MID-SEMESTER REPORT

CAPSTONE PROJECT

(CP302)

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Lastly, we thank everyone who has played a role in advancing this project. With profound gratitude to the Almighty, we reflect on our collective journey with humility and eagerly anticipate further accomplishments in the future.

1. Title of the Project

Heat Assisted Incremental Sheet Metal Forming for Ti_6Al_4V

2. Introduction

Incremental Sheet Forming (ISF) is a dieless manufacturing process that gradually deforms sheet metal using a computer-controlled tool. Unlike conventional stamping or forming techniques, ISF uses a series of small, localized deformations to produce complex shapes without the need for dedicated dies. Although this technique has been successfully applied to ductile materials like aluminium, its use for high-strength alloys such as Ti_6Al_4V is limited by the alloy's poor formability at ambient conditions.

Ti_6Al_4V, a widely used titanium alloy in aerospace, biomedical, and automotive applications, exhibits a high yield strength (approximately 900 MPa) and low ductility (around 10% elongation) at room temperature. This inherent rigidity poses significant challenges when attempting to achieve the large plastic deformations required in forming processes. **Heat-Assisted Incremental Sheet Forming (HA-ISF)** overcomes these limitations by preheating the workpiece—thereby lowering the material's yield stress, reducing springback, and allowing for deeper draws. Heating not only enhances ductility but also minimizes the forces required for forming, thus enabling the fabrication of components with complex geometries and reduced risk of fracture.

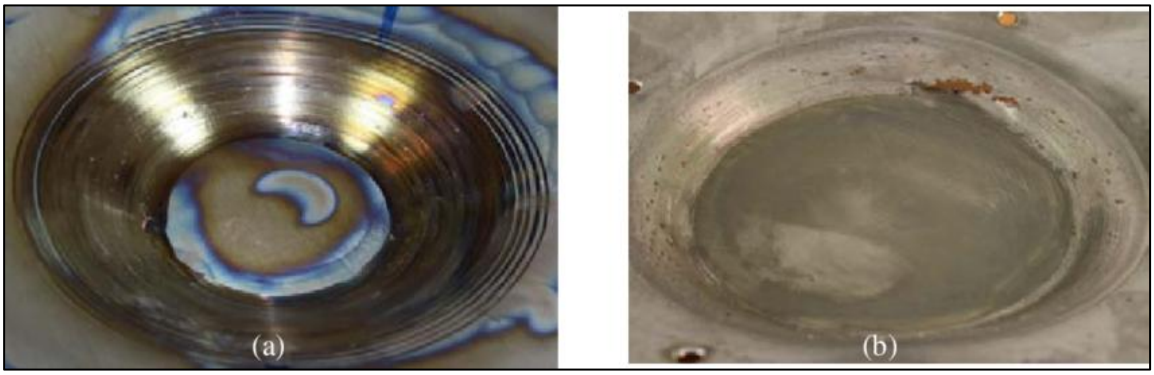

Fig.1: Sample Result of Incremental Sheet Forming (ISF)

In the present study, the focus is on analyzing the thermomechanical behavior of Ti6Al4V during HA-ISF using finite element simulations performed in Abaqus. The work encompasses simulation studies that examine:

- Temperature-dependent flow stress reduction at elevated temperatures 600°C
- Incremental forming simulations using a conical tool path generated via CAD/CAM integration.

A detailed analysis of the material's behavior under both mechanical and thermal loads is provided, alongside a discussion on future experimental validation using a prototype HA-ISF apparatus. The workpiece for this study is a Ti_6Al_4V plate with dimensions 150 mm × 150 mm and a thickness of 1 mm. An 80 mm × 80 mm area is designated for the forming operation, while the remainder of the plate serves as the clamping zone.

3. Literature Review

3.1 Challenges in Ti_6Al_4V Forming

Ti_6Al_4V is a dual-phase (α+β) titanium alloy characterized by its high strength-to-weight ratio and excellent corrosion resistance. However, its limited ductility at room temperature is a major challenge in forming processes. The alloy's microstructure contributes to its high yield strength but also results in early onset of plastic instability when subjected to large deformations. Researchers have documented that dynamic recovery and recrystallization occur at elevated temperatures (typically between 300°C and 700°C), which reduce flow stress by up to 55% [1]. For example, Li et al. (2022) demonstrated that induction heating to 600°C can improve the formability of Ti_6Al_4V by approximately 40% compared to its room-temperature behavior [2].

3.2 Heat-Assisted ISF Techniques

To overcome the challenges posed by the low formability of Ti_6Al_4V, several heat-assisted ISF techniques have been explored:

- **Global Heating:**
  The entire sheet is uniformly heated using furnaces or radiant heaters. While this method is straightforward, it may result in thermal gradients that cause non-uniform deformation.
- **Local Heating:**
  Techniques such as laser or induction heating focus thermal energy on the immediate area of contact between the tool and the sheet. This approach reduces energy consumption and minimizes thermal effects on the clamped regions.
- **Friction-Assisted Heating:**
  In this variant, heat is generated by friction between the forming tool and the sheet. The inherent heat produced during tool rotation can eliminate the need for an external heat source.

Key literature findings include:

- The optimal forming temperature for Ti6Al4V typically ranges between 500°C and 700°C [3].
- Toolpath optimization is essential to minimize geometric inaccuracies arising from thermal expansion [4].
- Appropriate lubricants, such as graphite or MoS_2, are used to reduce tool wear and prevent adhesion of the titanium alloy to the forming tool [5].

