 65 MPa, 50 MPa, and 58 MPa, each applied at their respective positions on the die.

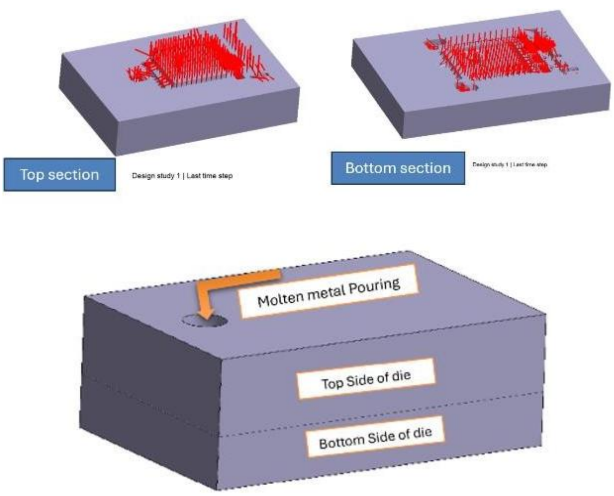

Fig. 9. Pressure mapping for last time step.

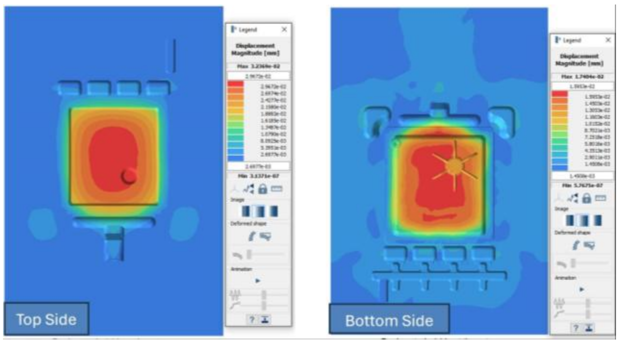

Fig. 10. Displacement magnitude from last-time step.

Figure 10 shows the outcomes of a finite element analysis (FEA) simulation, concentrating on the displacement magnitude at the final time step. It reports a maximum displacement of 0.032369 millimeters and a minimum of 0.00000031371 millimeters. The accompanying color scale represents the range of displacement values, with the deformed shape superimposed on the original for easy visual comparison. The bottom side similarly shows results from an FEA simulation, emphasizing the displacement magnitude at the last time step. In this case, the maximum displacement is 0.017404 millimeters, and the minimum is 0.00000057675 millimeters. Like the top figure, the color scale reflects displacement values, and the deformed shape is layered over the original for comparison purposes.

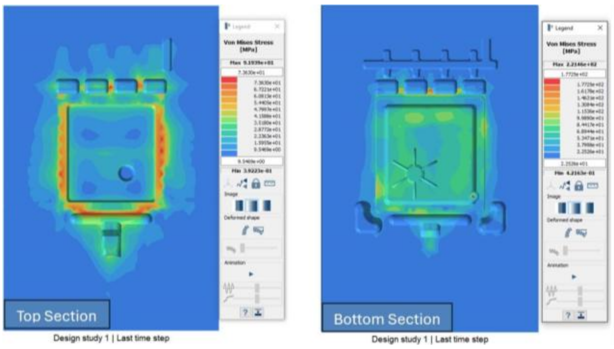

Fig. 11. Von Misses from last time step.

The above figure 11 shows the top section that displays the results of a finite element analysis (FEA) simulation, focusing on the von Mises stress distribution at the final time step. The maximum von Mises stress is 91.93 megapascals (MPa), while the minimum is 0.39 MPa. The color scale in the figure illustrates the range of von Mises stress, from minimum to maximum. The deformed shape of the object is superimposed on the original, providing a visual comparison.

The bottom section presents similar results from another FEA simulation, also detailing the von Mises stress distribution at the last time step. Again, the maximum von Mises stress is 221.46 MPa, with a minimum of 0.42163 MPa. The color scale reflects stress magnitude, and the deformed shape overlays the original shape for comparative analysis.

