MARMARA UNIVERSITY
FACULTY OF ENGINEERING

DESIGN AND ANALYSIS OF AN EXTRUSION DIE HAVING ROTATING DIE

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GRADUATION PROJECT REPORT

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Design and Analysıs of an Extrusion Die Having Rotating Die

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June, 2024 **Semih YILDIRIM**

CONTENT

ABSTRACT

This study investigates the design and analysis of a friction extrusion process with a rotating die. Using SolidWorks, 3D models of the billet, top die, and bottom die were created. The entrance geometry of the top die was analyzed in five different cases. The material used was Al 7075 Cold, chosen for its high strength, fatigue resistance, and machinability. Deform 3D software was employed to analyze critical parameters such as load estimation, damage, and effective strain.

The study aimed to optimize die design by examining the effects of different entrance geometries on the extrusion process. Each die design was meticulously crafted to ensure precision and reliability in simulations. The simulations provided detailed insights into load distribution, material damage, and strain behavior.

Results demonstrated that variations in the top die design significantly impacted the extrusion process's efficiency and effectiveness. By focusing on load estimation, damage, and effective strain, we identified which die design performed best under these criteria. Each parameter was thoroughly evaluated to determine which case offered the most efficient performance, leading to improved process outcomes.

These findings are crucial for optimizing extrusion processes and developing more efficient manufacturing techniques. This research offers valuable information for the design and optimization of friction stir extrusion dies, contributing to advancements in manufacturing technologies and material processing. The study underscores the importance of precise die design in enhancing process performance and product quality, providing a robust foundation for future innovations in the field.

SYMBOLS

MPa : MegaPascal

HRB : Hardness Rockwell B (scale for measuring material hardness)

F : Force

N : Newton

P : Power

t : Time

s : Second

W : Watt

J : Joule

mm : Milimeter

kWh : KiloWatt per hour

₺ : Turkish Lira

ABBREVIATIONS

FEA : Finite Element Analysis

FSE : Friction Stir Extrusion

CAD : Computer-Aided Design

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1. INTRODUCTION

Extrusion is a critical manufacturing process extensively studied in various research articles due to its versatility and efficiency in producing complex cross-sectional profiles. Traditional extrusion methods, such as direct extrusion and indirect extrusion, have been widely explored to enhance product quality and process efficiency. In direct extrusion, the billet is pushed through a stationary die, whereas in indirect extrusion, the die moves towards the stationary billet. Researchers have also investigated hot extrusion and cold extrusion, focusing on the effects of temperature on material properties and process outcomes. [1,2]

Figure 1 Aluminium Extrusion Machine

Significant advancements have been made in understanding the mechanics and thermodynamics of extrusion processes. Studies have highlighted the influence of die geometry, material flow, and temperature distribution on the final product's mechanical properties. For instance, researchers have examined how varying the die angle and channel design can optimize the extrusion process, leading to reduced material waste and improved surface finish. Additionally, the use of finite element analysis (FEA) tools, such as Deform 3D, has become prevalent in simulating extrusion processes, allowing for detailed analysis of strain, stress, and material flow.[3]

1.1. Historical Review of Friction Extrusion

Friction extrusion, a relatively novel technique compared to traditional methods, was first introduced in the early 1990s. The process was developed as an extension of friction stir welding, aiming to leverage the benefits of solid-state processing. Friction extrusion involves a rotating die that generates frictional heat, softening the material without melting it, which is then extruded through a die. This technique offers several advantages, such as lower energy consumption, improved mechanical properties, and the ability to process materials that are difficult to work with using conventional methods.[4]

Figure 2 C-frame milling machine modified for friction extrusion

Early research into friction extrusion focused on understanding the fundamental principles of the process. Initial studies demonstrated the potential of friction extrusion to produce fine-grained microstructures, enhancing the mechanical properties of the extruded products. Over the years, advancements in tooling and process parameters have led to significant improvements in the efficiency and applicability of friction extrusion. Recent studies have explored various materials, including aluminum, magnesium, and their alloys, highlighting the versatility of this technique in producing high-quality extruded components.[5]

1.2. Friction Stir Extrusion in This Study

Our project focuses on friction stir extrusion (FSE), leveraging its unique capabilities to enhance the extrusion process. The study involves designing and analyzing a rotating die for the FSE process, specifically examining the entrance geometry of the top die. By creating 3D models of the billet, top die, and bottom die in SolidWorks and conducting simulations using Deform 3D, we aim to optimize the die design for better performance and efficiency.

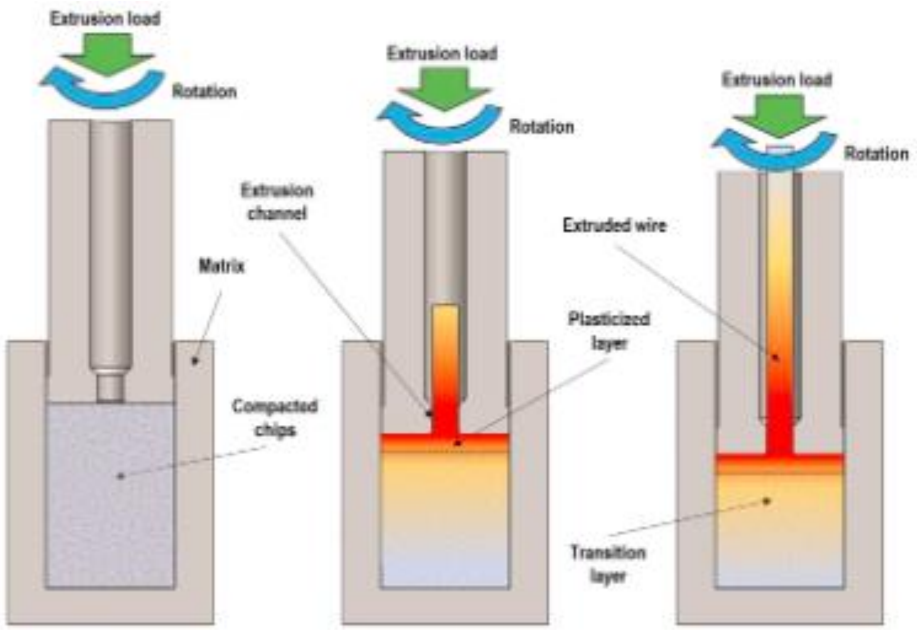

Figure 3 Friction Stir Extrusion Diagram

1.3. Objectives

The material chosen for this study is Al 7075 Cold, renowned for its high strength, excellent fatigue resistance, and superior machinability, making it ideal for high-performance applications. The objective of this research is to investigate the impact of different entrance geometries on the extrusion process parameters, specifically focusing on load estimation, damage, and effective strain. By analyzing these key parameters, we aim to determine which die design provides the most efficient performance.

Through comprehensive simulations and analyses, this study seeks to provide valuable insights into the influence of die design on the efficiency and effectiveness of the friction stir extrusion process. By identifying the optimal die design, the research will contribute to advancements in extrusion technology and material processing, paving the way for future innovations in die design and material efficiency.

2. MATERIAL AND METHOD

2.1. Material Selection

Al 7075 Cold was selected for this study due to its exceptional properties, making it highly suitable for the friction stir extrusion process. This aluminum alloy is renowned for its high strength, excellent fatigue resistance, and superior machinability, making it a preferred choice in demanding applications such as aerospace and automotive industries. The material's robustness and ability to withstand high stress without significant wear are critical for the success of extrusion processes.[6,7]

Figure 4 Aerospace and Automotive Industries

2.1.1. Properties of Al 7075 Cold

Al 7075 Cold offers a remarkable combination of properties that make it ideal for extrusion. Its tensile strength ranges from 572 MPa to 686 MPa, while its yield strength is approximately 503 MPa. The alloy also exhibits a good hardness value, typically around 87 on the Rockwell B scale (HRB). This high hardness contributes to the material's durability and resistance to deformation under load. Furthermore, Al 7075 Cold maintains good corrosion resistance, which is crucial for ensuring the longevity and reliability of the extruded products.[7]

Figure 5 7075 Aluminum

2.1.2. Application in Extrusion Process

The selection of Al 7075 Cold was pivotal for achieving precise and reliable results in this study. The material's high strength and machinability were essential for creating accurate 3D models in SolidWorks and conducting detailed simulations in Deform 3D. These properties allowed for a thorough analysis of critical parameters such as load estimation, damage, effective strain.. Overall, Al 7075 Cold provided a robust foundation for the extrusion process, enabling the identification of optimal die designs and contributing significantly to the advancement of extrusion technology.

2.2. Method

The primary objective of this study is to investigate the load prediction, damage, and effective strain parameters in a friction stir extrusion (FSE) process using a rotating die. This research aims to determine which die design is the most efficient for each parameter. The study begins with the design of each component using SolidWorks, followed by comprehensive simulations using Deform 3D. This section outlines the methodology in detail, including the design and simulation processes, as well as an in-depth explanation of the FSE process and its variants.

2.2.1. Friction Stir Extrusion (FSE)

Friction Stir Extrusion (FSE) is a solid-state process that involves the extrusion of material through the application of frictional heat generated by a rotating die. This process is an extension of friction stir welding and offers several advantages, including improved mechanical properties and reduced energy consumption. FSE is particularly useful for materials that are difficult to extrude using conventional methods.[4]

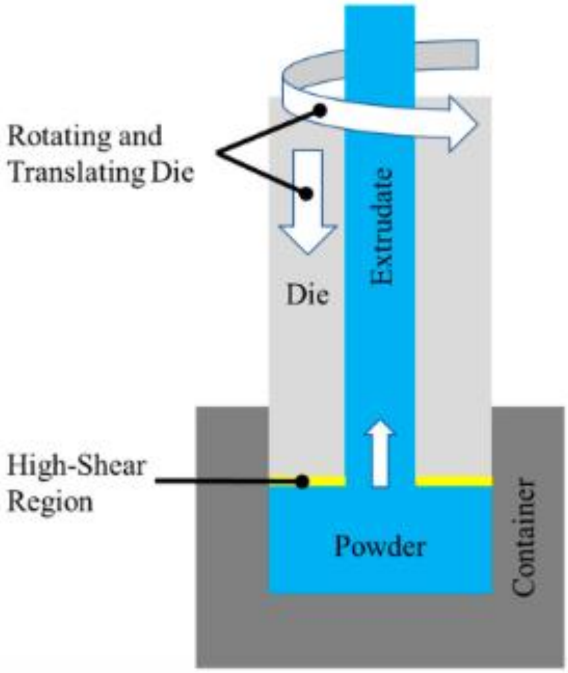

Figure 6 Simple view of FSE

2.2.1.1. Advantages

I. Enhanced Mechanical Properties: FSE produces parts with superior mechanical properties, such as higher strength and better fatigue resistance, due to the refined microstructure.[8,9]
II. Energy Efficiency: The process consumes less energy compared to traditional extrusion methods because it operates at lower temperatures.[9]
III. Material Efficiency: FSE can handle difficult-to-extrude materials, reducing waste and improving material utilization.[8,9]

2.2.1.2. Disadvantages

I. Complexity and Cost: The initial setup and tooling costs for FSE can be high, and the process requires precise control and expertise.[8]
II. Limited Material Compatibility: While FSE is versatile, it may not be suitable for all materials, particularly those with very low or very high melting points.[8]
III. Tool Wear: The rotating tool or die can experience significant wear, especially when processing hard materials, leading to maintenance challenges and additional costs.[8]

2.2.1.3. Variants of Friction Stir Extrusion

❖ Direct Friction Stir Extrusion

In this method, the rotating die directly contacts the billet, generating heat through friction and forcing the softened material through the die opening. This variant is characterized by its simplicity and effectiveness in processing high-strength materials.[10]

❖ Indirect Friction Stir Extrusion

Unlike direct FSE, this method involves an intermediate medium, such as a rotating tool, that generates heat and transfers it to the billet indirectly. This approach can reduce wear on the die and is suitable for delicate materials.[10]

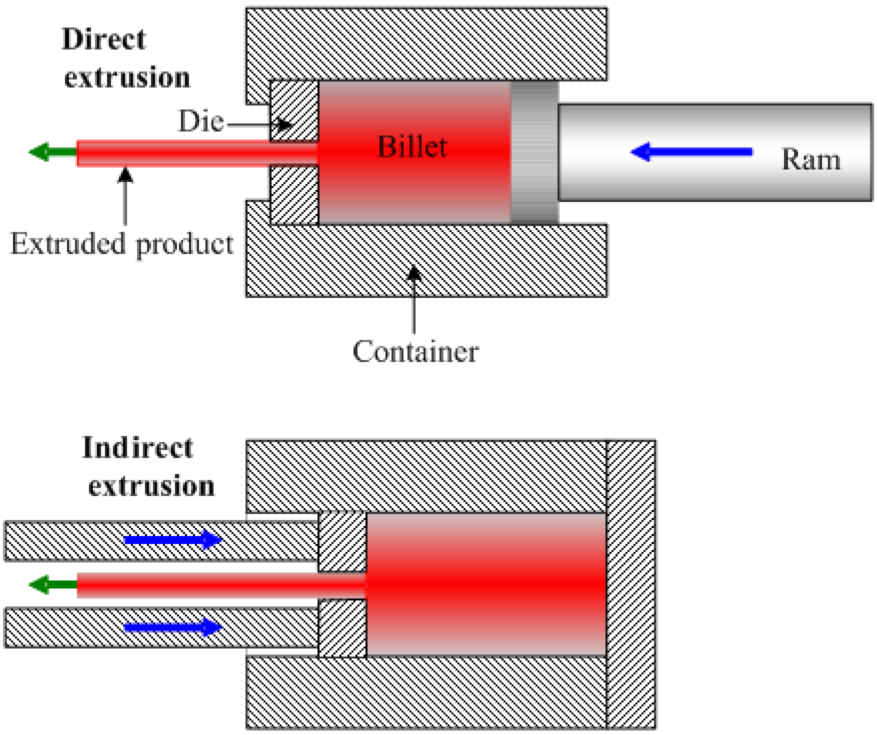

Figure 7 Diagram of Direct & Indirect FSE

❖ Continuous Friction Stir Extrusion

This variant is designed for continuous production processes, where the billet is fed continuously into the rotating die. It is ideal for producing long extruded sections and is commonly used in industrial applications.[11]

2.2.2. Software Tools

2.2.2.1. SolidWorks

SolidWorks is a powerful CAD software that enables engineers to create detailed 3D models and simulations. It offers a range of features for designing complex parts and assemblies, performing motion analysis, and validating design through simulations. In this study, SolidWorks was used to create accurate 3D models of the billet, top die, and bottom die, ensuring that the geometries were precise and suitable for subsequent simulations.[12]

2.2.2.2. Deform 3D

Deform 3D is an advanced FEA software used for simulating manufacturing processes such as forming, machining, and extrusion. It allows for detailed analysis of material behavior under various conditions, providing insights into stress, strain, and material flow. Deform 3D was chosen for this study due to its ability to handle complex simulations and provide accurate predictions of load, damage, and strain during the extrusion process. The software's robust capabilities ensured that the simulation results were reliable and could be used to optimize the die design.[13,14]

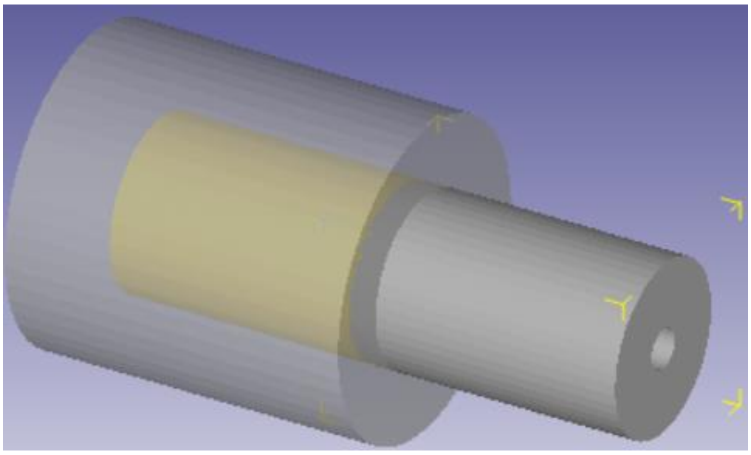

Figure 8 A design in 3D from the Deform 3D program

2.2.3. SolidWorks Modeling

The initial step in the methodology involves creating precise 3D models of the extrusion components using SolidWorks. SolidWorks is a comprehensive CAD software that enables the creation of detailed and accurate 3D models essential for simulations and manufacturing processes. The key components designed are:

- Billet: The raw material to be extruded.