3.3 Numerical Modelling in ISF

Numerical simulation plays a crucial role in predicting the outcomes of incremental forming processes. The Finite Element Method (FEM) is widely used to simulate complex forming operations. In the context of HA-ISF, FEM simulations must account for both the mechanical deformation and the thermal effects. One of the most commonly used material models for such analyses is the **Johnson-Cook plasticity model**, which captures the temperature- and strain-rate-dependent behavior of metals. The Johnson-Cook model is expressed as:

$$Y = \left[A + B\varepsilon_p^n\right]\left[1 + C\ln\varepsilon_p^*\right]\left[1 - T_H^m\right]$$

where

ε_p = effective plastic strain

ε_p^* = normalized effective plastic strain rate

T_H = homologous temperature = $(T - T_{room})/(T_{melt} - T_{room})$

4. Current Solutions

4.1 Traditional Forming Methods

Traditional forming processes for titanium alloys include:

- **Hot Stamping:**
  A process that involves preheating the metal before forming, which can lead to long cycle times and high energy consumption.
- **Superplastic Forming:**
  This technique takes advantage of the alloy's superplastic behavior at high temperatures and low strain rates. However, it is limited by the requirement for very low forming speeds and extensive cycle times.

4.2 Advanced ISF Systems

In recent years, several advanced systems have been developed for incremental forming:

- **Electric Resistance Heating:**
  In this approach, Joule heating is integrated into the forming tool to locally heat the sheet during the forming process.
- **Laser-Assisted ISF:**
  Laser heating provides precise control over the heated zones but comes with high capital costs.

- **Induction Heating:**
  This method uses electromagnetic induction to efficiently heat the workpiece and is particularly promising for scaling up production [7].

Despite these innovations, challenges remain:

- **Thermal Gradients:**
  Non-uniform heating can cause uneven deformation and residual stresses.
- **Tool Wear and Adhesion:**
  At temperatures above 400°C, Ti6Al4V tends to adhere to tools, increasing wear and potentially damaging both the tool and the workpiece [8].

5. Objective

The primary objectives of this project are:

1. **Temperature-Dependent Flow Stress Quantification:**
   Quantify the reduction in yield stress and associated increases in ductility when the material is heated to 600°C.
2. **Incremental Forming Simulation:**
   Simulate the incremental forming of a conical geometry by generating and integrating CNC-compatible toolpaths into Abaqus.
3. **Prototype Apparatus Development:**
   Design and develop an HA-ISF apparatus capable of both global and local heating for future experimental validation.
4. **Process Optimization:**
   Optimize forming parameters—including toolpath design, forming forces, and heating profiles—to achieve defect-free components with minimal residual stresses.
5. **Elastic-Plastic Deformation Analysis:**
   Evaluate the mechanical response of a Ti_6Al_4V sheet under point load conditions and determine the effects of thermal gradients on its deformation behavior.

6. Experimental and Analytical Details

6.1 Material Properties and Specimen Description

- **Material:** Ti_6Al_4V (Grade 5)
- **Plate Dimensions:** 150 mm × 150 mm
- **Sheet Thickness:** 1 mm
- **Exposed Forming Area:** 80 mm × 80 mm (remaining area used for clamping)

Properties:

- Thermal Conductivity: 7.2 W/m·K
- Specific Heat Capacity: 526 J/kg·K
- Coefficient of Thermal Expansion: 9.5 μm/m·K
- Mass Density: 4.43 g/cc
- Young's Modulus: 113.6 GPa

These properties are critical for accurately modeling both the mechanical and thermal behavior of the alloy during simulation.

6.2 Numerical Simulations in Abaqus

The project utilizes Abaqus to perform detailed finite element analyses (FEA) under various loading and thermal conditions. Three primary simulation cases were investigated:

6.2.1 Incremental Forming Simulation

Objective:

To simulate the incremental forming process for a conical geometry using a toolpath generated from CAD data.

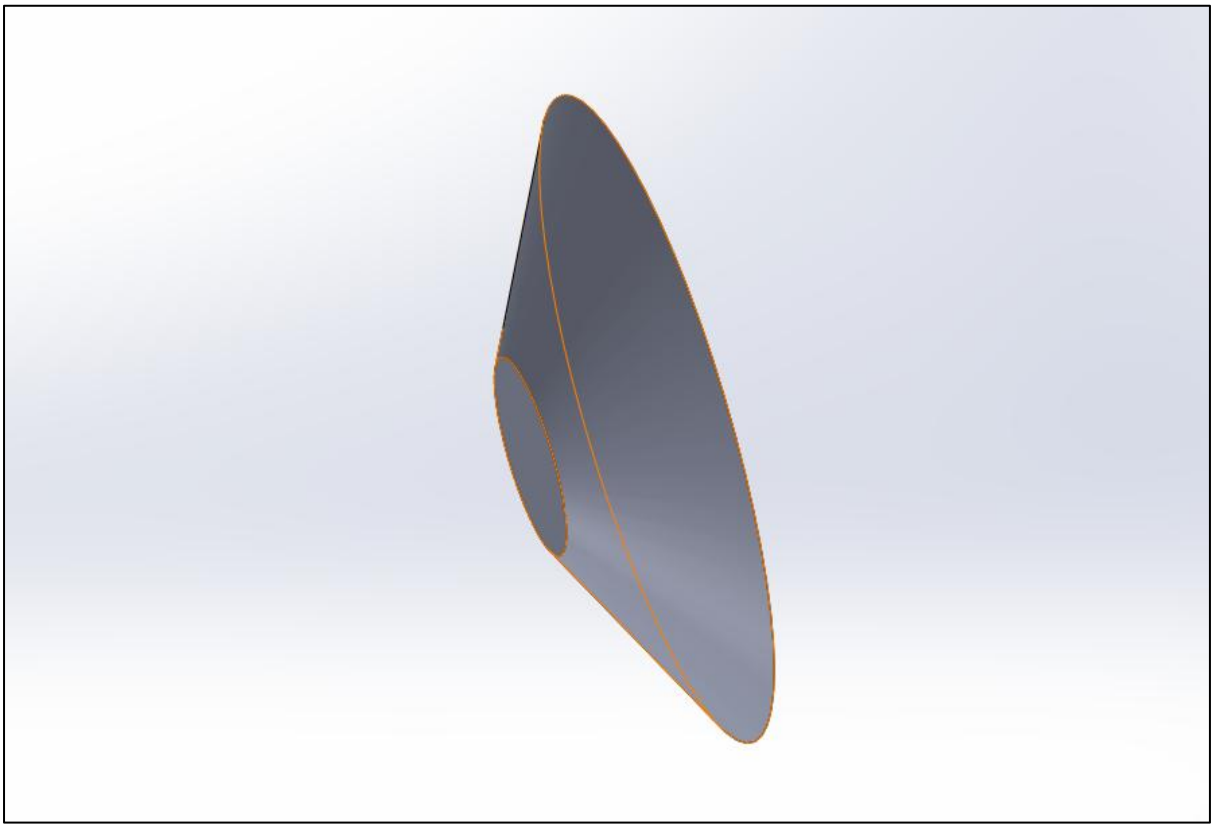

Fig. 2: Toolpath design created in SolidWorks, showing the planned forming trajectory for incremental deformation.