5.4 Thermal pressure mapping

5.4.1 Data acquisition

The temperature measurements were collected using a suitable temperature sensor or device. The sensor was likely placed at various points within the object or region of interest, and the corresponding coordinates (X, Y, and Z) were recorded.

5.4.2 Data processing

The collected temperature data was then processed using software like Inspire Cast and SIMSOLID. Data cleaning involves identifying and removing outliers or errors in the dataset to ensure accuracy. Following this, interpolation is performed to create a continuous temperature field from the discrete measurements, enhancing the resolution of the data. Finally, visualization techniques, such as heatmaps or contour plots, are employed to generate clear visual representations of the temperature distribution, making it easier to analyze and interpret the results.

5.4.3 Analysis

The processed temperature data can be analyzed to gain insights into the thermal behavior of the object or system. This might involve tasks such as identifying hot spots, cold spots, temperature gradients, and heat flow patterns.

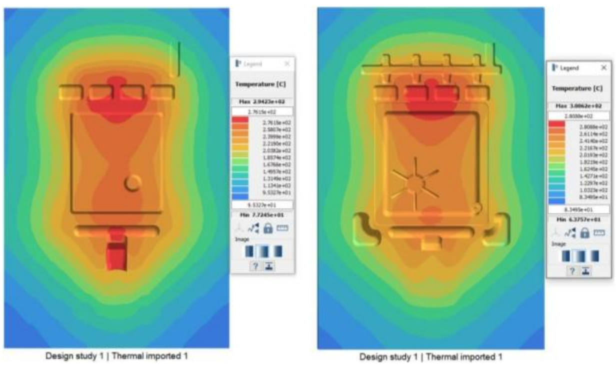

Fig. 12. Temperature mapping results at top section of the die.

Figure 12 shows the results of a thermal analysis performed on a part using Inspire Cast and then imported into Simsolid. The temperature distribution is visualized using a color scale, with warmer colors representing higher temperatures and cooler colors representing lower temperatures. The maximum temperature in the top section of the part is 294 degrees Celsius, while the minimum temperature is 77 degrees Celsius. In the bottom section, the maximum temperature is 300 degrees Celsius, and the minimum temperature is 63 degrees Celsius. These results provide valuable insights into the temperature distribution within the part, which can be used to assess potential thermal-related issues and optimize the design.

Figure 13 below shows the results of a thermal analysis performed using SIMSOLID. The highlighted text indicates that the average face temperature has been calculated after selecting a specific face on the component.

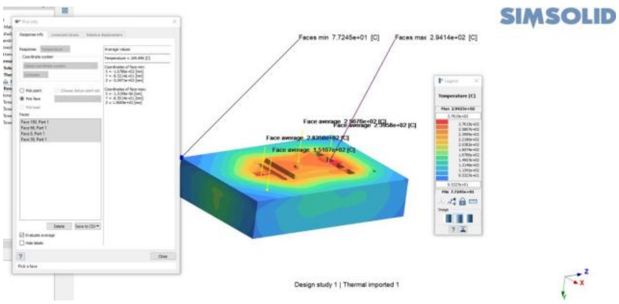

Fig. 13. Average face temperature.

It shows the minimum and maximum temperatures on the chosen face. The average temperature of faces 180, 66, 8, and 59 is 169.896°C, based on the thermal analysis results. This information helps us understand temperature distribution and identify potential hotspots or cold spots. It's useful for evaluating thermal performance and making design adjustments. The legend indicates temperature ranges represented by colors in the thermal map. Warmer colors mean higher temperatures, while cooler colors mean lower temperatures. The color pattern shows how temperature varies across the selected face, with hotspots and cold spots visible. By selecting different faces, you can analyze temperature distribution and identify areas with the highest or lowest temperatures. This helps understand the thermal behavior of the component and make design improvements to optimize its performance. Following the thermal analysis, SIMSOLID is used for stress analysis, evaluating both thermal and mechanical stresses. The software calculates the thermal stresses induced by temperature fluctuations, including the effects of thermal expansion and contraction on the die's structural integrity. Additionally, SIMSOLID assesses mechanical loads resulting from operational pressures, such as the force exerted by the injected molten metal, and their interaction with thermal stress. This combined stress analysis helps in identifying potential points of failure and vulnerabilities in the die.

