SIMULATION OF THE EFFECT OF BLANK GEOMETRY TOWARD THE MECANICAL PROPERTIES OF STRAINS AND STRESS ON DEEP DRAWING PROCESS USING MATERIAL ALUMINUM 7075

Adjie Yoga Pratama[1], Auzini Widyasari[1], Muhammad Fakhruddin[1]✉, Imam Mashudi[1], Mochamad Muzaki[1], Hilmi Iman Firmansyah[1]

[1] State Polytechnic of Malang, Indonesia

Author Email: adjieyogapratama04@gmail.com, auziniwidyasari508@gmail.com, fakhruddin91@polinema.ac.id, imam.mashudi@polinema.ac.id, mochamad.muzaki@polinema.ac.id, firmansyahilmi@polinema.ac.id

Article Information

Manuscript Received 2024-04-03
Manuscript Revised 2024-04-06
Manuscript Accepted 2024-04-10
Manuscript Online 2024-04-17

ABSTRACT

Using Aluminum 7075 at a high temperature of 50 degrees Celsius, this study examines the effect of various blank geometry angles on the mechanical properties of strain and stress during the deep drawing process. This study systematically examines the impact of different blank geometry angles on the deformation behavior, strain distribution, and stress concentration during the deep drawing process of Aluminum 7075 sheet using a numerical simulation approach. To describe the behavior of the material against the effect of the angle on the pressure in the simulation taking into account realistic parameters, the main point is the result of the pressure treatment of the predetermined angle on the results of the strains and stresses created. The obtained results, which include strain distribution, stress concentration, and overall mechanical reaction, provide important information for the choice of the best blank geometry angle in deep drawing of Aluminum 7075 at high temperatures. This research contributes to the advancement of process optimization in the metal forming industry, providing a solid foundation for improving efficiency and quality in deep drawing operations involving high-strength aluminum alloys.

Keywords: *Deep Drawing, Blank Geometri, Alumunium 7075, Simulation*

1. INTRODUCTION

Requirements for formatting figures: Before a figure, Deep drawing is a metal forming technique in which pressure is used to a flat sheet of material, usually metal, to create a three-dimensional shape[1], [2], [3]. The sheet is positioned over a die and bent into the required shape using a punch during the process. The material experiences plastic deformation as the punch lowers, stretching and taking on the shape of the die. Deep drawing is a common process in manufacturing that is used to create a wide range of products, including containers, home appliances, and automobile parts. It is an economical way to create intricate and seamless structures out of sheet metal[4], [5]. Maximizing productivity and minimizing errors are two important factors in the deep drawing process. Deep drawing technique is a very complicated, expensive, and frequently used manufacturing process in various industries[6], [7], [8]. Performing trial-and-error experiments on each product design before it is manufactured is one way to minimize errors, as deep drawing on products is unavoidable. This method wastes time, money and effort as it relies on individual expertise and experience. The manufacturing sector needs product design planning in the form of preliminary simulation to reduce losses due to design defects and eliminate product defects in the plate deep drawing process. One of the most used manufacturing techniques for creating a variety of goods across numerous industries is sheet metal forming[9], [10], [11], [12]. The deep sketching method is modified to produce products with the necessary shape without any failures. The study of the influence of the failures occurring in the deep drawing process of a circular cup using magnesium alloy is crucial to the ability to design a deep drawing product with the necessary blank material, size, shape, tool design, and lubrication choice. The study aims to estimate the LDR using variable BHF control and to comprehend the fracture mechanism of magnesium alloy sheet using FEM simulation. utilized numerical simulation technologies and the optimization approach in the sheet metal forming process to reduce design cycle time and enhance design quality. impacts of process factors utilizing both simulations and experiments on the formability of deep drawing of aluminum 7075[13].

One of the key methods in sheet metal forming, deep drawing, is crucial for forming materials into intricate shapes[14][15]. This study investigates the impact of blank geometry angle variation on the mechanical characteristics of strain and stress, specifically with relation to Aluminum 7075 at a high temperature of 50 degrees Celsius, in an effort to better understand this important manufacturing process. For deep drawing processes to effectively optimize process parameters, choosing the ideal blank geometry angle is essential. We investigated the deformation behavior, strain distribution, and stress patterns of 7075 Aluminum sheet during the deep drawing process using a numerical simulation approach[16], [17], [18], [19], [20]. This study attempts to capture the temperature-dependent behavior of the material and provide a thorough understanding of the influence of blank geometry angles on the mechanical response of the material by taking into account realistic settings, such as a thermal environment at 50 degrees Celsius[21][22]. It is expected that the findings of this study will make a substantial contribution to the field of metal forming by offering insightful information that will enhance the effectiveness and caliber of deep drawing processes utilizing high-strength aluminum alloys heated to high temperatures[23].