Modeling Details:

- **Toolpath Generation:**
  A spiral toolpath with a 30° wall angle is designed using Fusion 360. The toolpath is then exported and integrated into Abaqus.

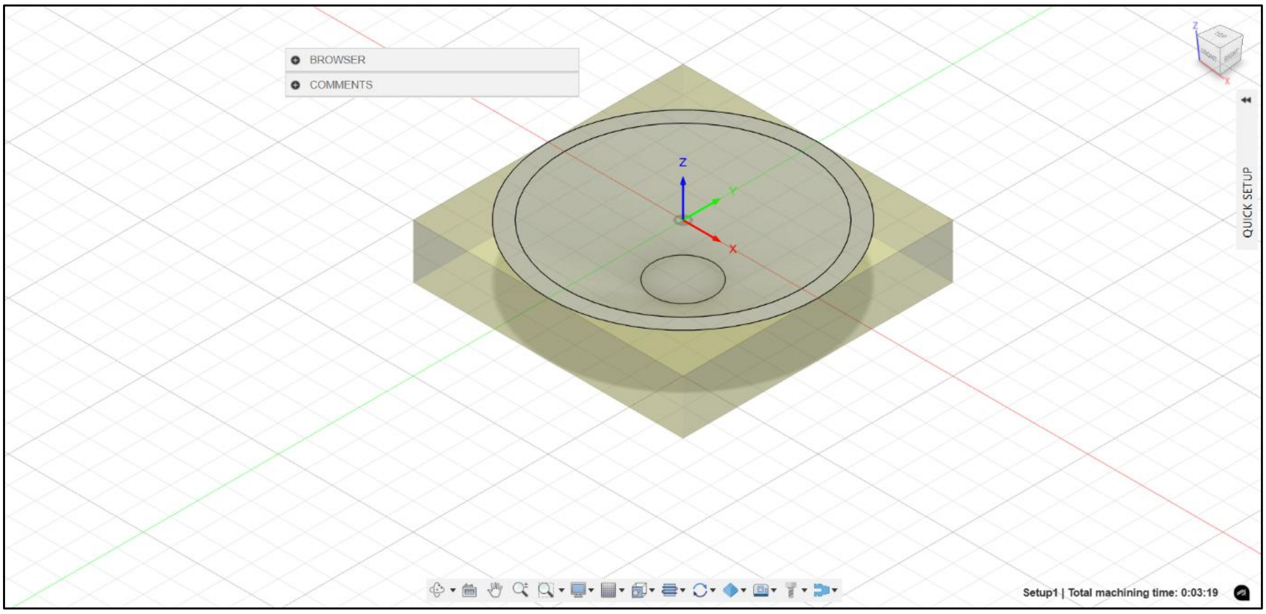

Fig. 3.1: Toolpath generation in Fusion 360, illustrating the CNC-compatible trajectory for incremental sheet forming.

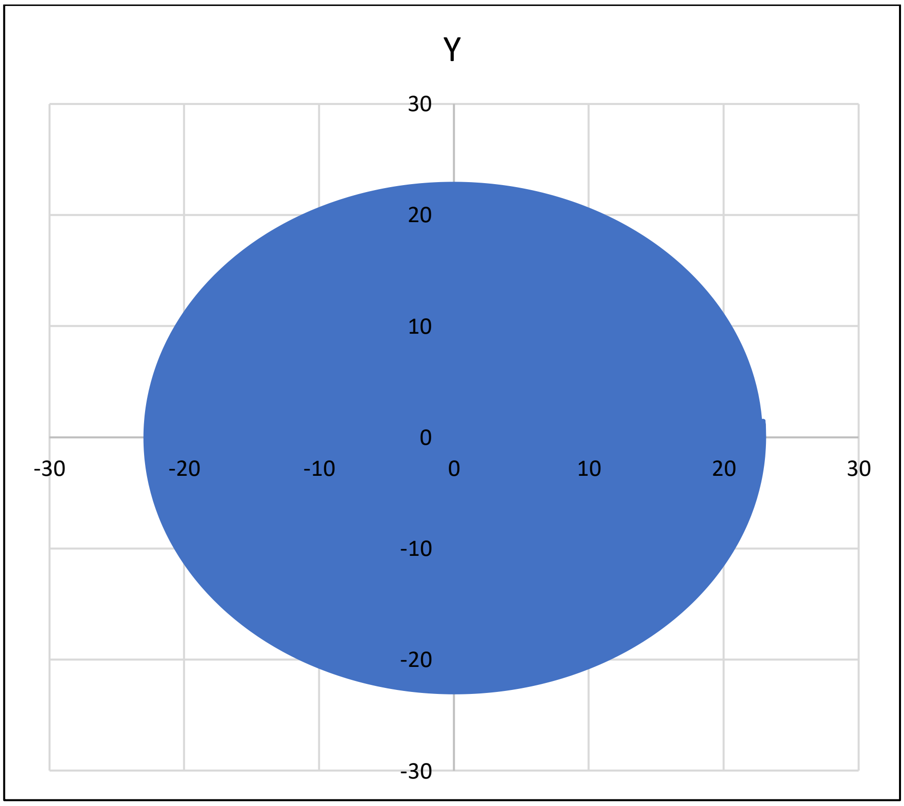

Fig. 3.2: Top View of the Deformed Ti6Al4V Plate in Y-Direction Showing Circular Symmetry