5.5 First time step linked to last time step

Figure 14 shows the results of a finite element analysis (FEA) simulation of a rectangular structure with a circular cutout. The legend indicates the range of displacement magnitudes (1.1629e-10 mm to 2.047e-06 mm), with warmer colors representing larger displacements and cooler colors representing smaller displacements. The deformed shape of the structure is shown, with the color scale indicating the magnitude of displacement at each point.

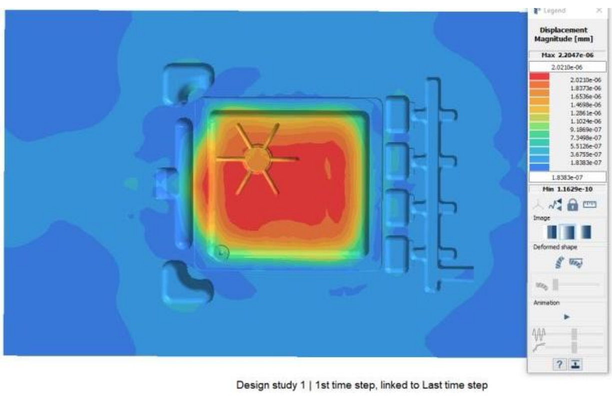

Fig. 14. Displacement achieved from First time step linked to last time step (bottom side/section).

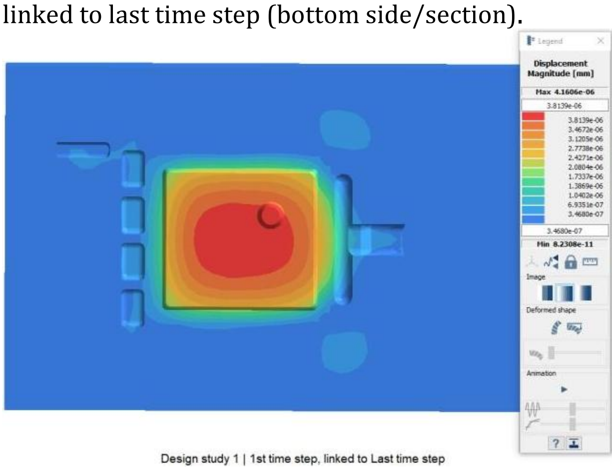

Fig. 15. Displacement achieved from First time step linked to last time step (top side/section).

Figure 15 shows the results of a finite element analysis (FEA) simulation of a rectangular structure with a circular cutout. The legend indicates the range of displacement magnitudes (8.2308e-11 mm to 4.1606e-06 mm), with warmer colors representing larger displacements and cooler colors representing smaller displacements. The deformed shape of the structure is shown, with the color scale indicating the magnitude of displacement at each point.

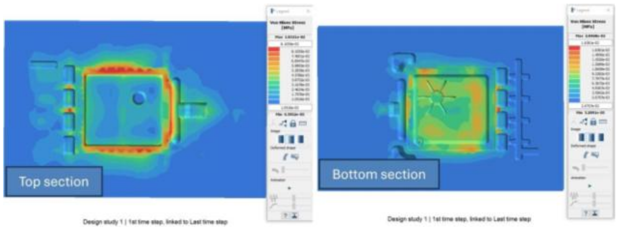

Fig. 16. Von Misses stress achieved from First time step linked to last time step (top and bottom side respectively).