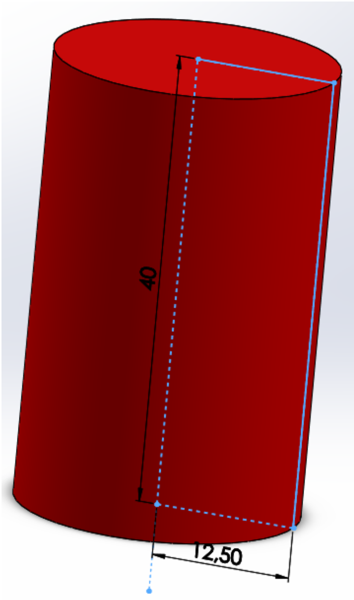

Figure 9 The billet used for all cases in SolidWorks

- Top Die: The rotating die with varying entrance geometries.

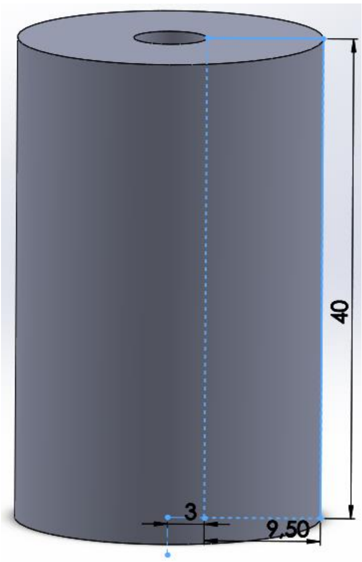

Figure 10 The top die used for Case 1 in SolidWorks

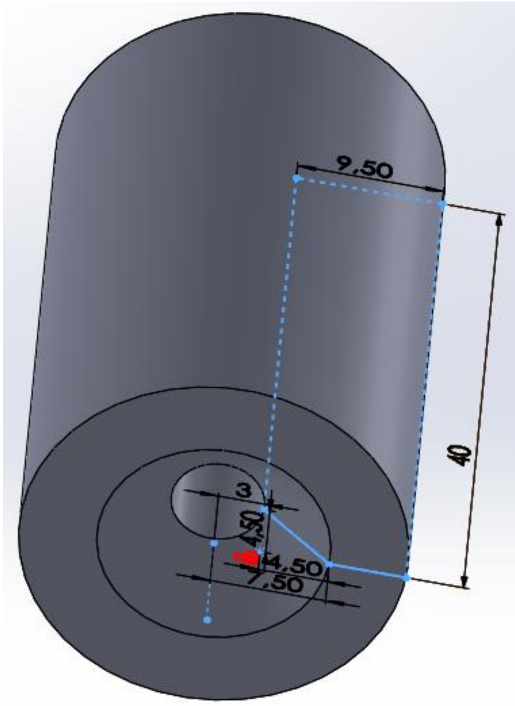

Figure 11 The top die used for Case 2 in SolidWorks

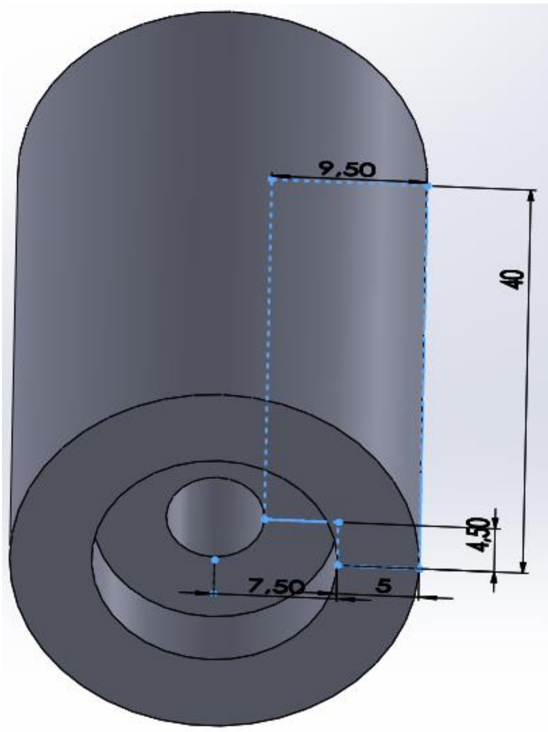

Figure 12 The top die used for Case 3 in SolidWorks

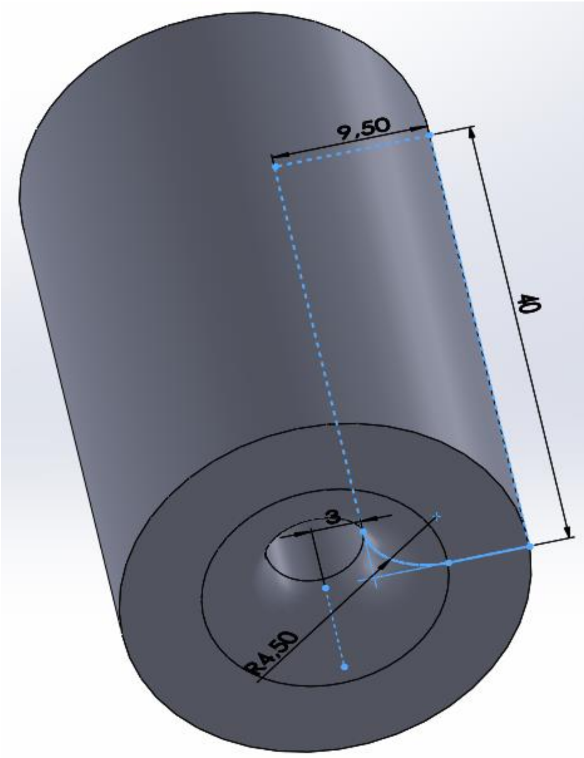

Figure 13 The top die used for Case 4 in SolidWorks

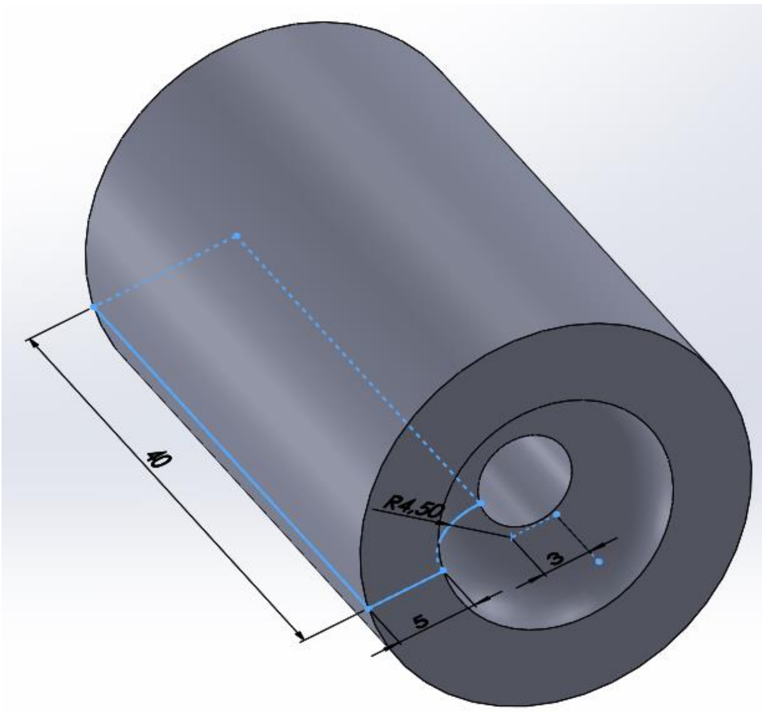

Figure 14 The top die used for Case 5 in SolidWorks

- Bottom Die: The stationary die that supports the billet.

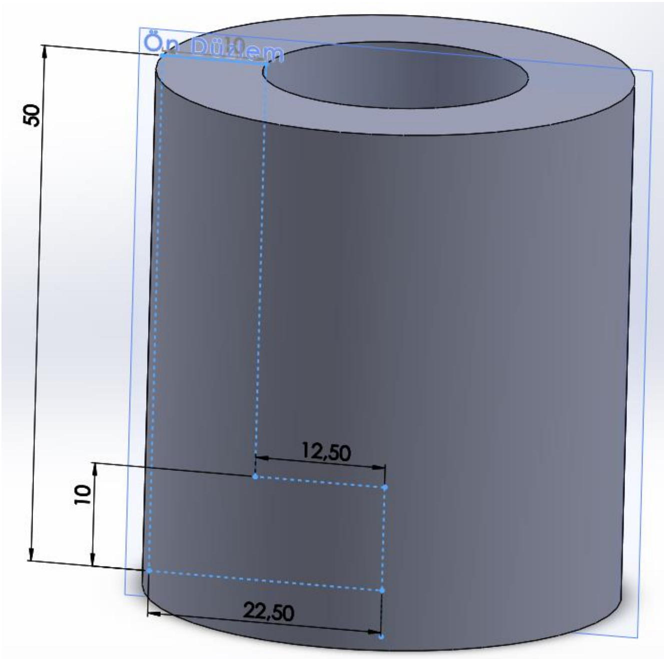

Figure 15 The container used for all cases in SolidWorks

Each component was meticulously modeled to ensure accuracy and reliability in subsequent simulations. The top die was designed with five different entrance geometries to analyze their effects on the extrusion process.

2.2.4. Deform 3D Simulations

Once the 3D models were created, the next step involved importing these models into Deform 3D for simulation. Deform 3D is a specialized FEA software designed for simulating manufacturing processes such as forming, machining, and extrusion. It provides detailed insights into various parameters like stress, strain, and load prediction.

The simulation process in Deform 3D included the following steps:

- **Model Import and Setup:** Import the SolidWorks models into Deform 3D and set up the simulation parameters.
- **Material Assignment:** Assign Al 7075 Cold as the material for the billet, utilizing its known mechanical properties such as tensile strength, yield strength, and hardness.

- **Meshing:** Generate a fine mesh for accurate results, ensuring that critical areas such as the die entrance and the billet-die interface are well-resolved.

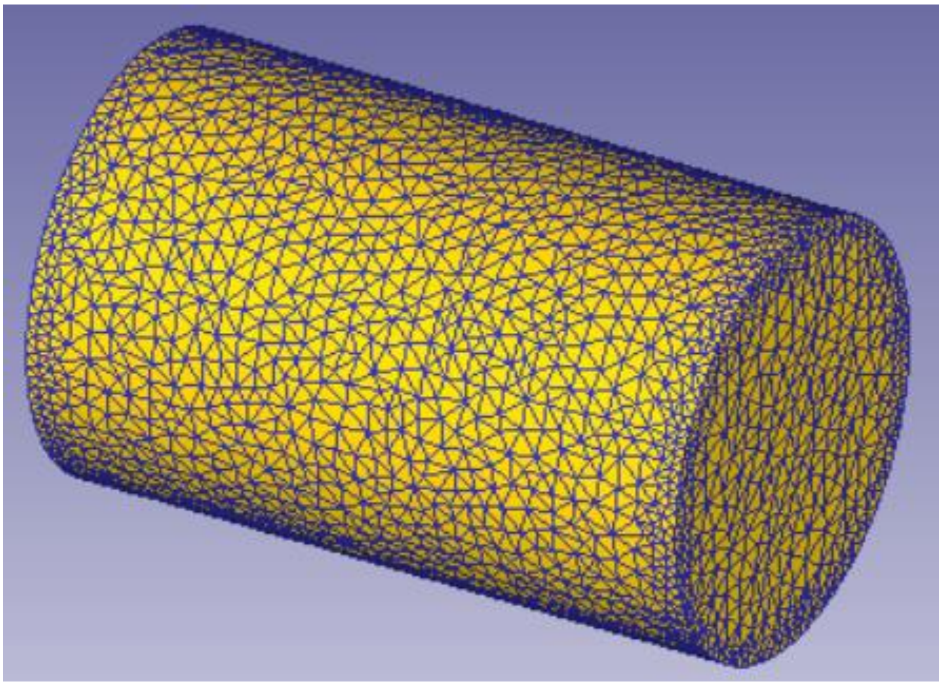

Figure 16 The meshed state of the billet

- **Boundary Conditions and Loading:** Apply appropriate boundary conditions and loading parameters to mimic real-world extrusion scenarios. The translation speed was set to 1 mm/s, and the rotational speed was set to 100 rad/s.
- **Simulation Execution:** Run the simulations for each of the five top die geometries.

2.2.4.1. Case 1

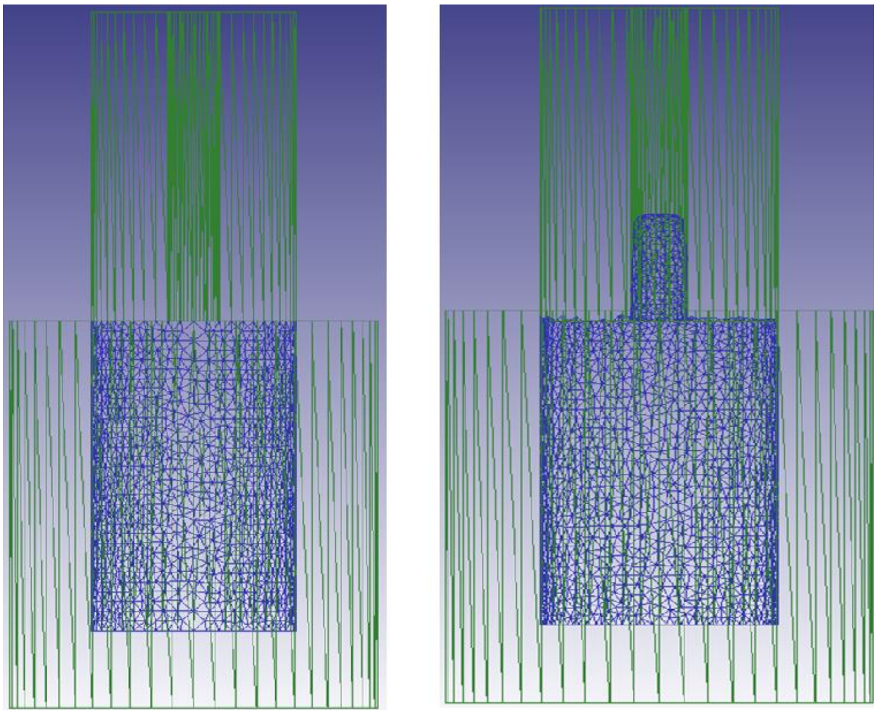

Figure 17 The image of Case 1 before the simulation starts and after it ends.