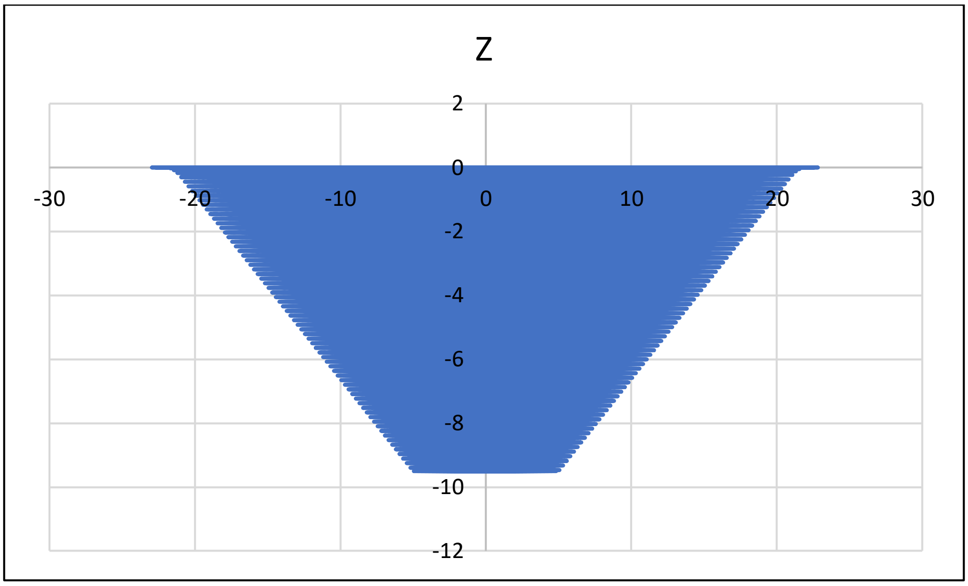

Fig. 3.3: Cross-sectional Profile of the Deformed Ti6Al4V Plate in Z-Direction During Incremental Forming

- **Contact and Friction:**
  Appropriate frictional properties are assigned at the interface between the tool and the sheet to mimic real forming conditions.

- **Material Behavior:**
  The Johnson-Cook plasticity model is adopted to capture the temperature- and strain-rate-dependent behavior of Ti_6Al_4V. The parameters used are:

Simulations

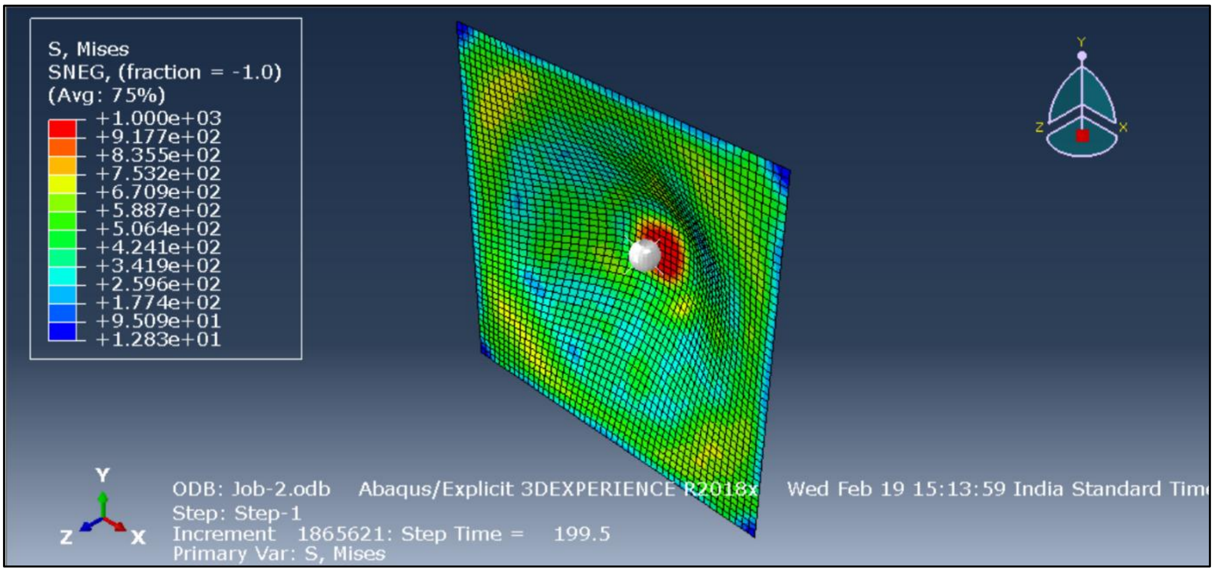

Fig 4: Von Mises stress distribution (S, Mises)

Description:
This image shows the **Von Mises stress distribution**, which is a scalar value derived from all three principal stresses to predict yielding in ductile materials under complex loading conditions.

Stress Values:

- **Maximum Von Mises Stress**: +1000.0 MPa (red zone near tool interaction).
- **Minimum Von Mises Stress**: +12.8 MPa (blue region away from deformation zones).