The above figure 16 shows the results of a finite element analysis (FEA) simulation of a rectangular structure with a circular cutout and several smaller features. The legend indicates the range of von Mises stress magnitudes (1.0513e-03 MPa to 8.1055e-02 MPa), with warmer colors representing higher stresses and cooler colors representing smaller stresses. The deformed shape of the structure is shown, with the color scale indicating the magnitude of von Mises stress at each point.

The bottom section figure shows the results of a finite element analysis (FEA) simulation of a rectangular structure with a circular cutout. The legend indicates the range of von Mises stress magnitudes (2.3091e-05 MPa to 2.0468e-02 MPa), with warmer colors representing higher stresses and cooler colors representing smaller stresses. The deformed shape of the structure is shown, with the color scale indicating the magnitude of von Mises stress at each point.

5.6 Fatigue analysis using SIMSOLID

To predict fatigue life, results from SIMSOLID are utilized in an energy-based semi-empirical model that assesses the durability of the die across multiple casting cycles. This model integrates information on mean stress, stress amplitudes, and strain to estimate the number of cycles the die can withstand before failure. The software's thorough fatigue analysis evaluates stress cycles and their impact on material properties, providing valuable insights into the die's performance under realistic conditions. Fatigue analysis was performed using Altair's SIMSOLID for various cycle counts, including 500, 1,000, 10,000, and 100,000 cycles, aligned with the EN time curve analysis. Furthermore, SIMSOLID supports design optimization by allowing modifications to die parameters based on simulation results. This includes adjustments to aspects such as material thickness, cooling channel design, and mold geometry to enhance durability. The software also facilitates scenario testing, enabling the evaluation of different operational conditions and design changes to identify the most effective strategies for extending die life and improving performance.

5.7 EN time fatigue 500 cycles

The above figure 17 shows the maximum fatigue damage is 0.53428, representing 100% of the total damage sustained. The color scale in the figure represents the fatigue damage magnitude, ranging from 0 to 0.53428. The deformed shape of the structure overlaid on the original shape, allowing for a visual comparison of the deformation. The color scale in the figure would also visually represent the range of fatigue damage, with warmer colors indicating higher damage and cooler colors indicating lower damage. The deformed shape of the structure, overlaid with the color scale, would provide a visual representation of the fatigue damage distribution throughout the component.

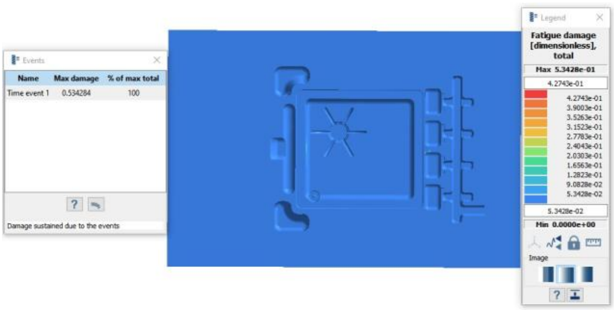

Fig. 17. Fatigue Damage on 500 cycles.

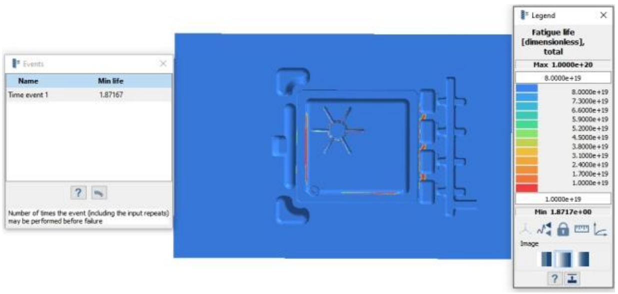

Fig. 18. Fatigue Life on 500 cycles.