2. RESEARCH SIGNIFICANCE

This research, Simulation of the effect of blank geometry on the mechanical properties of strains and stress in the deep drawing process using Aluminum 7075 is crucial for optimizing process parameters, enhancing formability, and improving material selection and design. This research helps in reducing costs and time, improving product quality, and aligning with sustainability goals by minimizing waste and energy consumption in manufacturing.

3. RESEARCH METHODS

3.1 Methods

Process variables include blank temperature, punch radius, die arc radius, punch die clearance, punch speed, mechanical characteristics, sheet metal thickness, and component geometry all affect how formable the sheet blank is. aluminum's formability focused on the temperature's impact on deep drawn cup formation[16], [17], [24], [25]. A proper die radius minimizes material waste while simultaneously enabling smooth material flow. In a similar vein, material flow into the die cavity is improved by punch speed conditions. The degree to which various process parameters affect sheet metal forming determines the quality of the formed product. Punch speed influences metal flow into the die cavity in addition to blank temperature and die radius in the deep drawing process[8]

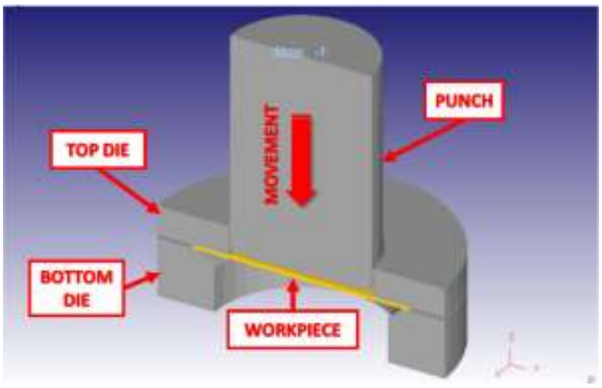

Fig 1. Experimental Setup

The present study used a simulation methodology to examine the effects of different angles of blank geometry on the mechanical properties of strains and stress during the deep drawing process of Aluminum 7075. In order to ensure accuracy and dependability, the study uses the DEFORM program to develop a numerical simulation model that is validated against established benchmarks. In order to depict a variety of configurations, blank geometry angles are methodically parameterized while taking known implications on the deep drawing process and industrial significance into account[26], [27]. To simulate real-world settings and accurately represent the temperature-dependent behavior of Aluminum 7075 material, the simulation is run at an enhanced temperature of 50 degrees Celsius. The study involves executing multiple simulation runs with varying blank geometry angles. The collected data is then evaluated to comprehend the impact of these angle variations on strain distribution, stress concentration, and the material's overall mechanical reaction. The goal of the project is to optimize blank geometry angles in deep drawing procedures to improve quality and efficiency while providing useful insights and useful suggestions for industrial use[12], [28], [29]. The technique concludes with a summary of findings and recommendations for future research areas. It involves validation against experimental data and sensitivity analysis to ensure robustness.

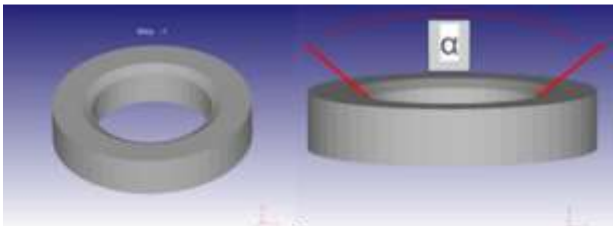

Fig 2. Bottom Die Geometry Variation

To maximize formability is the aim of this inquiry. Thus, using simulation tests, an effort has been made to examine the impact of the aforementioned critical process parameters—blank temperature, die arc radius, and punch speed—on the formability of AA 7075 in this examination[21], [23]. This study employs a practical and simulation-based methodology to analyze the impact of blank angle on the deep drawing process through the usage of Deform3D software. The last tool for mimicking deep drawing in Deform3D software is the form of blank drawings at different angles. The process begins with the preparation of engineering drawings in STL file format. (C1, C5, C10 30°, C10 45°, C10 60°, R1, R5, and R10), mold, and workpiece. The three types of tools put together will be arranged in such a way and simulated in the Deform3D software by paying attention to the Deform3D simulation parameter settings as follows:

a) Number of Elments : 83516
b) Material Temperature : 20°C
c) Punch Speed : 10 mm/sec.
d) Inter Object (Deformation) : 0.5
e) Step : 200
f) INC. to Save : 1
g) With Die Displacement : 0.25 mm

h) Blank Geometry : C1, C5, C10 30°, C10 45°, C10 60°
i) Workpiece Material : Alumunium 7075
j) Material Thickness : 2 mm

4. RESULTS AND DISCUSSION

Chamfer 1 mm tool blank result of load prediction,damage,strain effective,and stress effective.The following is a Deform3D simulation for Alumunium 7075, which examines the load generated by the punch load via graphs and looks at the outcomes of damage, stain, and stress absorbed by the workpiece. These are the outcomes of the simulation.