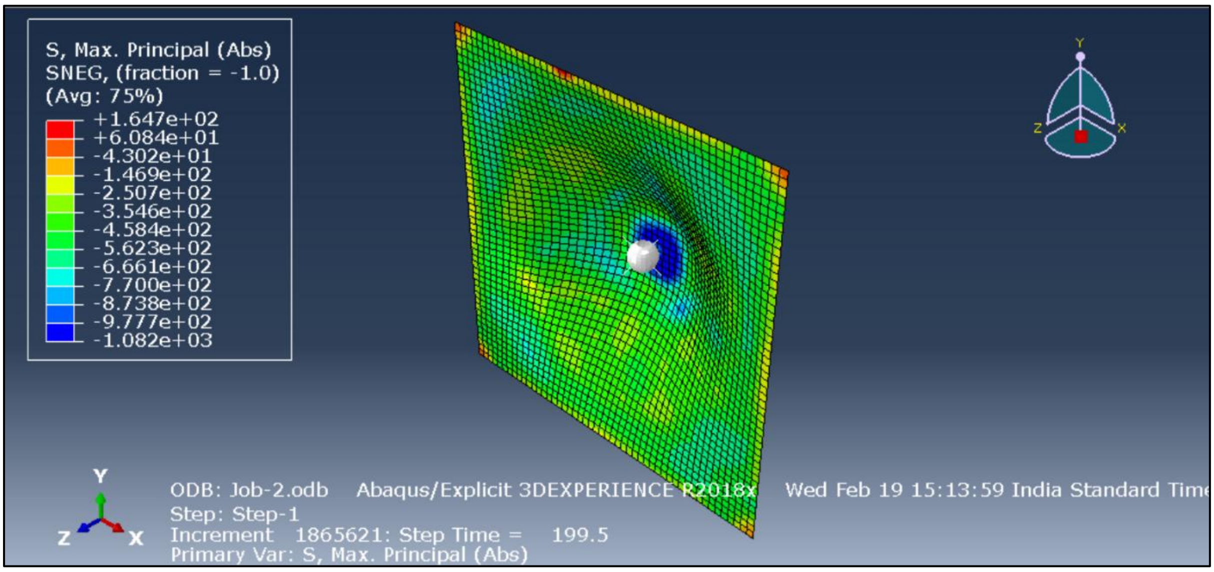

Fig. 5: Maximum absolute stress (S,Max(abs)) distribution

Description:
This image shows the **maximum principal stress** distribution across the Ti_6Al_4V plate.Principal stresses are the normal stresses acting on specific planes where shear stress is zero. The maximum principal stress highlights tensile stresses that could lead to material failure, such as cracking or fracture.

Stress Values:

- **Maximum Stress**: +164.7 MPa(red region near tool contact area).
- **Minimum Stress**: −1082.0 MPa(blue region away from the tool).

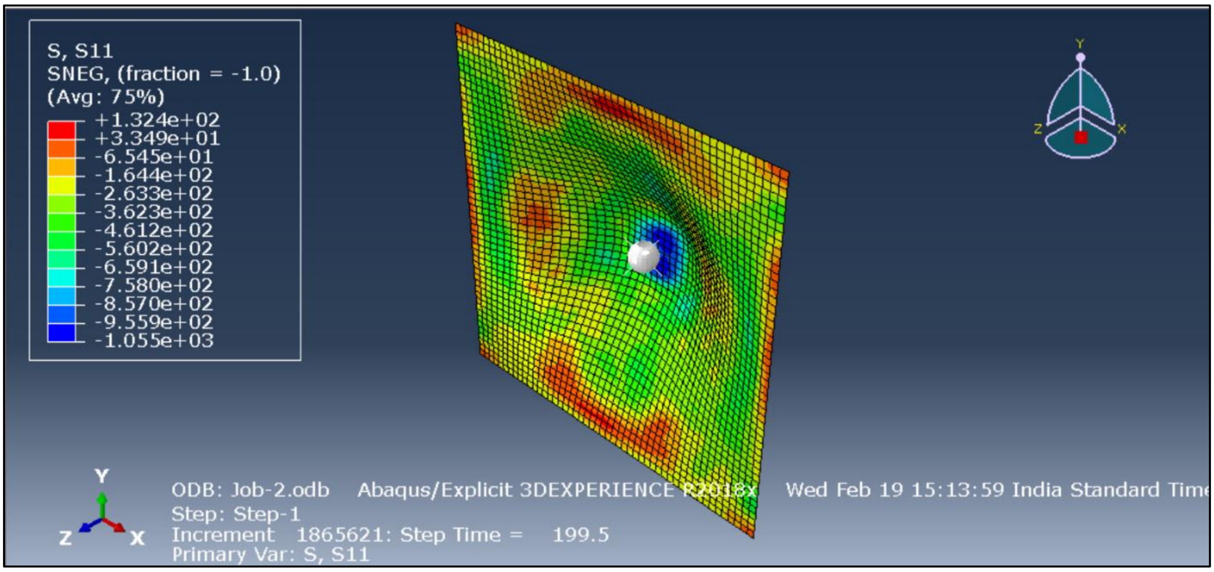

Fig.6: Axial stress (S, S11) distribution along the primary loading direction

Description:
This image represents the **normal stress (S, S11)** distribution along the X-axis during incremental forming. Normal stresses act perpendicular to surfaces and can be tensile or compressive depending on their direction and magnitude.

Stress Values:

- **Maximum Normal Stress (Tensile)**: +132.4 MPa (red zones near tool interaction).
- **Minimum Normal Stress (Compressive)**: −1055.0 MPa (blue regions away from deformation zones).