Figure 18 shows the results of a finite element analysis (FEA) simulation of a die casting. The maximum minimum fatigue life is 10^20 cycles, while the minimum fatigue life is 1.8717 cycles. The color scale in the figures represents the distribution of minimum fatigue life across the die casting, with warmer colors indicating lower fatigue life and cooler colors indicating higher fatigue life. The deformed shape of the die casting is overlaid on the original shape, allowing for a visual comparison of the deformation. Additionally, the table on the left side of the figures provides a breakdown of fatigue life for different events, including the minimum life and the number of times the event can be performed before failure. This information can be used to identify critical areas of the die casting that are prone to fatigue failure and to assess the overall fatigue life of the component.

5.8 EN time fatigue 1000 cycles

Figure 19 shows the results of a finite element analysis (FEA) simulation of a rectangular structure with a circular cutout. The maximum fatigue damage is 1.06857, while the minimum fatigue damage is 0. The color scale in the figure represents the distribution of fatigue damage across the structure, ranging from 0 to 1.06857. The deformed shape of the structure is overlaid on the original shape, allowing for a visual comparison. Additionally, the table on the left side of the figure provides information about the fatigue damage caused by the only event, including the maximum damage sustained and the percentage of the total maximum damage.

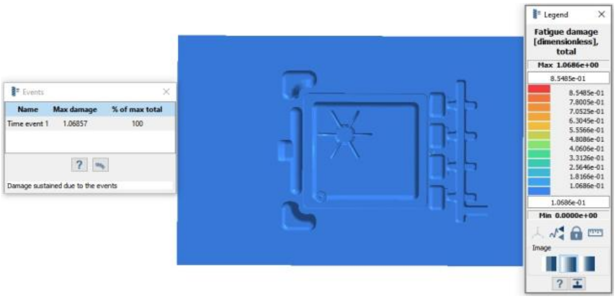

Fig. 19. Fatigue Damage on 1000 cycles.

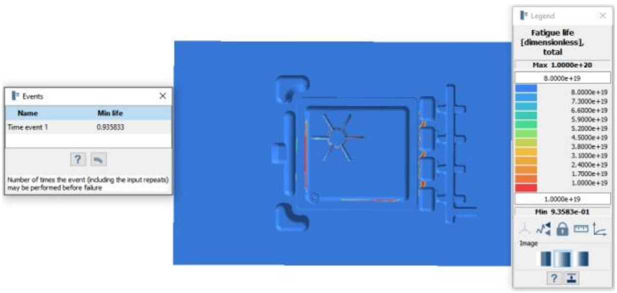

Fig. 20. Fatigue life on 1000 cycles.

The figure 20 indicates the part is expected to fail after 0.935833 cycles of a specific event, but it could potentially last up to 1.0000e+20 cycles. The actual lifespan will depend on the loading conditions. The part can withstand 1.0000e+19 cycles of the event before failing. Overall, the figure provides information about the part's fatigue life, including the minimum life, maximum life, and expected number of cycles before failure.

5.9 EN time fatigue 10,000 cycles

The figure 21 shows that a part has reached its maximum allowable fatigue damage, which means it is at risk of failure. The primary cause of this damage is a specific event called "Time event 1." The part has sustained 1.6666e-01 of fatigue damage, which is 100% of its maximum capacity.

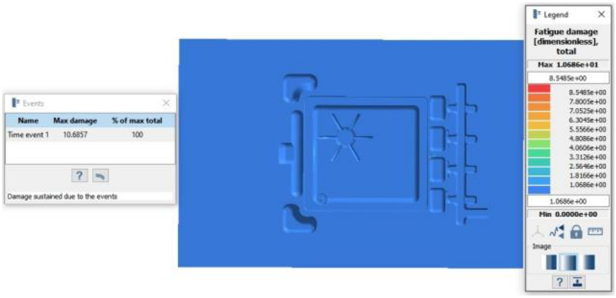

Fig. 21. Fatigue Damage on 10,000 cycles.