2.2.4.2. Case 2

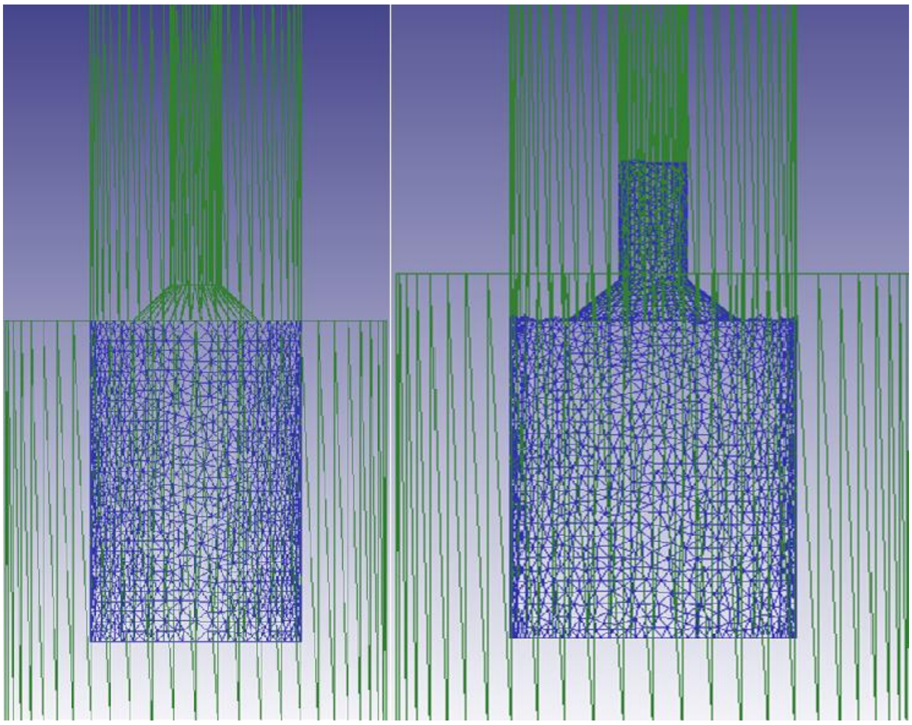

Figure 18 The image of Case 2 before the simulation starts and after it ends.

2.2.4.3. Case 3

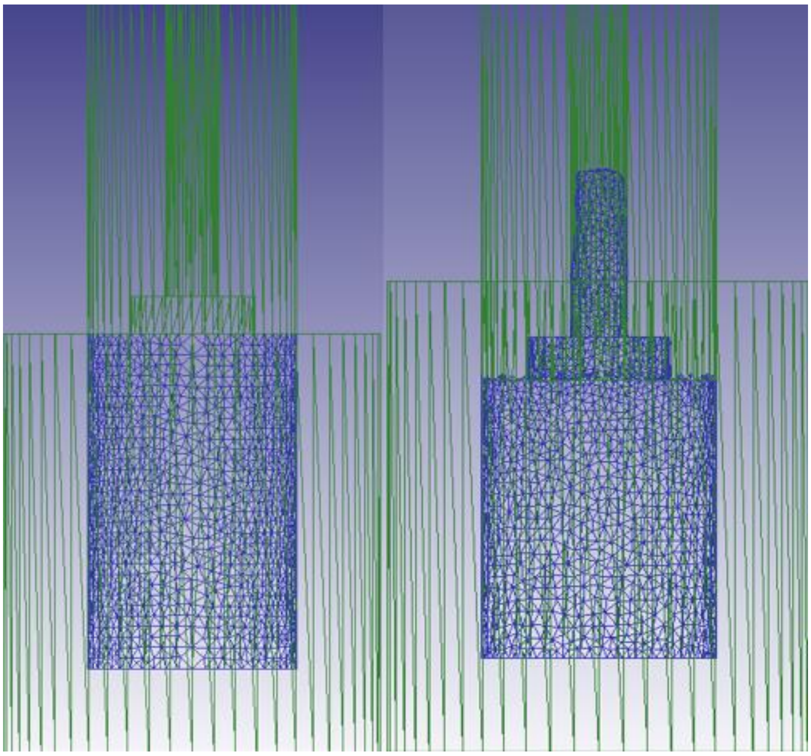

Figure 19 The image of Case 3 before the simulation starts and after it ends.

2.2.4.4. Case 4

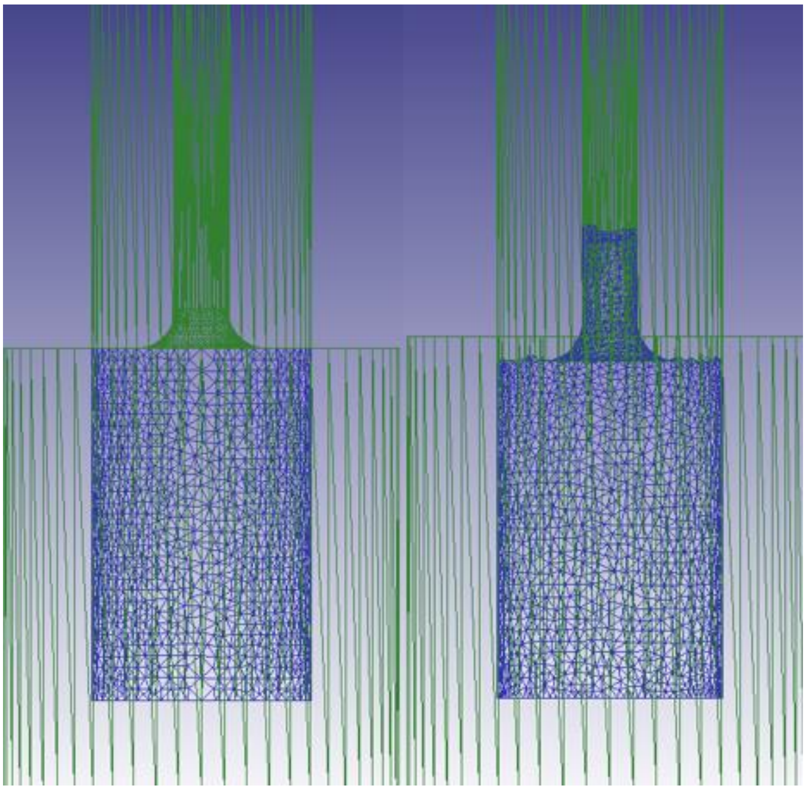

Figure 20 The image of Case 4 before the simulation starts and after it ends.

2.2.4.5. Case 5

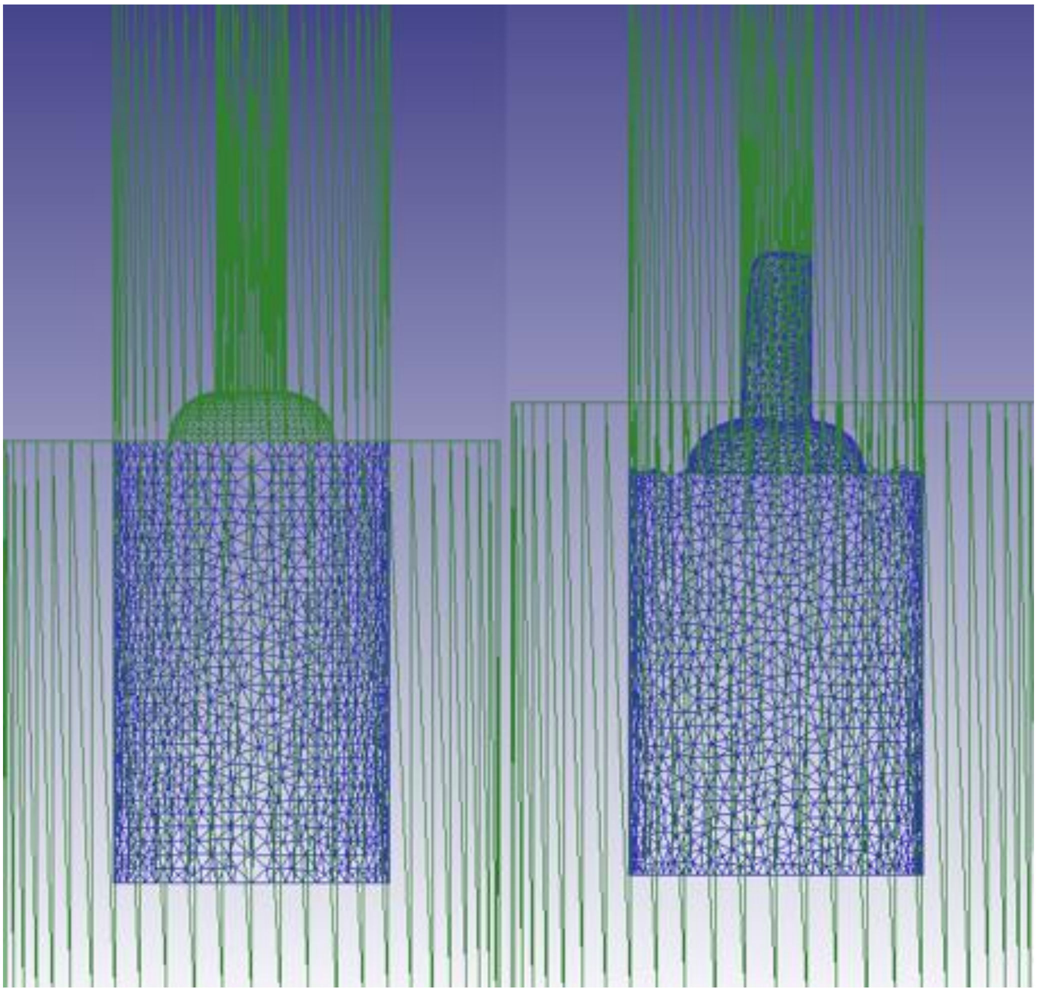

Figure 21 The image of Case 5 before the simulation starts and after it ends.

The simulations focused on three key parameters:

Load Prediction: Analyzing the force required to extrude the billet through the die. Lower load values indicate a more efficient process.

Damage: Damage specifies the damage factor at each element, which can be used to predict fracture in cold forming operations. The damage factor increases as the material is deformed, and fracture occurs when it reaches its critical value. This critical value must be determined through physical experimentation.[16]

Strain (Effective): Effective strain quantifies deformation magnitude; higher values indicate greater material deformation, altered internal structure, and reduced grain size.

Each parameter was analyzed for all five die geometries to determine the most efficient design.

2.2.5. Analysis and Results

After running the simulations, the results for load prediction, damage, and effective strain were extracted and analyzed. Comparative analysis was conducted to evaluate the performance of each die design based on the following criteria:

- **Load Prediction:** The die design with the lowest load requirement was identified as the most efficient.
- **Damage:** The die design that minimized material damage was deemed superior in terms of product quality.
- **Strain (Effective):** The die design that provided the highest strain value is believed to yield the best result in improving mechanical properties, as higher effective strain indicates greater material deformation capability.

2.2.6. Conclusion of Methodology

The methodology outlined in this study provides a comprehensive approach to optimizing die design for friction stir extrusion processes. By focusing on critical parameters such as load prediction, damage, and effective strain, this research aims to identify the most efficient die geometry for high-performance applications. The combination of SolidWorks modeling and Deform 3D simulations ensures precise and reliable results, contributing to advancements in extrusion technology and material processing.

3. RESULTS and DISCUSSION

3.1. Results

In this section, we analyze the results obtained from the simulations for load prediction, effective strain, and material damage for each of the five die design cases. These results are crucial in determining the optimal die design for the friction stir extrusion process.

Before obtaining the results from the program, 'point tracking' needs to be performed. The program conducts all analyses for each point. During these analyses, five different points were identified, ensuring that the five points have the same coordinates for each case.

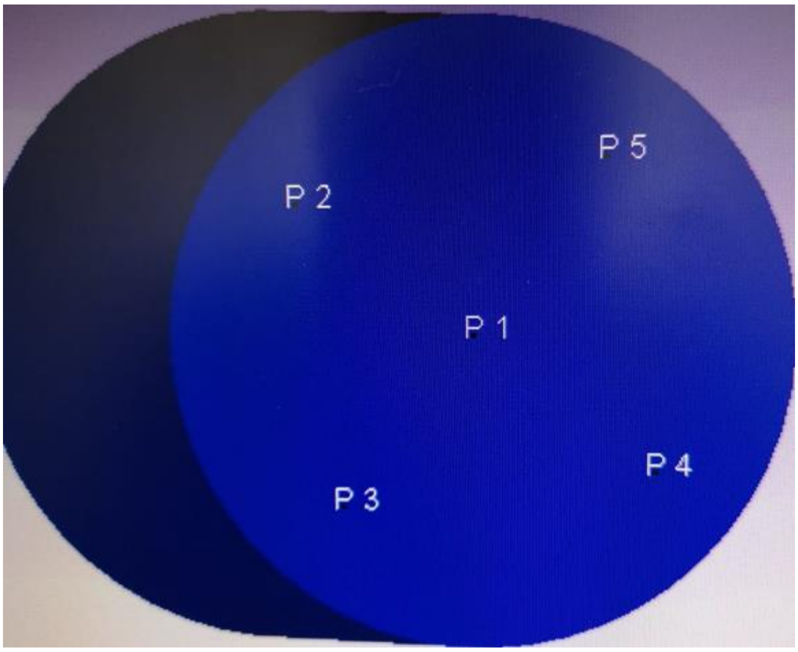

Figure 22 The exact 5 points used for each case

3.1.1. 3D Simulations

In this section, there are 3D simulations of the damage and strain (effective) parameters we analyzed. Other simulation images obtained are in the appendix section.