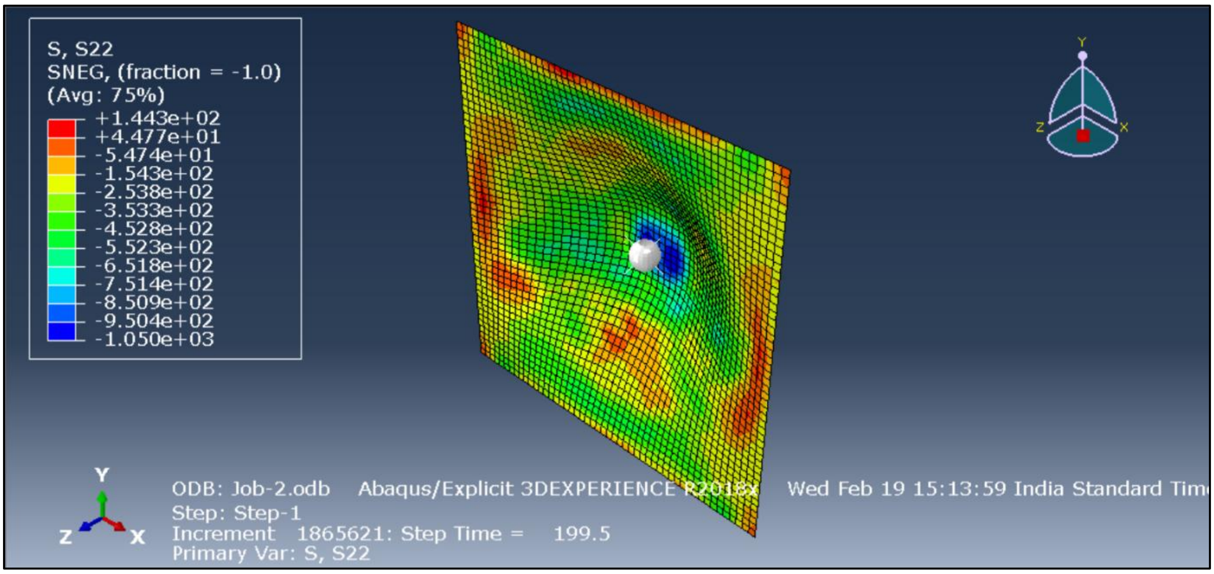

Fig. 7: Axial stress (S, S22) distribution perpendicular to the primary loading direction.

Description:
This image shows the **normal stress (S, S22)** distribution along the Y-direction during incremental forming of the Ti_6Al_4V plate. Normal stresses act perpendicular to surfaces in the Y-direction and are critical for analyzing material deformation and stability during forming operations.

Stress Values:
- **Maximum Shear Stress**: **+144.3 MPa** (red regions near tool interaction).
- **Minimum Shear Stress**: **-1050 MPa** (blue regions away from deformation zones).

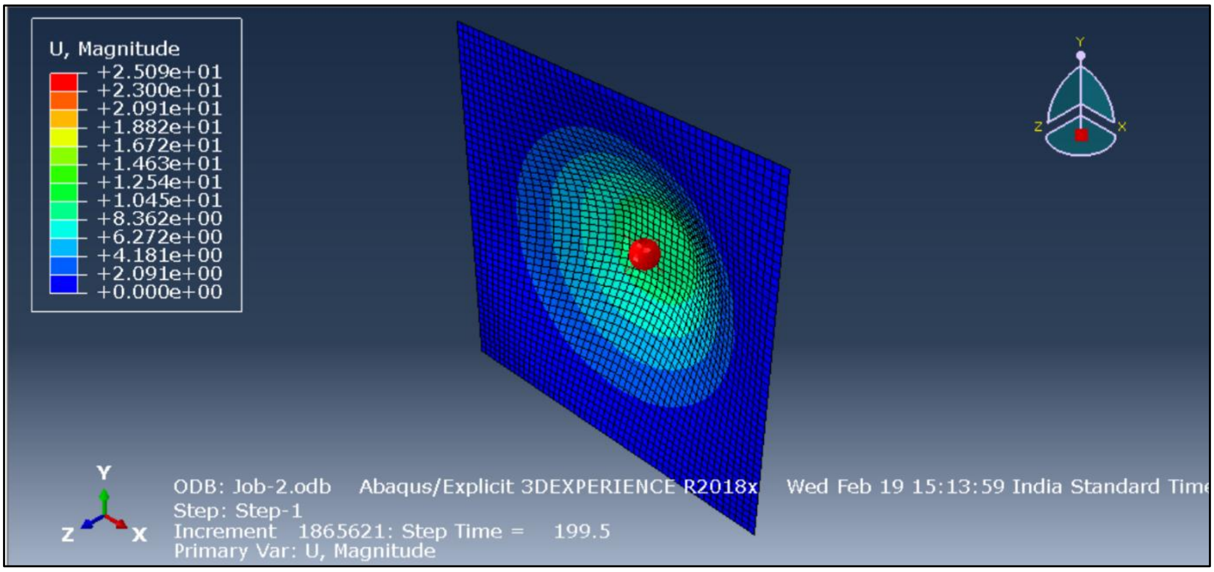

Fig. 7: Displacement field (Magnitude) illustrating the overall deformation of the sheet

Description:
- **Maximum Displacement**: **25.09 mm** (red region near the tool contact area).
- **Minimum Displacement**: **0 mm** (blue region far from the tool path).
- **Gradient**: Displacement decreases radially outward from the tool, transitioning from red to blue.

Results: -
1. High-stress regions near the tool contact area indicate significant localized deformation, with maximum principal stress at **+164.7 MPa** and Von Mises stress at **+1000 MPa**, confirming controlled plastic deformation for forming complex geometries.

2. Normal stress distributions (S11 and S22) show tensile stresses near the tool aiding elongation and thinning (**S11: +132.4 MPa, S22: +144.3 MPa**), while compressive stresses dominate away from the tool path, ensuring material stability (**S11: -1055 MPa, S22: -1050 MPa**).

3. Von Mises stress distribution confirms that yielding occurs near the tool interaction zone, with values reaching **+1000 MPa**, validating the effectiveness of incremental forming forces in inducing plastic deformation while ensuring stresses remain within safe limits to prevent fracture.

4. High displacement near the tool confirms localized plastic deformation, which is critical for incremental forming, while the gradual reduction in displacement away from the tool indicates controlled force propagation, preserving material stability.

5. The results validate the effectiveness of incremental forming in shaping Ti6Al4V while maintaining structural integrity in undeformed regions.

6.2.2 Thermal Analysis

Objective:

To study the influence of elevated temperatures on the deformation behavior of the Ti_6Al_4V plate.