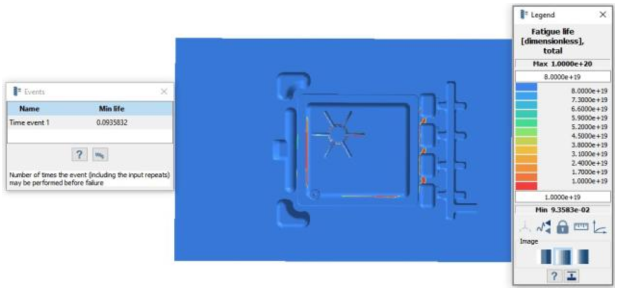

Fig. 22. Fatigue Life on 10,000 cycles.

Figure 22 depicts the results of a fatigue analysis for a design study, highlighting fatigue life, which measures the number of loading cycles it can endure before failure. The maximum fatigue life is shown as 8.0000e+20 cycles, while the minimum for time event 1 is 0.0935832 cycles, indicating that the die can withstand this specific loading condition only a fraction of a cycle before failing. The analysis also reveals that the event can occur 1.0000e+19 times before failure, suggesting the die is likely to fail during time event 1. However, it's important to note that these conclusions depend on the specific assumptions and parameters of the study, and a more complete understanding would require considering factors like material properties, manufacturing processes, and operational conditions.

5.10 EN time fatigue 50,000 cycles

Figure 23 presents the results of a fatigue analysis labeled as "Design Study 1 | EN Time fatigue 50000," indicating an evaluation based on the EN standard for 50,000 cycles. It includes a legend defining fatigue life as a dimensionless measure of how many cycles a component can withstand before failing. The maximum fatigue life is reported as 1.0000e+20. Each event or load case analyzed is named, with "Time event 1" showing a minimum fatigue life of 0.0187167 cycles, suggesting that the component may fail after only a few cycles under this condition. Although the number of times this event can occur before failure is not displayed, the figure visually represents fatigue life distribution across the component, with colors indicating different values. Overall, the analysis indicates a relatively low fatigue life for Time event 1, prompting the need for further evaluation to determine its suitability for the component's intended use. This interpretation serves as a preliminary assessment, and a more comprehensive analysis would be necessary for a complete understanding of the results.

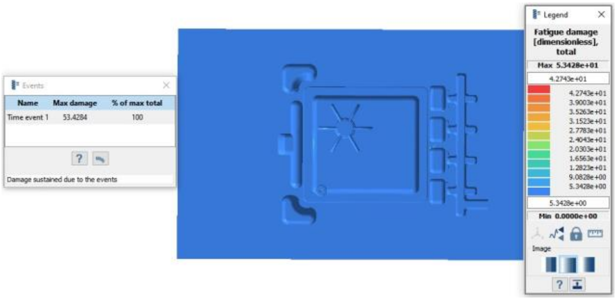

Fig. 23. Fatigue damage on 50,000 cycles.

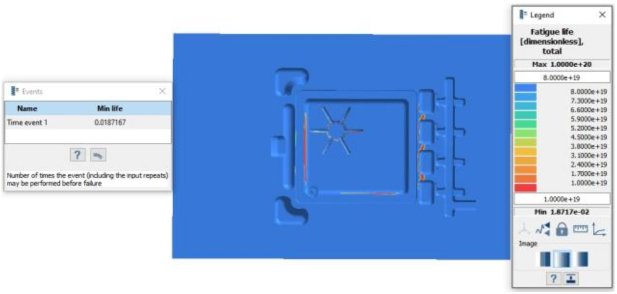

Fig. 24. Fatigue life on 50,000 cycles.

Figure 24 displays the results of a fatigue analysis titled "Design Study 1 | EN Time fatigue 50000," indicating that this is the first study based on the EN standard for an analysis covering 50,000 cycles. The legend defines fatigue damage as a dimensionless measure of the damage a component accumulates due to fatigue, with a maximum value of 5.3428e+01 noted in the analysis. Each event or load case analyzed is identified by name, with "Time event 1" showing a maximum damage of 53.4284. This event contributes 100% to the total fatigue damage, highlighting its critical role. The damage distribution across the component is likely visually represented, with colors indicating varying levels of fatigue damage.