CASE 1

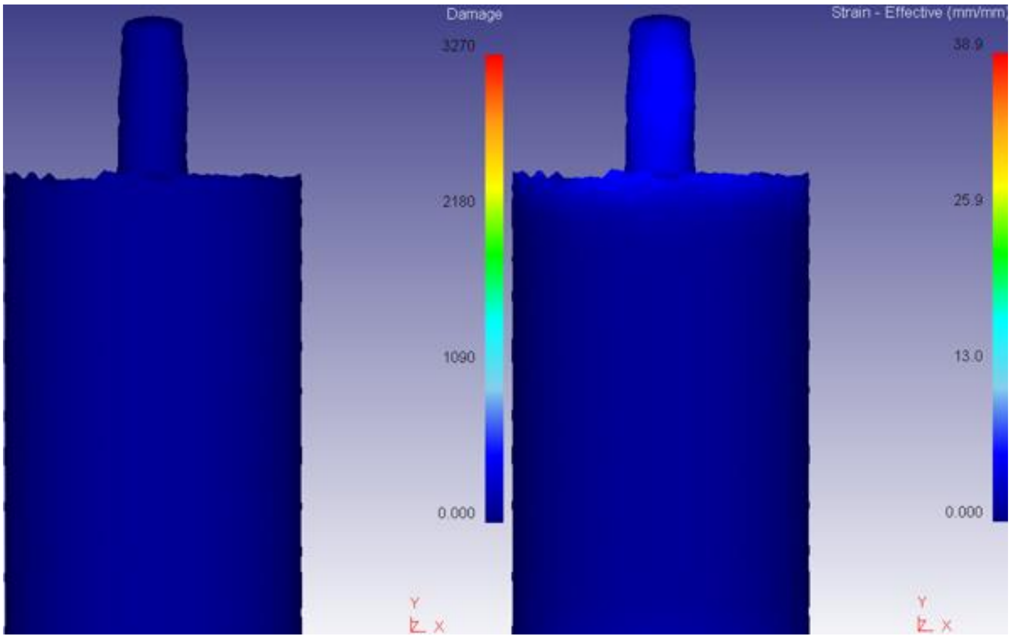

Figure 23 3D damage and strain (effective) results of Case 1

CASE 2

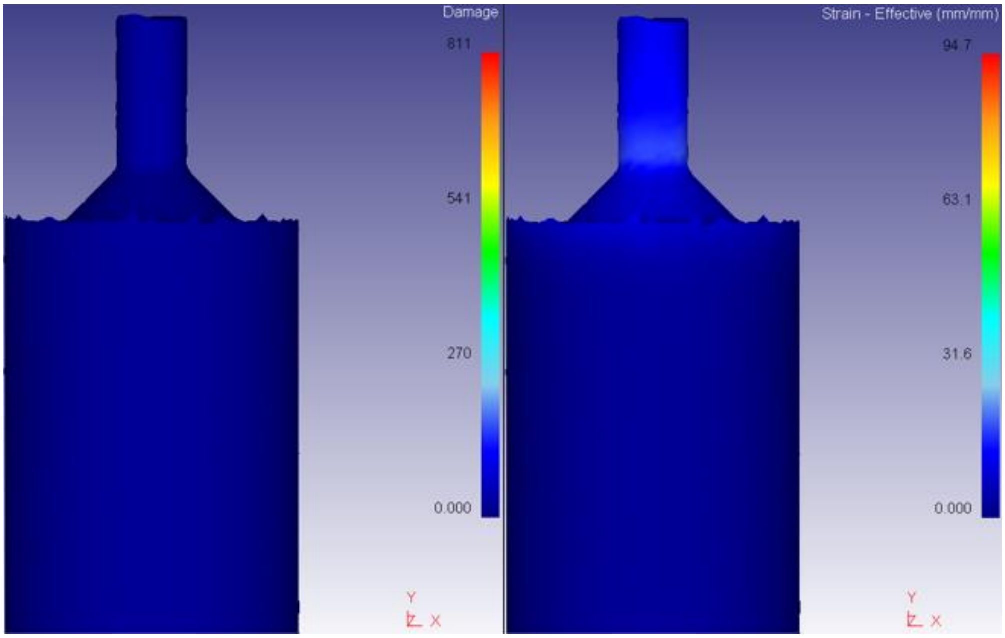

Figure 24 3D damage and strain (effective) results of Case 2

CASE 3

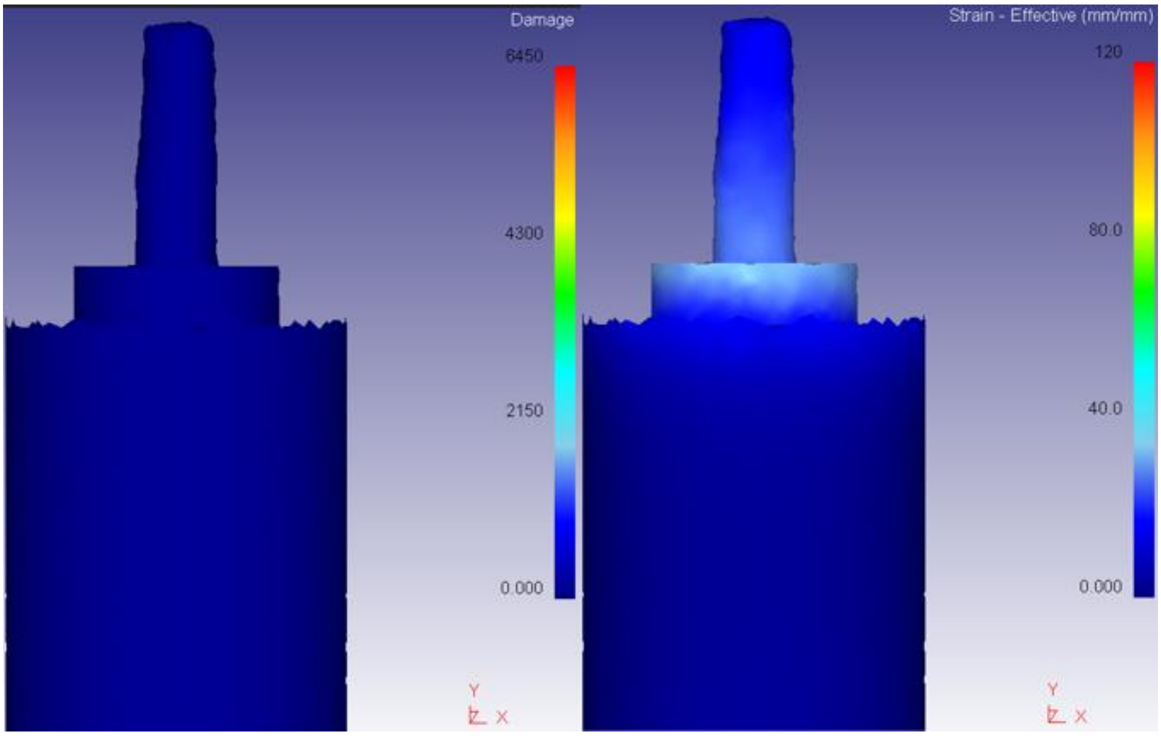

Figure 25 3D damage and strain (effective) results of Case 3

CASE 4

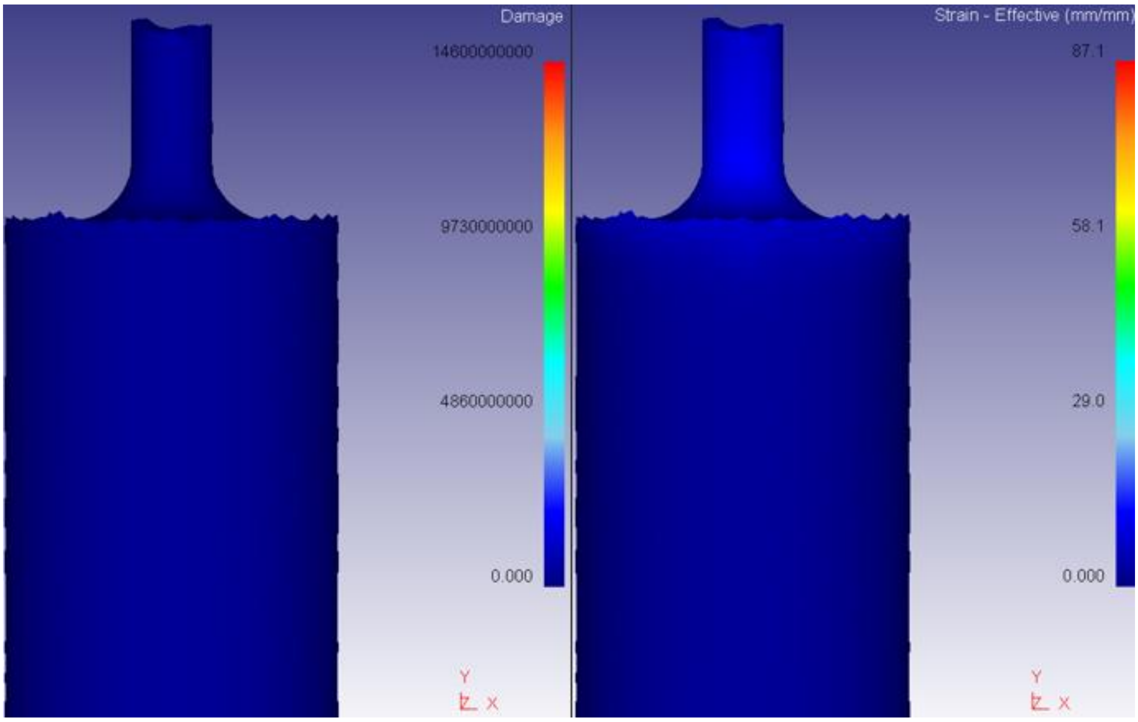

Figure 26 3D damage and strain (effective) results of Case 4

CASE 5

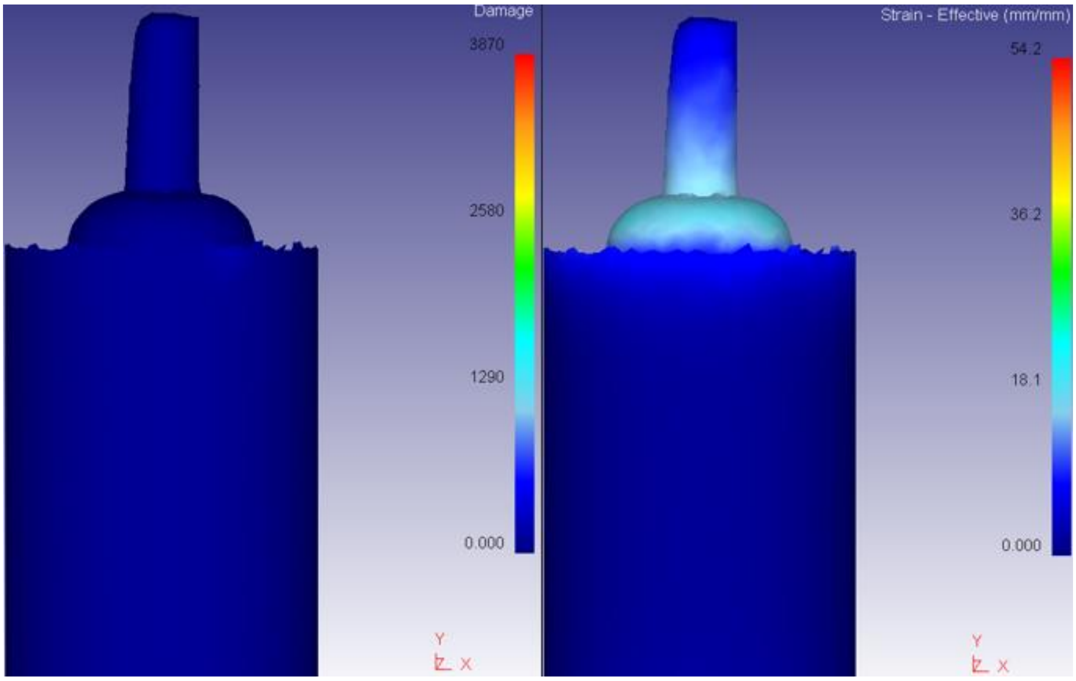

Figure 27 3D damage and strain (effective) results of Case 5

3.1.2. Load Prediction

In the load prediction section, the maximum points that can be reached for each case are specified.

CASE 1

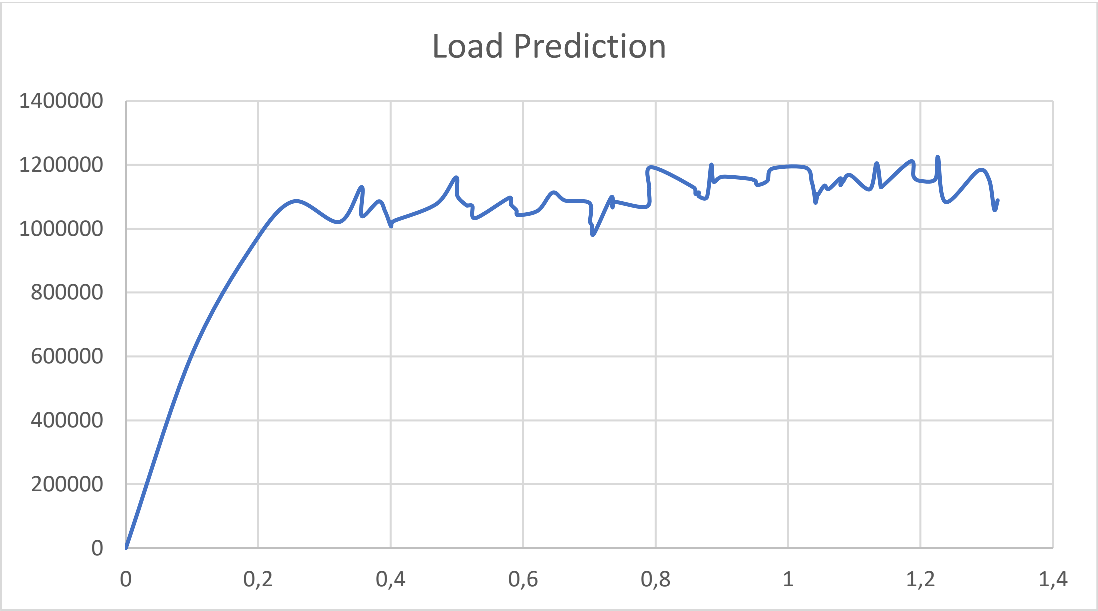

Figure 28 Load Prediction (N) vs time (s) for case 1

The maximum load in Case 1 reaches 1.223.368 N, indicating significant resistance.

CASE 2

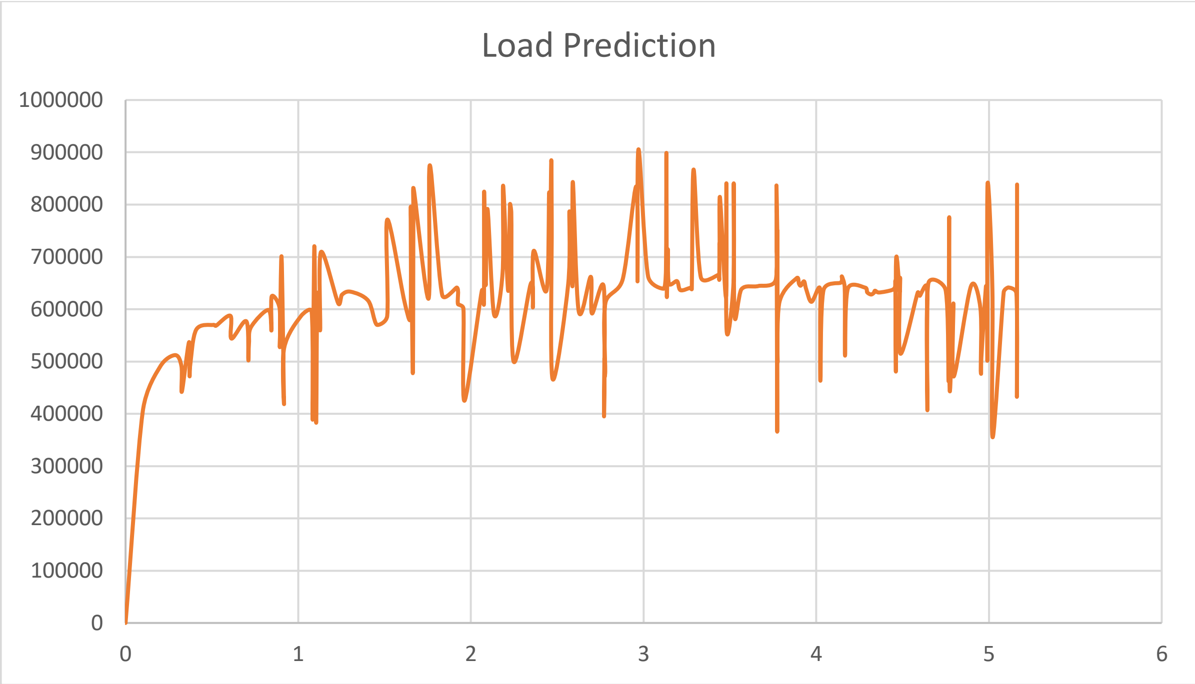

Figure 29 Load Prediction (N) vs time (s) for case 2

Case 2 shows a maximum load of 905.782,5 N, the lowest among all cases.