Modeling Details:

- **Simulation Cases:**
  The entire sheet is heated to 600°C.
- **Coupled Analysis:**
  A coupled temperature-displacement analysis is conducted to account for thermal expansion and temperature-dependent material properties.
- **Material Model:**
  The yield stress is modeled as temperature-dependent, following an Arrhenius-type relationship:

Simulations: -

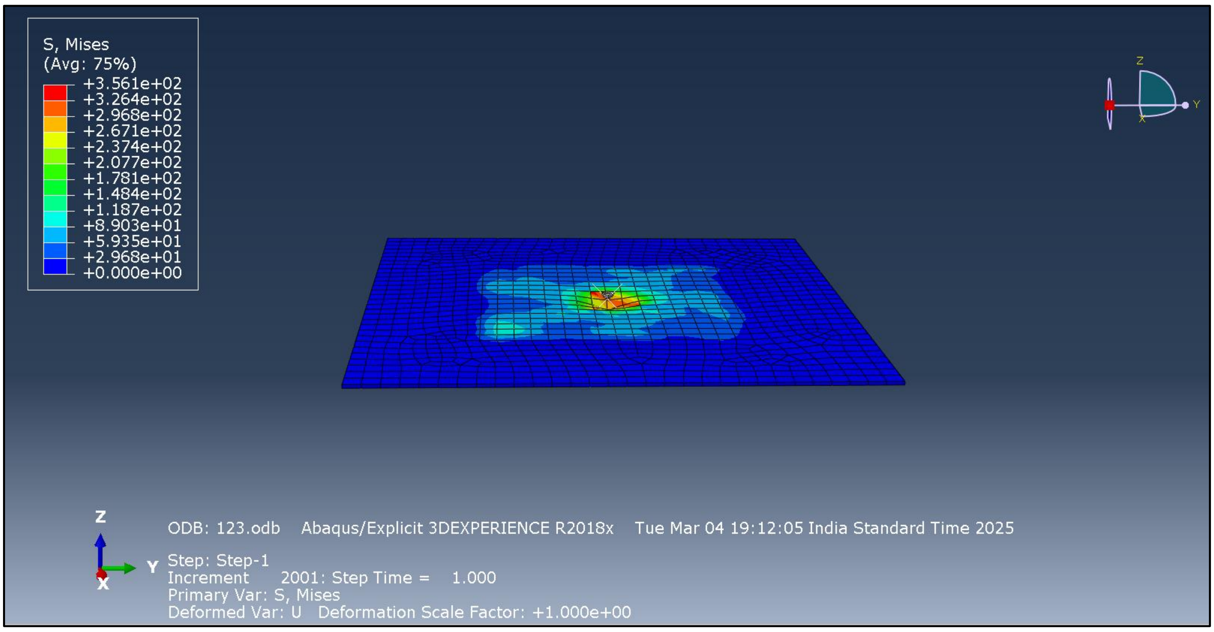

Fig. 8: Von Mises Stress Distribution on Ti_6Al_4V Plate at 600°C

Description:
This image represents the **Von Mises stress distribution** on the Ti_6Al_4V plate during a simulation conducted at 600°C. Von Mises stress is used as a yield criterion for ductile materials to predict plastic deformation under complex loading conditions.

Stress Values:
- **Maximum Von Mises Stress**: **356.1 MPa** (red region near the tool contact area).
- **Minimum Von Mises Stress**: **0 MPa** (blue regions far from the tool path).

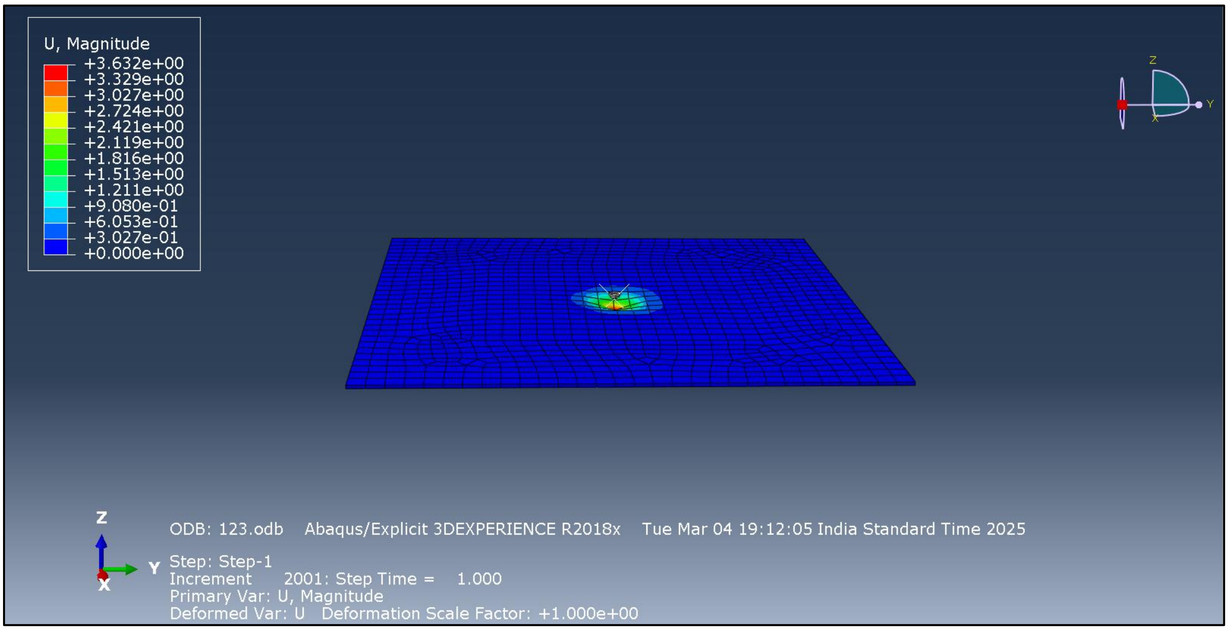

Fig. 9: Displacement Magnitude Distribution on Ti_6Al_4V Plate at 600°C

Description:
This image represents the **displacement magnitude (U)** distribution on the Ti6Al4V plate during a simulation conducted at 600°C. Displacement magnitude refers to the total deformation experienced by each point on the plate, combining displacements in all three directions (X, Y, Z).