Overall, the analysis suggests that Time event 1 is the most significant contributor to fatigue damage in the component. Further investigation would be necessary to assess whether this level of damage is acceptable for the component's intended application. This interpretation serves as a preliminary overview, and a more detailed analysis would be needed for a comprehensive understanding of the results.

5.11 EN time fatigue 100,000 cycles

An EN time fatigue analysis for 100,000 cycles is a technique used to predict the fatigue life of a part or component under cyclic loading. This analysis involves generating an EN curve that plots stress amplitude against the number of cycles to failure. By examining the EN curve for 100,000 cycles, engineers can estimate the remaining useful life of the part, identify potential failure mechanisms, and make informed design, manufacturing, and maintenance decisions. This analysis is essential for ensuring the reliability and safety of components across various industries, including aerospace, automotive, and manufacturing.

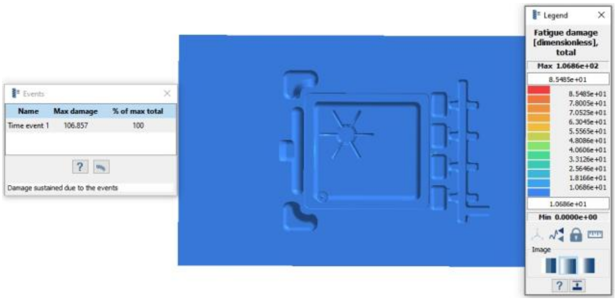

Fig. 25. Fatigue damage on 100,000 cycles.

Figure 25 presents the results of a fatigue analysis labeled "Design Study 1 | EN Time fatigue 100000," indicating the first study using the EN standard for a 100,000-cycle evaluation. It shows that fatigue damage, measured as a dimensionless value, has a maximum of 1.0686e+02. Each analyzed event is named, with "Time event 1" reporting a maximum damage of 106.857, which accounts for 100% of the total fatigue damage, highlighting its significance. The analysis likely includes a visual representation of fatigue damage distribution across the component, using colors to indicate different damage levels. Overall, the results suggest that Time event 1 is the main contributor to fatigue damage, necessitating further investigation to determine if this level is acceptable for the component's intended use. This overview serves as a preliminary interpretation, and a more detailed assessment would be needed for a comprehensive understanding.

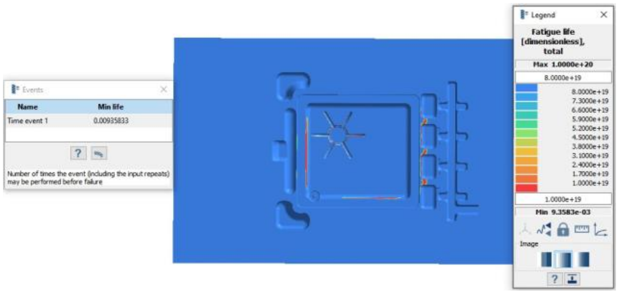

Fig. 26. Fatigue life on 100000 cycles.

The above figure 26 presents the findings of a fatigue analysis. It's the initial study employing the EN standard for an analysis exceeding 100,000 cycles. Fatigue life is defined as a dimensionless measure of a component's endurance before failure, with a maximum value of 1.0000e+20. The analysis includes events, particularly "Time event 1," which has a minimum fatigue life of 0.00935833 cycles, suggesting potential failure after a limited number of cycles under this load. While the figure probably includes a visual representation of fatigue life distribution across the component, using colors to denote varying fatigue life values.

Table 1 below shows the results of a fatigue analysis for a component made of AISI H11 tool steel, measuring 505.75 mm x 335.711 mm x 179.375 mm. The "100%" in the picture likely refers to the maximum fatigue damage that has occurred during the simulated event or time period. It indicates that the component has experienced its highest level of damage due to fatigue, which is often measured in terms of a dimensionless quantity. This value is likely used to assess the component's remaining life or to determine if it needs to be replaced or repaired to prevent failure. A value of 100% suggest that the component is approaching or has reached its critical damage threshold.