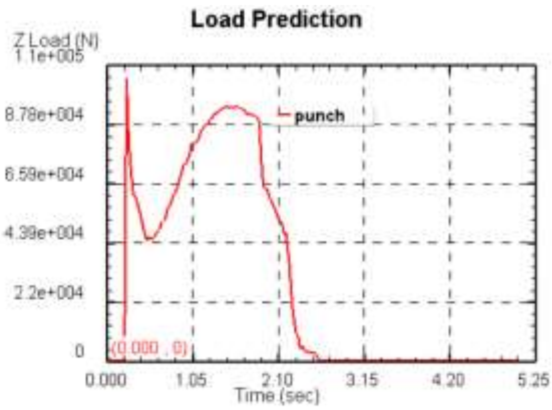

Fig 3. Load prediction for punch of C1 blank of deep drawing process of alumunium 7075

Important insights are revealed in step 82 of the deep drawing process of a chamfered 1 mm thick blank composed of aluminum 7075. The material shows significant degradation, measured at 5.87, which suggests localized necking or thinning. The greatest strain, 3.46 mm/mm, indicates how much the aluminum was distorted throughout the procedure. Concurrently, the material experiences a critical point where its maximum effective stress approaches 360 MPa, highlighting the need to evaluate its resistance to applied pressures. Bending or folding is significant at this point because it is a critical stage in the process where the aluminum experiences patterns of deformation that could result in flaws or problems in the finished product. These results highlight how crucial it is to have a thorough grasp of the material's behavior at various points during the deep drawing process in order to make any necessary adjustments to improve the overall performance and quality of the aluminum 7075 product.

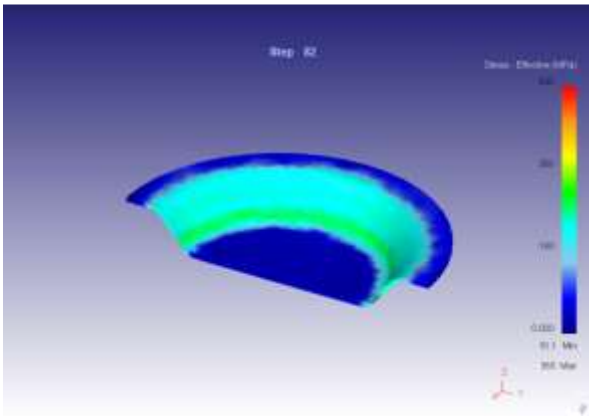

Fig 4. Damage, Strain, Stress for punch of C1 on step 82 stating fold blank of deep drawing process of alumunium 7075

workpiece starts to tear, suggesting that the material may be vulnerable. The material then experiences severe stress at step 114, peaking at 371 MPa and exhibiting a corresponding strain of 4.80 mm/mm. Additionally, a maximum damage value of 6.27 is recorded in this stage, indicating a significant degree of deformation and possible failure. Step 115 is where things get really bad since the material starts to fray and shatter completely. The damage at this point is 5.88, indicating that the trend of deformation and damage is still present. While the maximum effective stress of 360 MPa indicates a significant level of material deformation, the maximum strain is 3.47 mm/mm. Together, these results point to crucial stages in the deep drawing process where the aluminum 7075 shows fragility, especially with regard to tearing and breaking. Process optimization and maintaining the integrity of the finished product depend on recognizing and resolving these problems. To address the issues that have been discovered and improve the overall performance of the deep drawing process for the aluminum blank in question, modifications to the material qualities or process parameters may be required.

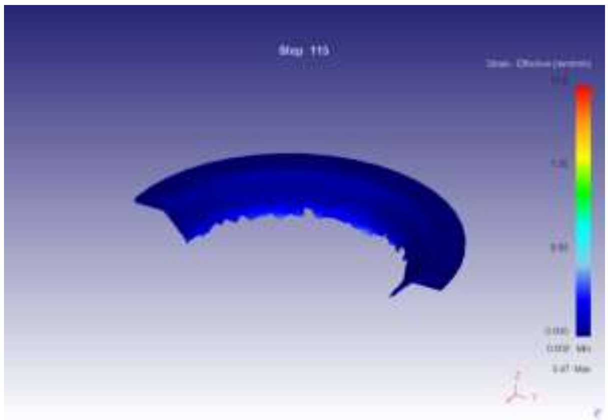

Fig 5. Damage, Strain, Stress for punch of C1 on step 115 after tearing blank of deep drawing process of alumunium 7075