Key Observations:
- **Maximum Displacement**: **3.63 mm** (red region near the tool interaction zone).
- **Minimum Displacement**: **0 mm** (blue regions far from the tool path).

Results:
1. Significant plastic deformation occurs at the tool contact area, with high stress (356.1 MPa) and displacement (3.63 mm).
2. Stress and displacement decrease gradually away from the tool path, ensuring controlled deformation and stability in surrounding regions.
3. Elevated temperature (600°C) reduces flow stress, allowing higher deformation with lower forces and lowering fracture risks.

7. Work Done and Future Plans

7.1 Work Completed

The project has achieved several key milestones to date:

1. **Toolpath Integration and Incremental Forming Simulation:**
   - Successfully generated CNC-compatible toolpaths using a spiral strategy for conical geometries.
   - Integrated the toolpath into Abaqus simulations and observed realistic deformation patterns, validating the numerical model based on the Johnson-Cook plasticity framework.

2. **Thermal Analysis:**
   - Conducted coupled temperature-displacement simulations at 600°C
   - Quantified the reduction in yield stress (up to 28.37% at 600°C) and observed corresponding increases in plastic strain.
   - These findings confirm that heat assistance significantly enhances the formability of Ti6Al4V.

7.2 Future Work

The upcoming phases of the project will focus on further integrating thermal effects with incremental forming and advancing towards experimental validation:

1. **Coupled Thermo-Mechanical Simulation:**
   - Develop a simulation that integrates localized heating with the incremental forming process.
   - Implement a dynamic heat source along the toolpath to model the effects of laser-assisted or induction heating.
   - Assess the impact of local heating on residual stresses and deformation uniformity.

2. **Prototype Apparatus Development:**
   - Design an experimental setup incorporating induction heating coils capable of achieving target temperatures in the range of 600–700°C.
   - Develop a closed-loop temperature control system to ensure uniform and precise heating during the forming process.
   - Fabricate or procure ceramic-coated tools (e.g., WC-Co) to mitigate adhesion issues associated with high-temperature forming of Ti6Al4V.

3. **Local Heating Analysis:**
   - Compare the efficiency and energy consumption of local heating techniques (e.g., laser-assisted ISF) against global heating.
   - Investigate the effect of localized heat input on minimizing thermal gradients and reducing the formation of residual stresses.

4. **Process Parameter Optimization:**
    - Conduct a comprehensive parametric study to optimize key forming parameters such as tool path geometry, incremental step size, and dwell times.
    - Utilize simulation results to define a robust operational window for HA-ISF of Ti_6Al_4V.
    - Implement optimization algorithms to further refine process conditions for maximum formability and minimum defect occurrence.

5. **Advanced Constitutive Model Refinement:**
    - Enhance the numerical models by incorporating more sophisticated temperature-dependent strain hardening laws.
    - Consider dynamic recrystallization and microstructural evolution effects at high forming temperatures.
    - Validate refined models through comparison with both simulation and future experimental data.

8. Conclusion and Discussion

8.1 Key Findings

The simulation studies presented in this report provide critical insights into the feasibility and benefits of heat-assisted incremental sheet forming for Ti_6Al_4V:

- High-stress regions near the tool contact area indicate significant localized deformation, with a maximum principal stress of +164.7 MPa and a Von Mises stress of +1000 MPa, confirming controlled plastic deformation for complex geometries.

- Normal stress distributions show tensile stresses near the tool (S11: +132.4 MPa, S22: +144.3 MPa) that aid in elongation and thinning, while compressive stresses away from the tool (S11: -1055 MPa, S22: -1050 MPa) ensure overall material stability.

- The Von Mises stress pattern confirms that yielding occurs predominantly in the tool interaction zone, with values reaching +1000 MPa, validating the incremental forming forces as effective yet safe.

- High localized displacement near the tool, along with a gradual reduction away from it, underscores both the targeted plastic deformation (with overall high displacement of 3.63 mm and stress of 356.1 MPa) and controlled force propagation.

- Operating at an elevated temperature of 600°C further reduces the flow stress, enabling higher deformation with lower applied forces and minimizing the risk of fracture.

8.2 Challenges and Considerations

Despite these promising findings, several challenges remain:

- **Thermal Expansion and Residual Stresses:**
  Non-uniform heating, particularly in global heating scenarios, can lead to significant thermal gradients and residual stresses. These must be mitigated to avoid distortion and defects in the final component.
- **Tool Wear and Material Adhesion:**
  At temperatures exceeding 400°C, Ti_6Al_4V exhibits a tendency to adhere to the forming tool, leading to increased wear. The use of ceramic coatings and optimized lubricants is recommended to alleviate this issue.
- **Control of Localized Heating:**
  Implementing an effective localized heating strategy that synchronizes with tool motion is technically challenging. Closed-loop control systems and precise heat source positioning are necessary to ensure uniform heating and prevent overheating of non-targeted regions.

8.3 Recommendations

Based on the simulation results and current challenges, the following recommendations are proposed:

- **Tool Material and Coatings:**
  Employ ceramic-coated tools (e.g., tungsten carbide-cobalt composites) to reduce high-temperature adhesion and prolong tool life.
- **Temperature Control:**
  Integrate a closed-loop control system for the heat source to achieve uniform temperature distribution and minimize thermal gradients.
- **Process Parameter Optimization:**
  Further optimization studies should be conducted to refine toolpath geometry, incremental step size, and heating profiles. This will help to define a robust process window that maximizes formability while minimizing defects.
- **Experimental Validation:**
  The development of a prototype HA-ISF apparatus is essential for validating the simulation findings. Experimental tests should focus on measuring real-time temperature distributions, force responses, and deformation characteristics to confirm and calibrate the numerical models.

In summary, the integration of heat assistance with incremental sheet forming presents a viable solution for fabricating complex components from high-strength alloys such as Ti_6Al_4V. The reduction in flow stress achieved through controlled heating enables significant improvements in formability and deformation uniformity. Although challenges remain regarding thermal control and tool wear, the simulation studies provide a solid foundation for future experimental work and process optimization.

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