CASE 3

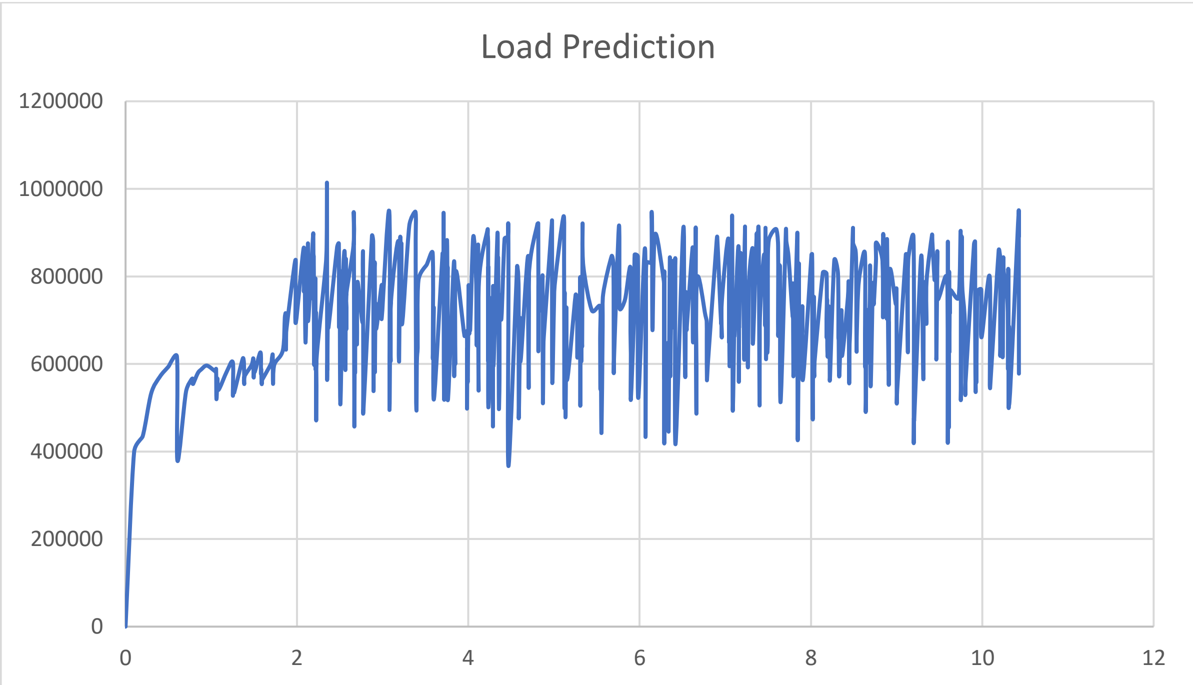

Figure 30 Load Prediction (N) vs time (s) for case 3

The maximum load in Case 3 is 1.000.970 N, demonstrating moderate resistance.

CASE 4

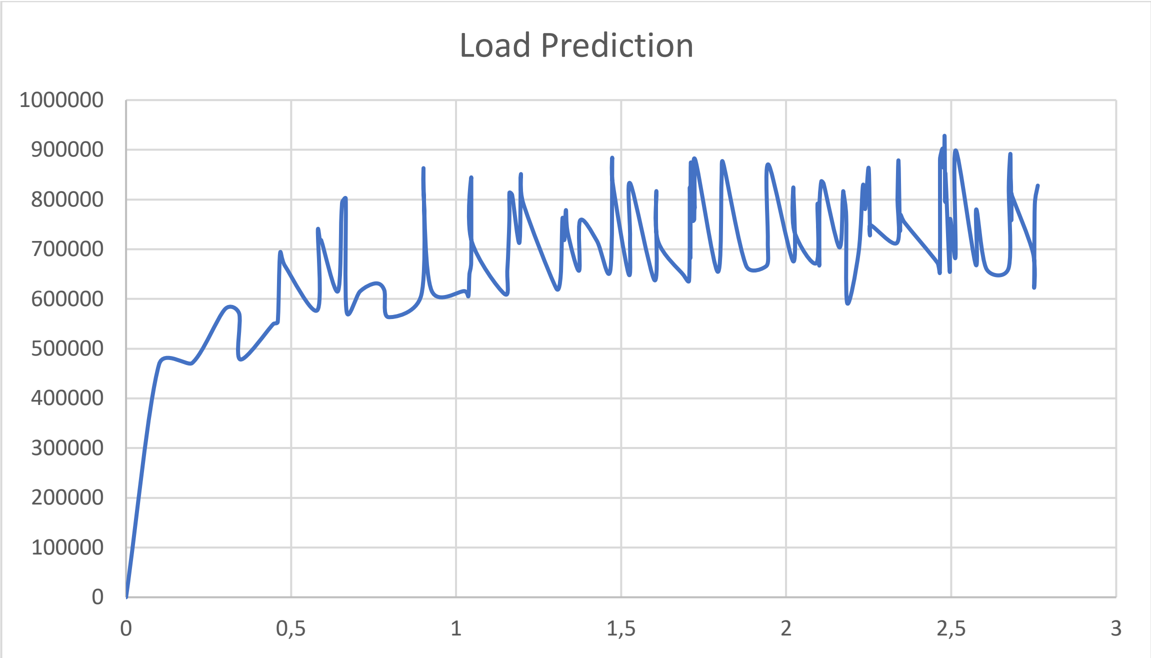

Figure 31 Load Prediction (N) vs time (s) for case 4

Case 4's maximum load is 928.262,6 N, slightly higher than Case 2.

CASE 5

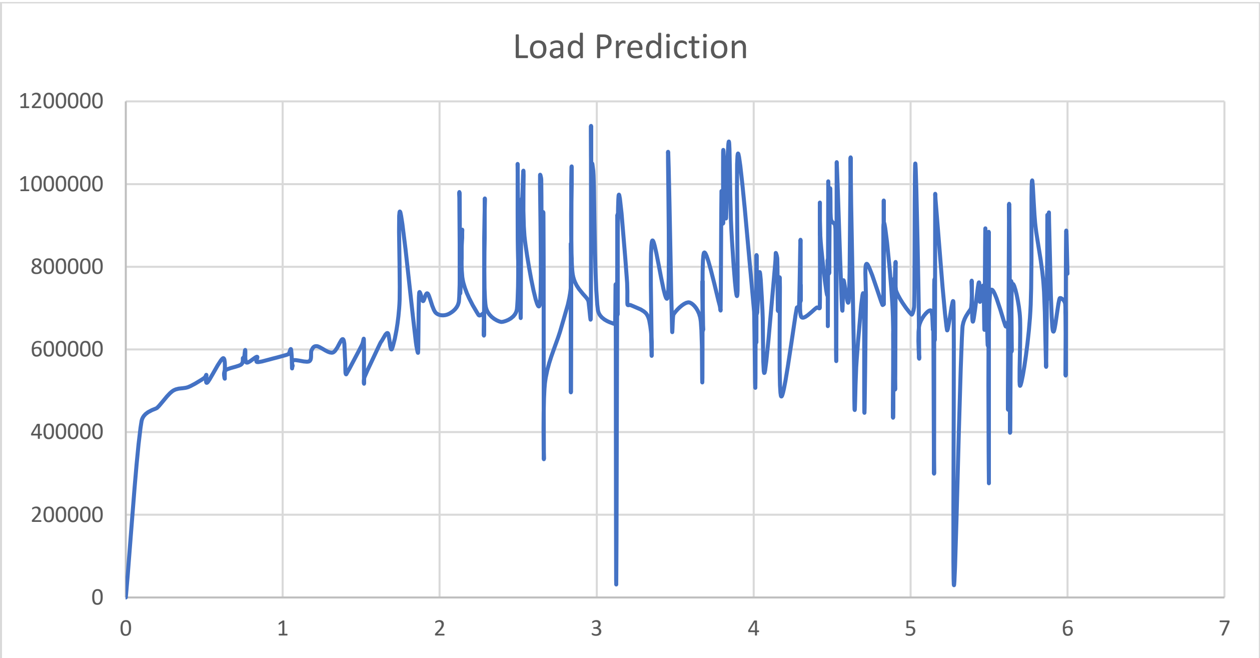

Figure 32 Load Prediction (N) vs time (s) for case 5

The maximum load for Case 5 is 1.129.565 N, indicating higher resistance.

3.1.3. Strain (Effective)

CASE 1

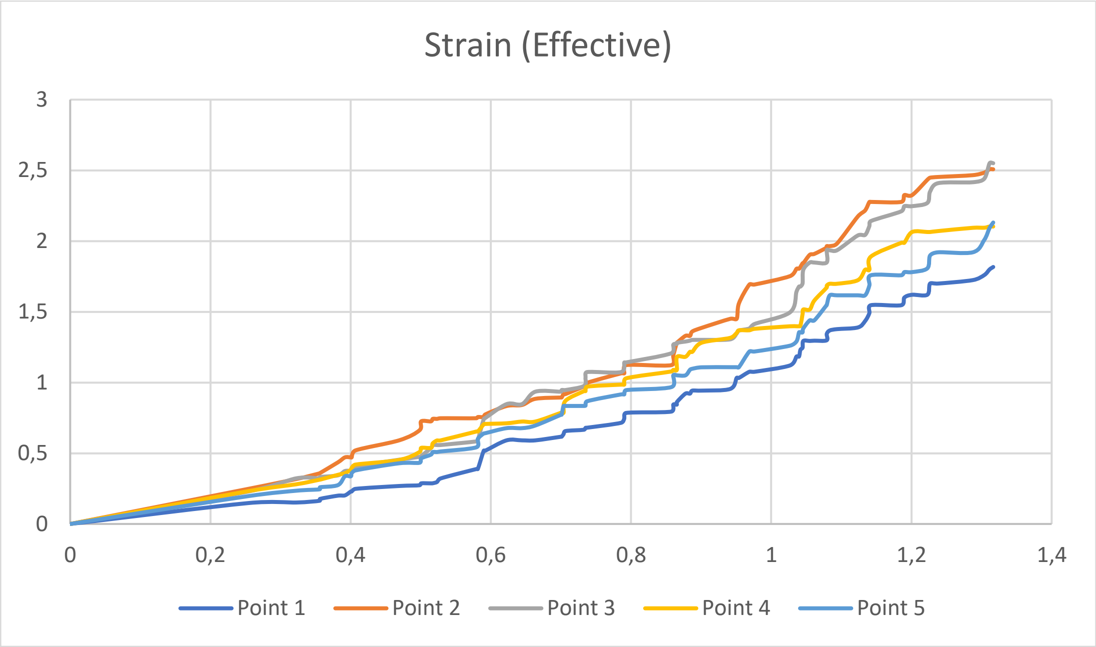

Figure 33 Strain (effective) (mm/mm) vs time (s) for case 1

Case 1 shows a maximum effective strain of 2.55 mm/mm, indicating moderate deformation.

CASE 2

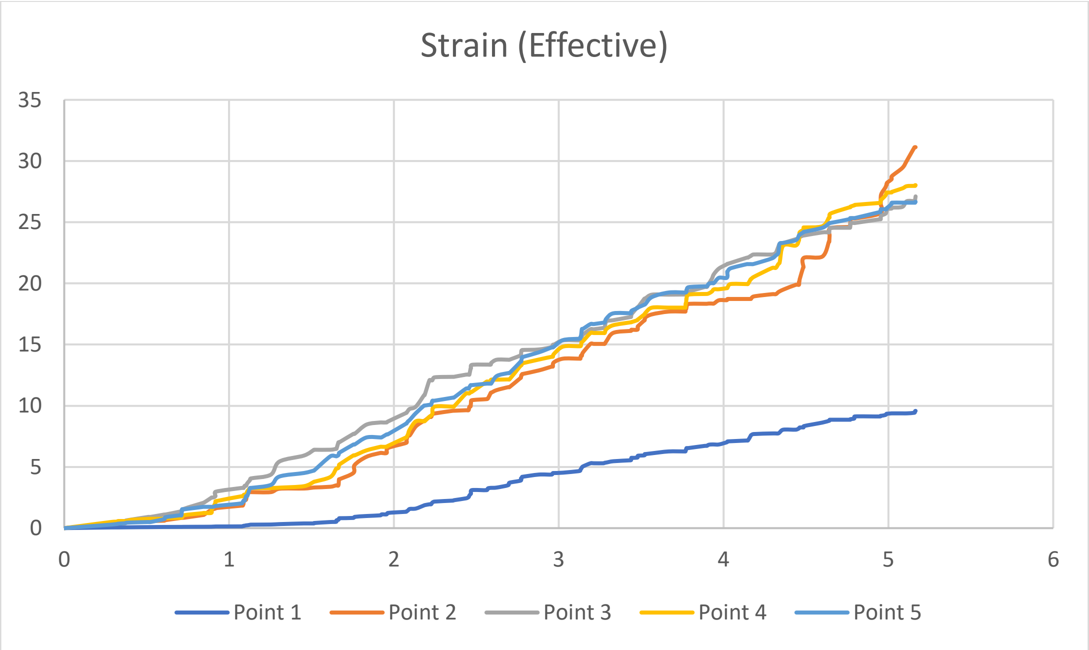

Figure 34 Strain (effective) (mm/mm) vs time (s) for case 2

The maximum effective strain in Case 2 is 31.1235, showing high deformation.

CASE 3

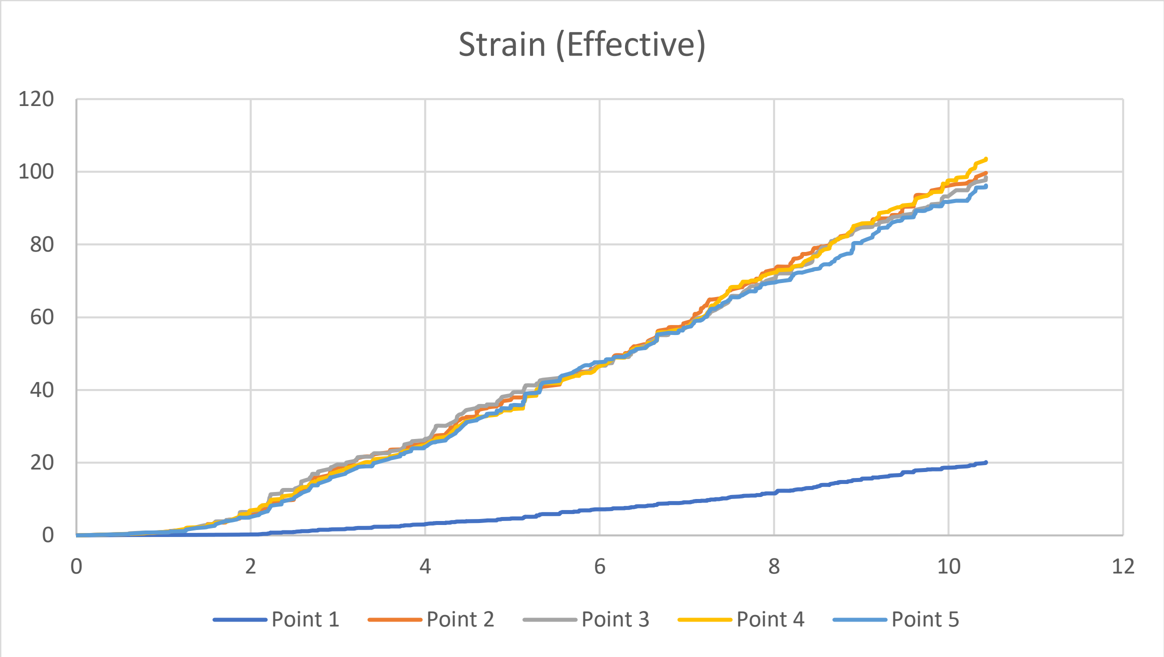

Figure 35 Strain (effective) (mm/mm) vs time (s) for case 3

Case 3 exhibits a maximum effective strain of 103.6, the highest deformation observed.

CASE 4

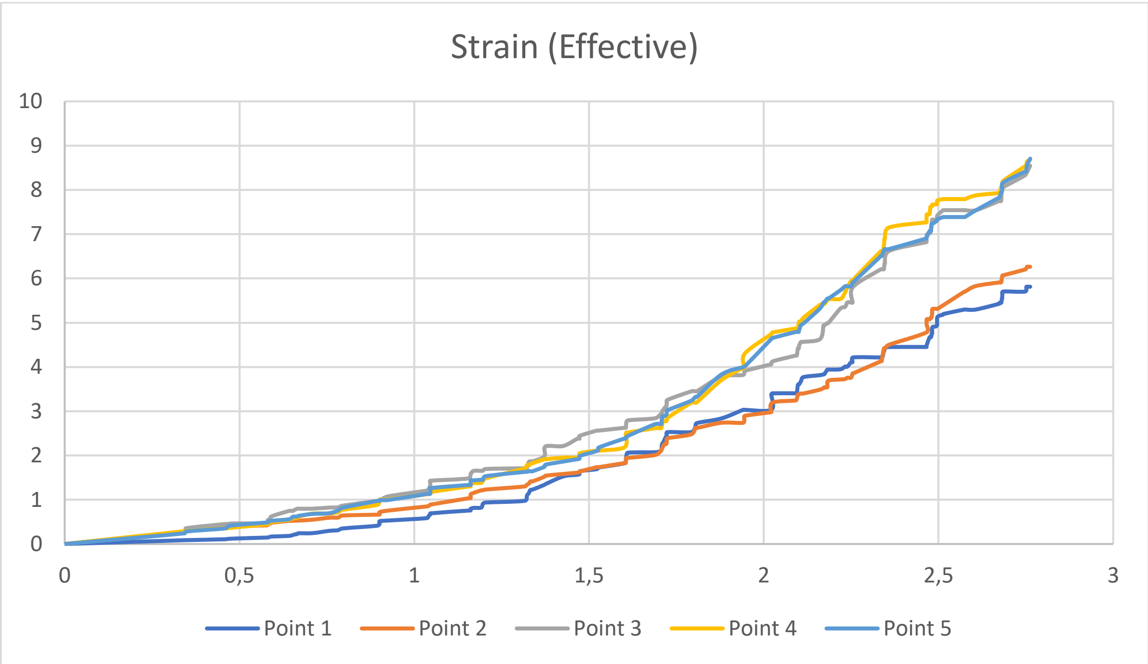

Figure 36 Strain (effective) (mm/mm) vs time (s) for case 4

The maximum effective strain for Case 4 is 8.706, indicating low to moderate deformation.