Table 1. Results of a fatigue analysis for a component made of AISI H11 tool steel, measuring 505.75 mm x 335.711 mm x 179.375 mm.

EN Cycle Count	Fatigue Damage (max)	Fatigue Life (min)
500	5.3428e-01	1.87167
1000	1.0686e+01	0.935833
10000	1.0686e+01	0.0935832
50000	5.3428e+01	0.0187167
100000	1.0686e+02	0.00935833

It outlines key data regarding maximum fatigue damage and minimum fatigue life for various cycle counts. For 500 cycles, the maximum fatigue damage is 5.3428e-01, with a minimum fatigue life of 1.87167 cycles. At 1,000 cycles, the maximum fatigue damage increases to 1.0686e+00, while the minimum fatigue life drops to 0.935833 cycles. For 10,000 cycles, maximum fatigue damage reaches 1.0686e+01, and the minimum fatigue life decreases to 0.0935832 cycles. At 50,000 cycles, maximum fatigue damage rises to 5.3428e+01, and the minimum fatigue life falls to 0.0187167 cycles. Finally, at 100,000 cycles, maximum fatigue damage is 1.0686e+02, with the minimum fatigue life declining to 0.00935833 cycles. Overall, these results indicate that as the number of cycles increases, maximum fatigue damage rises while minimum fatigue life decreases, suggesting that the component becomes increasingly susceptible to fatigue failure with higher cycle counts.

6. RESULTS AND DISCUSSION

The fatigue analysis results for the AISI H11 tool steel component reveals significant insights into its performance under cyclic loading. The data indicates that as the number of cycles increases, both maximum fatigue damage and minimum fatigue life show notable trends. For the lowest cycle count of 500, the maximum fatigue damage recorded is 5.3428e-01, accompanied by a minimum fatigue life of 1.87167 cycles. This suggests that even after a relatively small number of cycles, the component begins to experience considerable damage, indicating its vulnerability to fatigue under initial loading conditions. As the cycles increase to 1,000, maximum fatigue damage escalates to 1.0686e+00, while the minimum fatigue life decreases to 0.935833 cycles. This trend continues with 10,000 cycles, where maximum fatigue damage reaches 1.0686e+01 and the minimum fatigue life drops significantly to 0.0935832 cycles. Such a decline in fatigue life emphasizes the component's increasing susceptibility to failure as it is subjected to repetitive loads. At higher cycle counts, particularly at 50,000 and 100,000 cycles, the maximum fatigue damage further increases to 5.3428e+01 and 1.0686e+02, respectively, while the minimum fatigue life diminishes to 0.0187167 cycles and 0.00935833 cycles. This dramatic reduction in fatigue life suggests that the component is at high risk of failure under prolonged cyclic loading, reinforcing the necessity for careful design considerations in applications where such conditions are expected. Overall, the results indicate a clear correlation between increased cycle counts and the accumulation of fatigue damage, leading to reduced fatigue life. This finding underscores the importance of conducting thorough fatigue analyses during the design phase to ensure the reliability and safety of components in critical applications. Future studies may focus on exploring material enhancements or design modifications that could improve fatigue resistance and extend the useful life of such components.

7. CONCLUSIONS

The fatigue analysis of the AISI H11 tool steel component indicates a critical correlation between cycle count and fatigue damage accumulation. As cycle count increases, both maximum fatigue damage and minimum fatigue life exhibit concerning trends, highlighting the component's growing vulnerability to failure under cyclic loading. To ensure component reliability and safety, comprehensive fatigue evaluations are crucial during the design process. Future research should prioritize material improvements and design optimizations to enhance fatigue resistance and extend component lifespan. This study provides valuable insights for engineers and designers seeking to mitigate fatigue-related failures in critical applications.

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