CASE 5

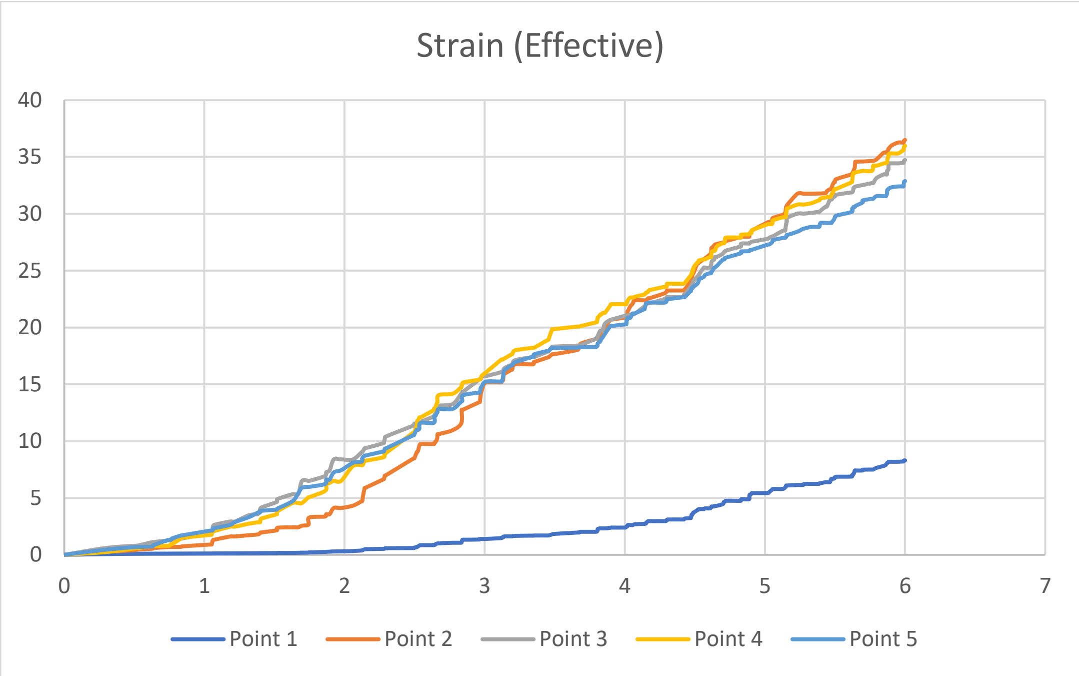

Figure 37 Strain (effective) (mm/mm) vs time (s) for case 5

Case 5's maximum effective strain reaches 36.499, showing substantial deformation.

3.1.4. Damage

Case 1

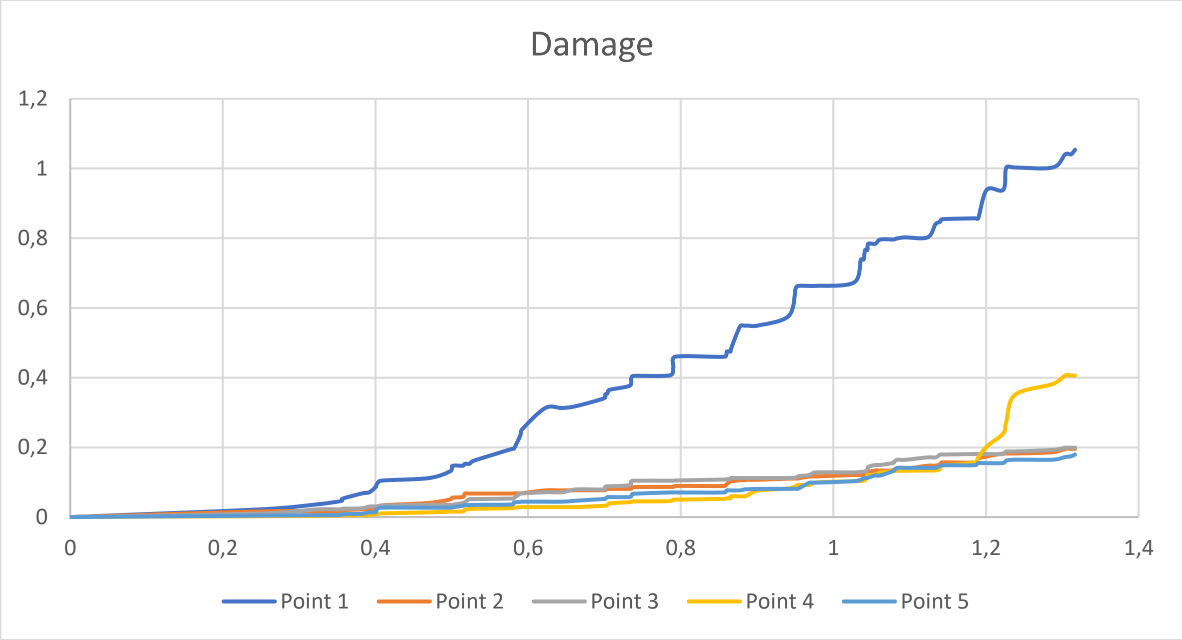

Figure 38 Damage vs time (s) for case 1

Case 1 shows a maximum damage value of 1.05, indicating minimal material damage.

Case 2

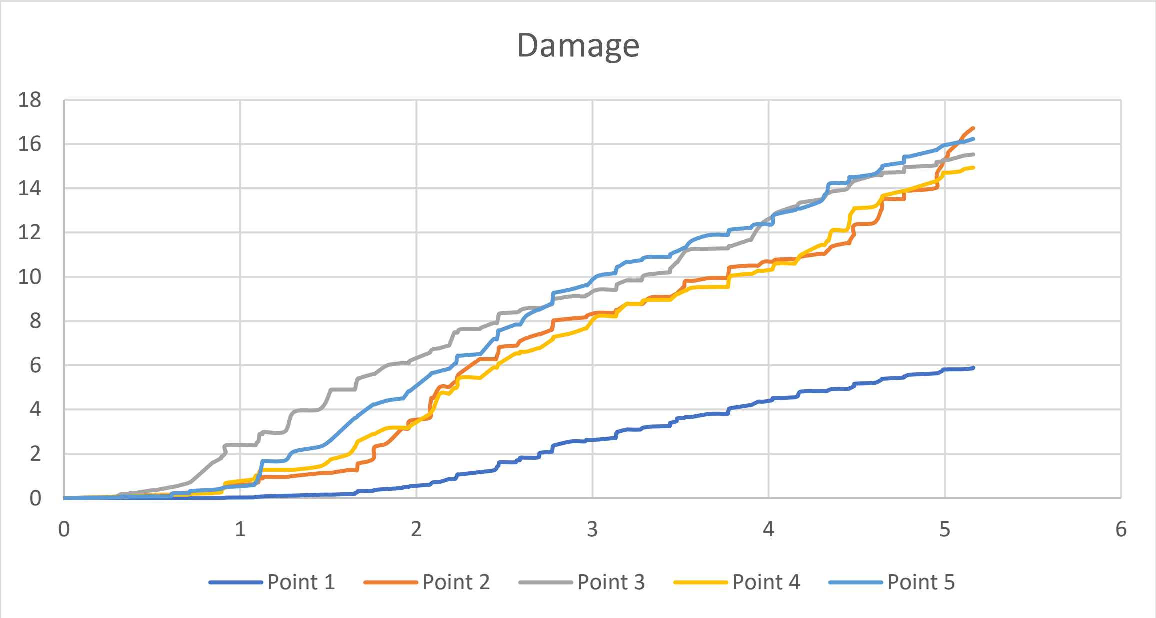

Figure 39 Damage vs time (s) for case 2

The maximum damage in Case 2 is 16.7, demonstrating moderate material damage.

Case 3

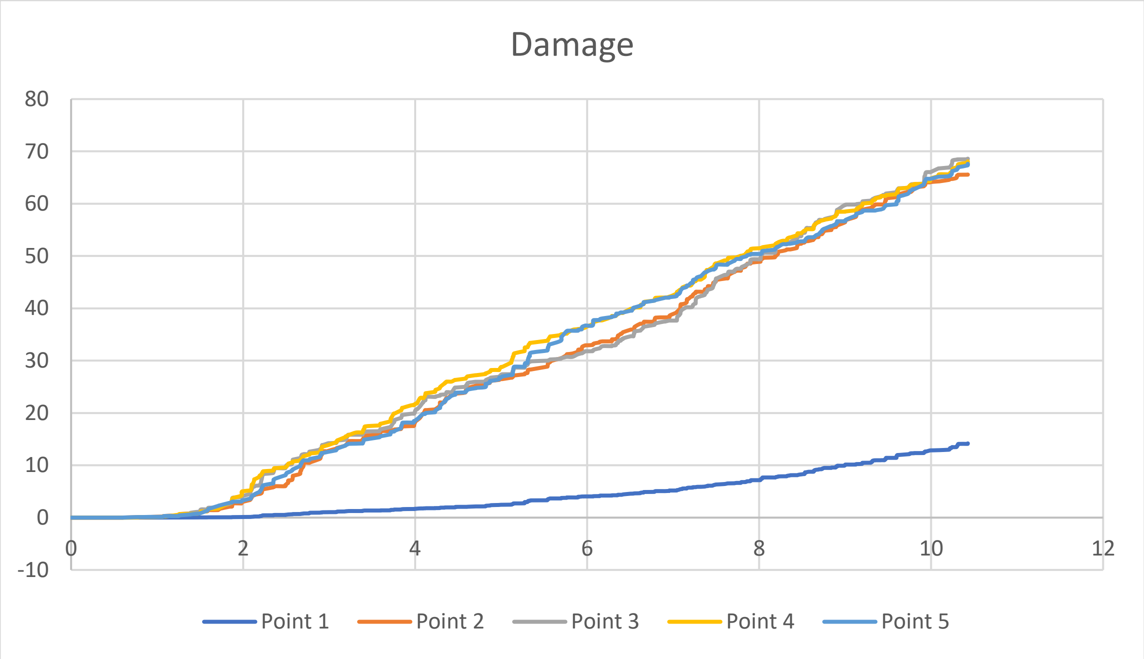

Figure 40 Damage vs time (s) for case 3

Case 3 exhibits a maximum damage value of 68.6, indicating the highest material damage.

Case 4

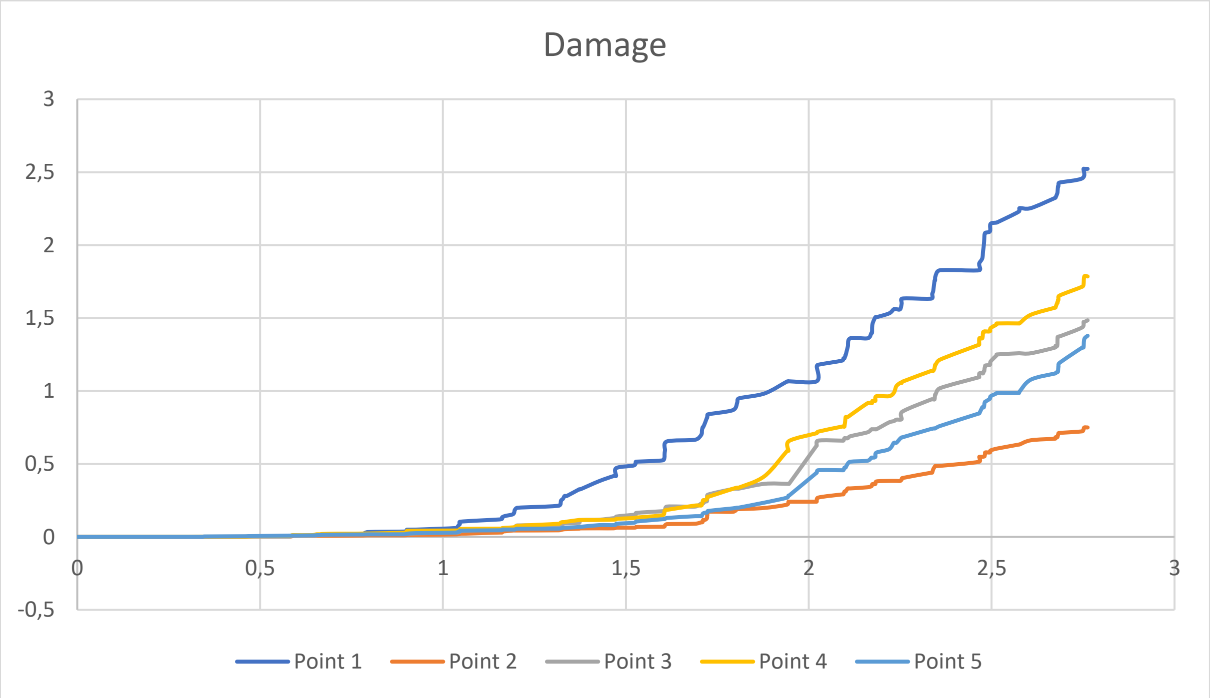

Figure 41 Damage vs time (s) for case 4

Case 4's maximum damage is 2.52, showing low material damage.

Case 5

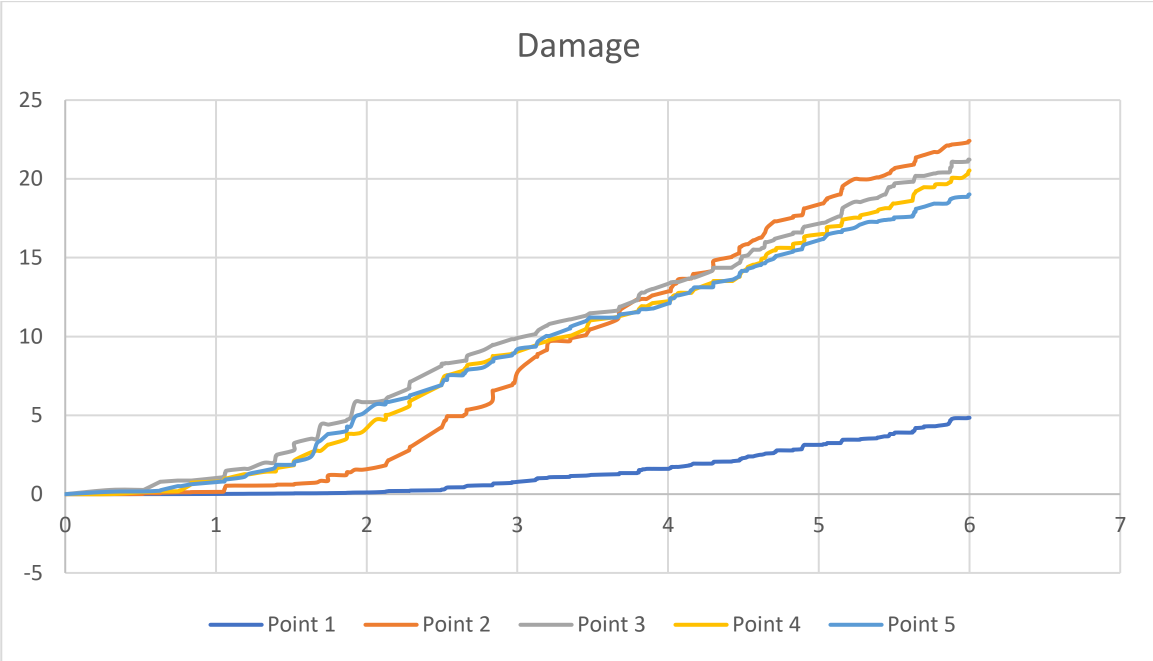

Figure 42 Damage vs time (s) for case 5

The maximum damage for Case 5 is 22.4, indicating significant material damage.

Load Prediction

Load prediction is a critical parameter as it indicates the force required for the extrusion process. Lower load values are preferable as they imply a more efficient process with less mechanical stress on the equipment.

Table 1 Load predictions for all cases

Case	Load Prediction (N)
1	1.223.368
2	905.782,5
3	1.000.970
4	928.262,6
5	1.129.565

Effective Strain

Higher effective strain values are preferable as they indicate greater material deformation capability, which is beneficial for improving mechanical properties.

Table 2 Strain (effective) for all cases

Case	Strain (Effective)
1	2.55
2	31.1235
3	103.6
4	8.706
5	36.499

Damage

Material damage is a crucial factor, especially in high-stress applications. Lower damage values indicate better preservation of the material's integrity.

Table 3 Damage for all cases

Case	Damage
1	1.05
2	16.7
3	68.6
4	2.52
5	22.4

3.2. Discussion

In comparing the five cases, each presents unique advantages and challenges based on the load prediction, effective strain, and damage factor.

3.2.1. Load Prediction Discussion

Case 2 demonstrates the lowest load requirement (905,782.5 N), indicating this die design is the most efficient in terms of mechanical force needed. This lower load suggests that less energy is required, and the extrusion equipment will experience reduced wear and tear, leading to potentially lower operational costs and longer equipment life.

Case 4 also shows a relatively low load (928,262.6 N), which is only slightly higher than Case 2. This indicates that Case 4 is also efficient but may not offer as significant energy savings and equipment longevity as Case 2.

Cases 1, 3, and 5 have significantly higher load requirements, making them less efficient compared to Cases 2 and 4. These higher loads suggest more energy consumption and greater stress on the extrusion equipment.

3.2.2. Strain (Effective) Discussion

Case 3 has the highest effective strain (103.6), indicating that this design allows for the greatest material deformation. Higher strain values suggest that the material undergoes significant deformation, which can improve mechanical properties by enhancing its ductility and strength.

Case 5 (36.499) and Case 2 (31.1235) also exhibit high strain values, making them suitable for applications where substantial deformation is required. These cases would be preferable in scenarios aiming for improved mechanical performance through increased deformation.

Case 4 performs moderately well with an effective strain of 8.706. While not as high as Cases 2, 3, and 5, it still allows for a decent level of material deformation, making it a viable option for certain applications.

Case 1 has the lowest effective strain (2.55), indicating minimal material deformation. Lower strain values suggest that the material undergoes less deformation, which may not be ideal for applications requiring enhanced mechanical properties through deformation. Thus, Case 1 would be the least preferable design in this context.

3.2.3. Damage Discussion

Case 1 again shows the least material damage (1.05), making it the most favorable in this aspect. Lower damage values suggest better preservation of the material’s integrity, which is crucial for high-stress applications where the material's durability is vital.

Case 4 also performs well with a damage factor of 2.52, indicating moderate damage. This suggests that Case 4 provides a good balance between efficiency and material integrity.

Case 2 (16.7), Case 5 (22.4), and Case 3 (68.6) show significantly higher damage values. These high damage factors indicate that these designs are less effective at preserving material integrity during the extrusion process, which could lead to defects and reduced performance in the final product.

3.2.4. Comparative Analysis and Multicriteria Analysis

From the results, it is evident that no single case outperforms others across all parameters. Therefore, a balance must be struck to determine the optimal die design based on the priorities of the application.

- Load Prediction: Case 2 is the most efficient, requiring the lowest load.
- Material Integrity (Effective Strain): Case 3 exhibits the highest strain, indicating better material flow characteristics.
- Damage Resistance: Case 1 has the least damage, closely followed by Case 4.

Multicriteria Analysis

In this section, we present the optimal die design selection based on a multicriteria analysis approach. We normalize the results for load prediction, damage, and effective strain to compare the different cases effectively. Here’s how the normalization and the metric calculation were performed:

Normalization Process

The normalization process converts different scales of data to a common scale (0 to 1), enabling a fair comparison. The formulas used for normalization are as follows:

- Damage:

$$Normalized\ Damage\ = \frac{(Max\ Damage\ -\ Damage\ Value)}{(Max\ Damage\ -\ Min\ Damage)}$$

This formula normalizes the damage values, where the highest damage value (68.6) corresponds to 0 and the lowest damage value (1.05) corresponds to 1.

- Strain (Effective):

$$Normalized\ Strain\ = \frac{(Strain\ Value\ -\ Min\ Strain)}{(Max\ Strain\ -\ Min\ Strain)}$$

This formula normalizes the strain (effective) values, where the lowest strain value (2.55) corresponds to 0 and the highest strain value (103.6) corresponds to 1.

- Load Prediction:

$$Normalized\ Load\ = \frac{(Max\ Load\ -\ Load\ Value)}{(Max\ Load\ -\ Min\ Load)}$$

This formula normalizes the load prediction values, where the highest load prediction value (1.223.368) corresponds to 0 and the lowest load prediction value (905.782,5) corresponds to 1.

- Metric Calculation

The normalized values for each criterion are then averaged to calculate the overall metric for each case. The formula for the metric calculation is:

$$Metric\ = (Normalized\ Damage\ +\ Normalized\ Strain\ +\ Normalized\ Load) / 3$$

Table 4 Multi-Criteria Analysis Results for Die Designs

Case	Damage	Strain (Effective)	Load Prediction (N)	Norm_D	Norm_S	Norm_L	Metric
1	1,05	2,55	1223368	1	0	0	0,333333
2	16,7	31,1235	905782,5	0,7683198	0,282766	1	0,683695
3	68,6	103,6	1000970	0	1	0,7002776	0,566759
4	2,52	8,706	928262,6	0,9782383	0,0609203	0,9292156	0,656125
5	22,4	36,499	1129565	0,6839378	0,3359624	0,295363	0,438421

Analysis and Optimal Case Selection

Based on the multicriteria analysis, we can determine the optimal die design by comparing the metrics calculated for each case. The higher the metric value, the better the overall performance of the case considering all criteria.

- Case 1: With a metric of 0.333, this case has the highest normalized damage value (indicating the least damage) but the lowest normalized strain and load prediction values, making it less favorable overall.
- Case 2: This case has a metric of 0.683, showing a balanced performance with good normalized values across damage, strain, and load prediction, making it a strong candidate.
- Case 3: With a metric of 0.567, it excels in strain but falls short in damage and load prediction.

- Case 4: This case, with a metric of 0.656, demonstrates a strong performance in both damage and load prediction, with a moderate strain value.
- Case 5: The metric of 0.438 indicates a balanced but less optimal performance compared to Case 2 and Case 4.

Optimal Die Design

Considering the multicriteria analysis, Case 2 emerges as the optimal die design. Although it does not have the lowest damage or force values, its overall balance across all criteria makes it the best choice. It provides a reasonable trade-off between load prediction, effective strain, and damage, ensuring efficiency while maintaining material integrity and minimizing deformation. Case 4 also presents a strong alternative, especially in applications where damage and load prediction are prioritized over strain.

In conclusion, by applying a multicriteria analysis approach, we have identified Case 2 as the optimal die design for our Friction Stir Extrusion process, offering the best balance between efficiency, material preservation, and mechanical performance.

3.2.5. Conclusion

The analysis demonstrates the importance of selecting the right die design for optimizing the friction stir extrusion process. By evaluating load prediction, effective strain, and material damage, this study provides a comprehensive understanding of how different die designs impact the process. Future work could involve physical experimentation to validate these simulation results and further refine the die designs for enhanced performance.

4. COST ANALYSIS

With the correction that the translation speed is 1 mm/s (0.001 m/s), let's recalculate the power and energy consumption, and subsequently the costs.

Power Calculation:

The power (P) required for the extrusion process can be calculated using the formula:

$P = F \times V$ where:

F is the load prediction (N)

V is the translation speed (m/s)

Given that the translation speed (V) is 0.001 m/s for all cases, the power calculation simplifies to: $P=F\times 0.001$

Energy Consumption:

The total energy consumption (E) during the process can be calculated using the formula:

$E = P \times t$ where:

P is the power (W)

t is the operation time (s)

In this calculation, it was assumed that the press operates for 1 hour per day, with the industrial electricity cost set at 3.7066 ₺ per kWh.[15]

$$Cost = E \times (Cost\ per\ kWh)$$

4.1. Case Analysis

Case 1

Load Prediction: 1.223.368 N

$$P_1 = 1.223.368\ N \times 0.001\ m/s = 1223.368\ W$$

Assuming $t = 3600\ s\ (1\ hour)$

$$E_1 = P_1 \times t = 1223.368\ W \times 3600\ s = 4.404.124{,}8\ J$$

$$E_1\ (kWh) = \frac{4.404.124{,}8\ J}{3600000} = 1.223368\ kWh$$

$$Cost_1 = 1.223368\ kWh \times 3.7066\ \frac{₺}{kWh} = 4.534\ ₺$$

Case 2

Load Prediction: 905.782,5 N

$$P_2 = 905.782{,}5\ N \times 0.001\ m/s = 905{,}7825\ W$$

Assuming $t = 3600\ s\ (1\ hour)$

$$E_2 = P_2 \times t = 905{,}7825\ W \times 3600\ s = 3.260.817\ J$$

$$E_2\ (kWh) = \frac{3.260.817\ J}{3600000} = 0{,}90578\ kWh$$

$$Cost_2 = 0{,}90578\ kWh \times 3.7066\ \frac{₺}{kWh} = 3.36\ ₺$$

Case 3

Load Prediction: 1.000.970 N

$$P_3 = 1.000.970\ N \times 0.001\ m/s = 1000.970\, W$$

Assuming $t = 3600\ s\ (1\ hour)$

$$E_3 = \ P_3\ \times t = 1000.970\ W \times 3600\ s = 3.603.492\ \ J$$

$$E_3\ (kWh) = \ \frac{3.603.492\ \ J}{3600000} = 1.001\ kWh$$

$$Cost_3 = 1.001\ kWh\ \times 3.7066\ \frac{₺}{kWh} = 3.71\ ₺$$

Case 4

Load Prediction: 928.262,6 N

$$P_4 = 928.262{,}6 \times 0.001 = 928{,}2626\, W$$

Assuming $t = 3600\ s\ (1\ hour)$

$$E_4 = \ P_4\ \times t = 928{,}2626\ W \times 3600\ s = 3.341.745\ \ J$$

$$E_4\ (kWh) = \ \frac{3.341.745\ \ J}{3600000} = 1.001\ kWh$$

$$Cost_4 = 0{,}93\ kWh\ \times 3.7066\ \frac{₺}{kWh} = 3.44\ ₺$$

Case 5

Load Prediction: 1.129.565 N

$$P_5 = 1.129.565 \times 0.001 = 1129.565\, W$$

Assuming $t = 3600\ s\ (1\ hour)$

$$E_5 = P_5 \times t = 1129.565\ W \times 3600\ s = 4.066.434\ J$$

$$E_5\ (kWh) = \frac{4.066.434\ J}{3600000} = 1.13\ kWh$$

$$Cost_5 = 1.13\ kWh \times 3.7066\ \frac{₺}{kWh} = 4.187\ ₺$$

Table 5 Cost of each case

Case	Cost (₺)
Case 1	4.534
Case 2	3.360
Case 3	3.710
Case 4	3.440
Case 5	4.187

The cost analysis reveals that Case 2 stands out as the most cost-effective option, with the lowest operational cost of 3.360 ₺. This is primarily due to its low load prediction, which minimizes energy consumption. On the other hand, Case 1 and Case 5 are the most expensive, with costs of 4.534 ₺ and 4.187 ₺, respectively. These high costs are attributed to the significant load and damage factors, leading to higher energy use and potential equipment maintenance costs.

Case 4 also presents a cost-efficient alternative at 3.440 ₺, with balanced load and strain parameters that contribute to lower operational expenses. Case 3, despite having the highest effective strain and damage, maintains a moderate cost of 3.710 ₺, suggesting that the energy efficiency of the process offsets the high material stress and damage.

In conclusion, the cost analysis underscores the importance of balancing load, strain, and damage parameters to achieve cost-effective and efficient extrusion processes. Case 2, with its low operational cost, emerges as the most viable option, while Case 4 also offers a cost-efficient alternative.

5. CONCLUSION

This study provides a comprehensive analysis of the friction extrusion process using a rotating die, focusing on key parameters such as load prediction, effective strain, and damage. The objective was to determine the most efficient and cost-effective die design through meticulous simulations and analyses.

Evaluating the overall performance based on these parameters, Case 2 stands out as the most balanced and efficient option. It exhibited the lowest load requirement at 905.782,5 N, suggesting reduced energy consumption and operational costs. The effective strain for Case 2 was 31.1235, indicating a significant amount of material deformation, which is beneficial for achieving high-quality extrusion. The damage factor for Case 2 was moderate at 16.7, implying a reasonable lifespan for the die with lower maintenance needs.

In contrast, Case 1, despite having the lowest damage factor (1.05), required a significantly higher load (1.223.368 N). This high load requirement translates to higher energy consumption, making it less economically viable despite its durability. Case 3 showed the highest effective strain (103.6) and damage factor (68.6), indicating significant material deformation but also a high likelihood of die fracture, leading to increased maintenance costs and a shorter die lifespan.

Case 4 presented a balanced performance with a load requirement of 928.262,6 N, effective strain of 8.706, and a damage factor of 2.52. While it does not excel in any single parameter, it offers a balanced trade-off between performance and cost, making it suitable for scenarios where moderate performance is acceptable. Case 5 had a load requirement of 1.129.565 N, effective strain of 36.499, and damage factor of 22.4. Although it showed good material flow, the high damage factor and associated costs reduce its overall viability.

A comprehensive multi-criteria analysis was conducted to balance load prediction, effective strain, and damage, providing a holistic assessment of the die designs. The analysis revealed that Case 2 emerges as the optimal choice due to its balanced performance across all parameters. Case 2 exhibits the lowest load requirement, moderate effective strain, and a reasonable damage factor, making it the most efficient and cost-effective die design. In contrast, Case 1, despite having the lowest damage, is less optimal due to its high load requirement and relatively lower effective strain. Case 3, while showing the highest effective strain, is diminished in desirability by its high damage factor and substantial load requirement. Case 4 offers a balanced performance but is less efficient and cost-effective compared to Case 2. Case 5, although demonstrating good material flow, is reduced in viability due to its high damage factor and load requirement. Overall, the multi-criteria analysis confirms that Case 2 provides the best combination of performance metrics, reinforcing its status as the optimal die design for efficient and cost-effective friction extrusion.

The cost analysis reinforced these findings, with Case 2 emerging as the most cost-effective option at 3.360 ₺. The low cost is a direct result of its reduced load requirement and moderate damage factor, leading to lower energy consumption and maintenance expenses. Case 1 and Case 5 were the most expensive, costing 4.534 ₺ and 4.187 ₺, respectively. These higher costs are attributed to their higher load requirements and damage factors, necessitating more frequent maintenance and higher energy use.

Summary and Future Recommendations

In summary, this study highlights the critical role of die design in the friction extrusion process. By evaluating load prediction, effective strain, and damage parameters, it identifies Case 2 as the most efficient and cost-effective option. The insights gained from this analysis can guide future improvements in extrusion die design, leading to more efficient and sustainable manufacturing processes.

Future work should focus on optimizing die entrance geometry to further reduce load requirements and damage factors while maintaining acceptable effective strain levels. Exploring different materials and coatings for the die could enhance durability and performance. Additionally, experimental validation of the simulation results is recommended to confirm the findings and refine the simulation models.

Ultimately, the comprehensive understanding of the trade-offs between load requirements, effective strain, and damage factors will aid in making informed decisions in the extrusion industry, enhancing productivity and reducing costs. This study provides a solid foundation for further research and development in the field of friction extrusion, paving the way for more efficient and cost-effective manufacturing solutions.

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7. APPANDIX

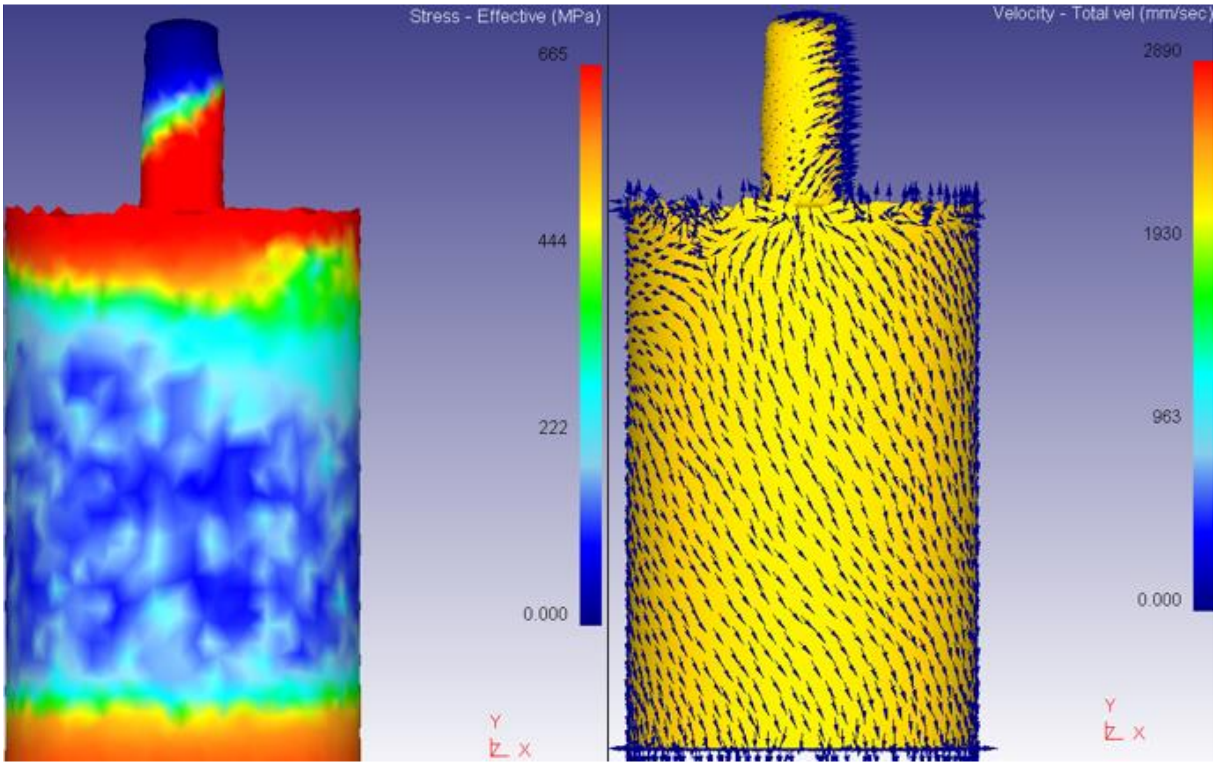

Figure 43 Stress (effective) and Velocity - Total Velocity 3D simulations for case 1

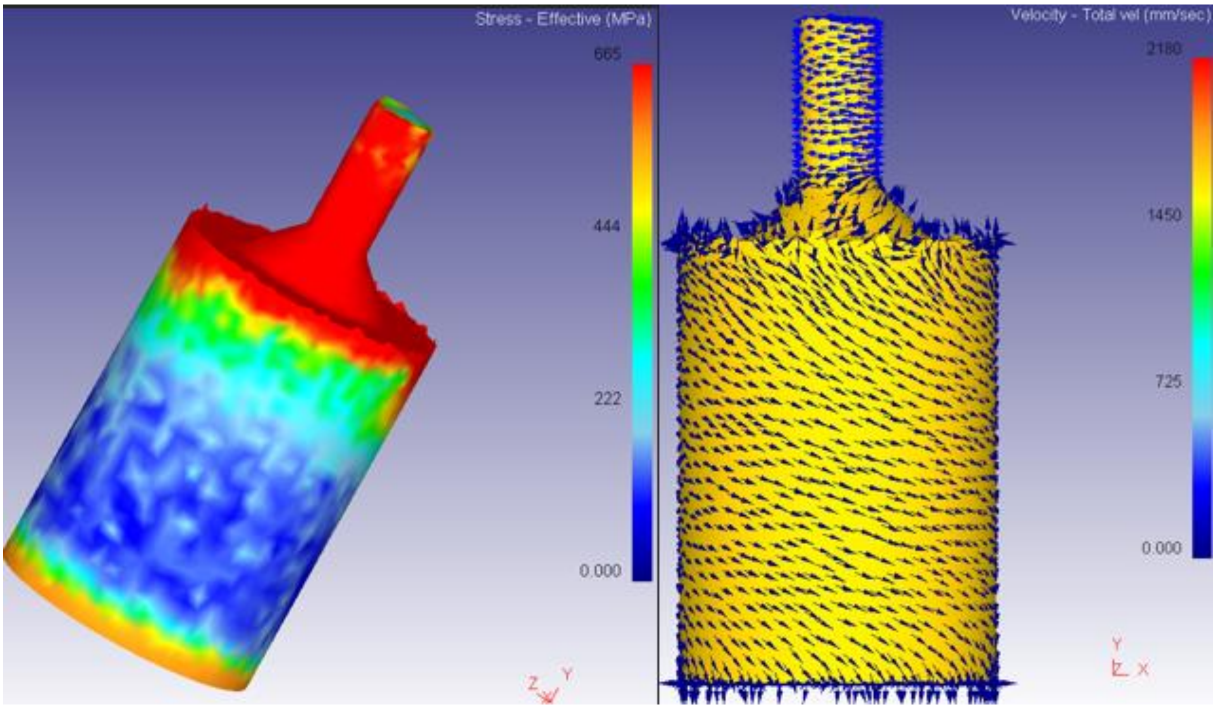

Figure 44 Stress (effective) and Velocity - Total Velocity 3D simulations for case 2

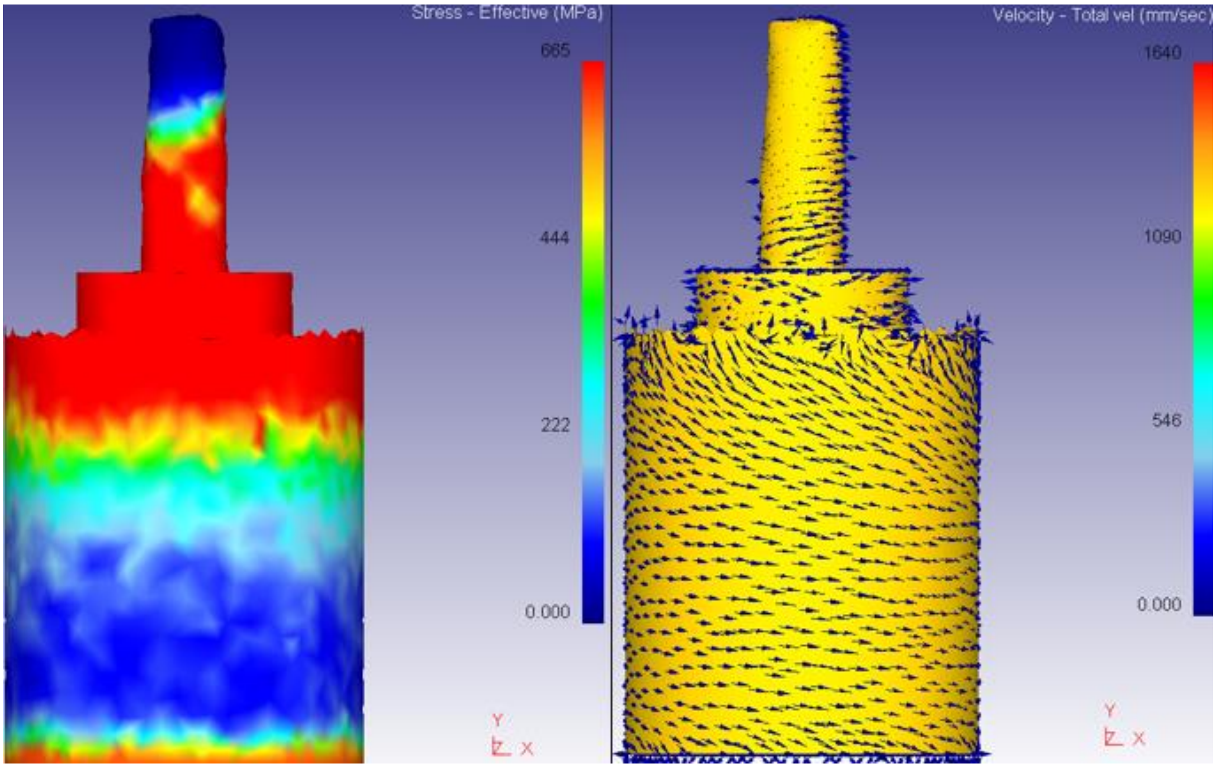

Figure 45 Stress (effective) and Velocity - Total Velocity 3D simulations for case 3

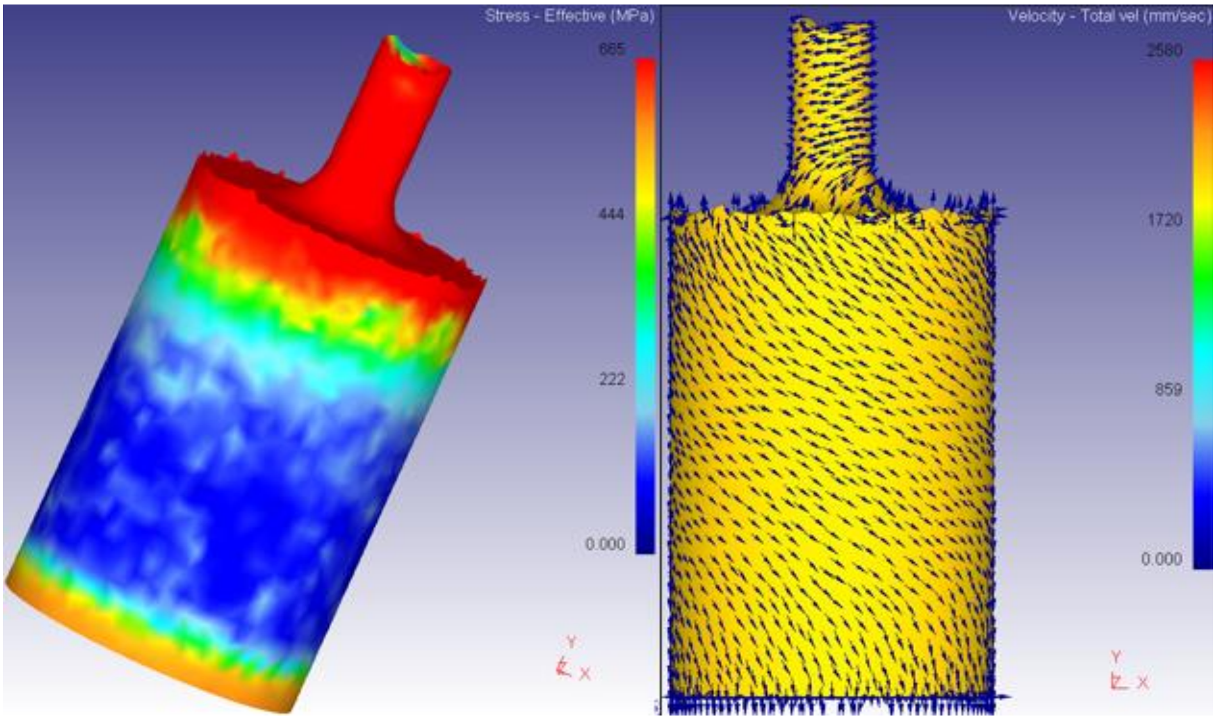

Figure 46 Stress (effective) and Velocity - Total Velocity 3D simulations for case 4

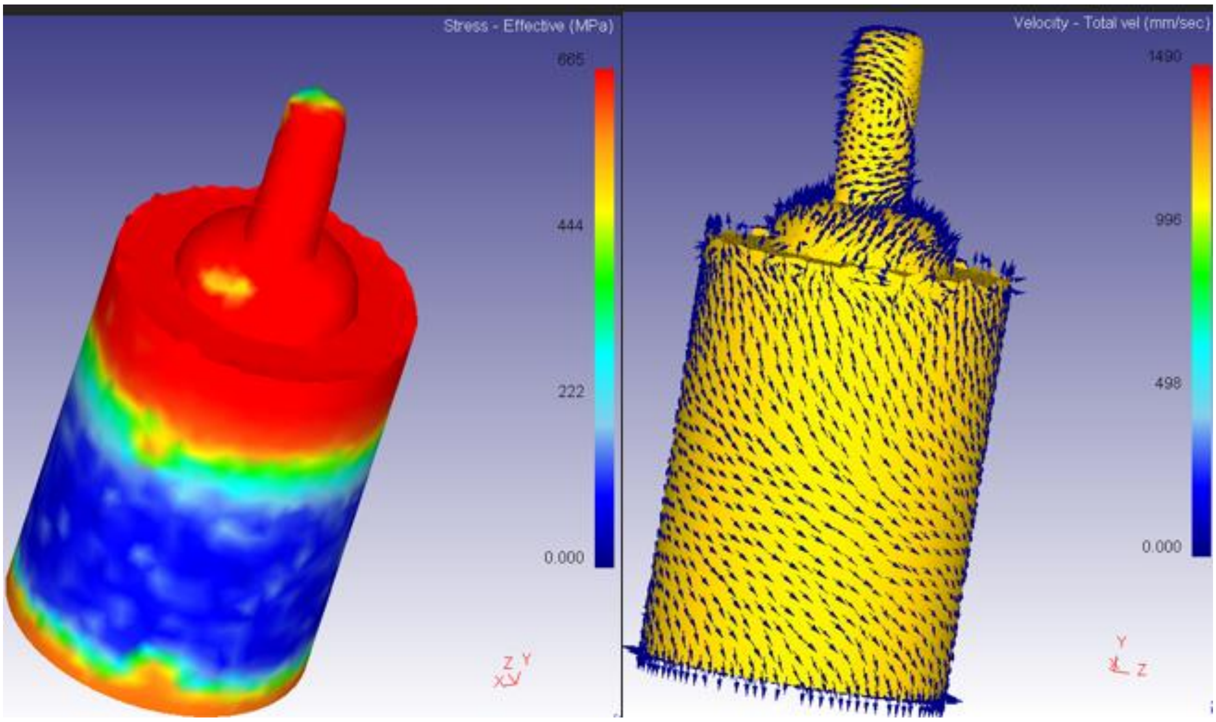

Figure 47 Stress (effective) and Velocity - Total Velocity 3D simulations for case 5