Chamfer 5 mm tool blank result of load prediction, damage, strain effective, and stress effective. The following is a Deform3D simulation for Alumunium 7075, which examines the load generated by the punch load via graphs and looks at the outcomes of damage, stain, and stress

Journal of Evrimata: Engineering and Physics
Vol. 01, No. 02, Desember, 2023, p.70 – 77 e-ISSN: 3025-1265

absorbed by the workpiece. These are the outcomes of the simulation. Figure 5 illustrates that in order for the punch tool to press 2 mm thick Alumunium 7075 material and reach the maximum yield strength phase, the material must harden within 0 seconds, requiring a load force of 70000 N.

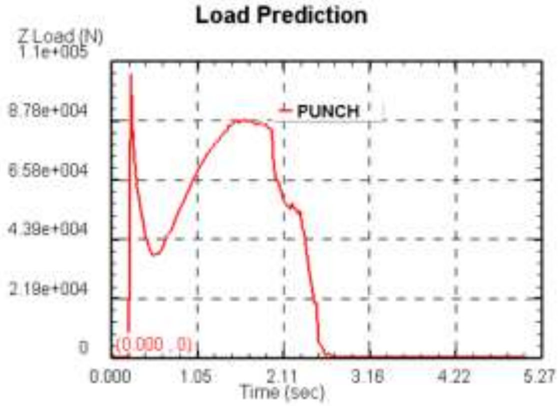

Fig 5. Load prediction for punch of C5 blank of deep drawing process of alumunium 7075

A C5 mm chamfer on the blank and a 1 mm chamfer on the punch have been used in the deep drawing process of aluminum 7075. Important parts of the procedure are revealed by the collected outcomes. The damage parameter, which is 2.71, indicates the degree of material damage that occurs during deep drawing and includes things like tearing or cracking. In addition, a maximum strain of 5.48 mm/mm denotes significant deformation and raises the possibility of a material breakdown. The peak stress effectiveness at step 88, which is 401 MPa, indicates the critical stress levels that the material is subjected to at that particular moment. The aluminum 7075 material notably bends or folds at step 88, marking a critical juncture in the process where the material may experience stress concentrations or instability. These results highlight the necessity of a detailed examination of the process parameters, tool design, and possible modifications to improve the final product. Optimizing the deep drawing process and minimizing flaws in the finished product require addressing the individual issues, such as the reason for bending or folding at step 88.

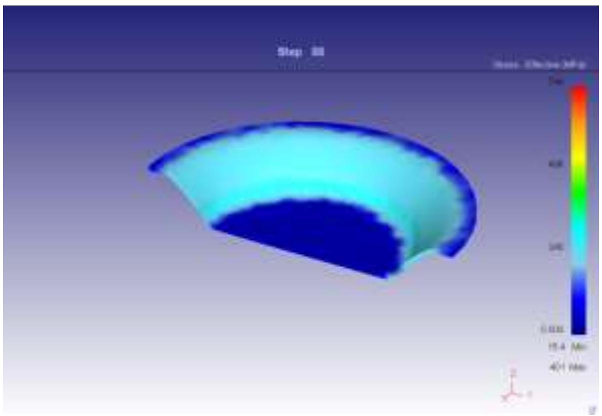

Fig 6. Damage, Strain, Stress for punch of C5 on step 88 starting fold blank of deep drawing process of alumunium 7075

A chamfered C5 mm thick aluminum 7075 blank was deep drawn, and during the process, important observations were made at particular stages that provided insight into the behavior of the material. The workpiece starts to shred at step 107, before a flaw occurs, exhibiting early indications of material fragility. At this point, the strain peaks at 6.99 mm/mm, the maximum stress hits 429 MPa, and the damage is recorded at 3.45 all at once. These numbers indicate a significant degree of stress concentration and deformation, which may have contributed to the later defect. Step 108 is where things get very bad since the material starts to fray and shatter. At step 33.15, the documented damage is unusually high, indicating a severe degree of deformation and material breakdown. The highest strain is recorded at 2.47 mm/mm, and the highest effective stress is noteworthy at 332 MPa, underscoring the difficulties faced at this specific deep drawing stage. These results point to crucial stages in the process where the aluminum 7075 blank shows significant susceptibility, especially to tearing and breaking. Optimizing the deep drawing process requires an analysis and knowledge of these problems. To address these obstacles and improve process performance for the particular aluminum blank, changes to the material's characteristics or process parameters may be required.

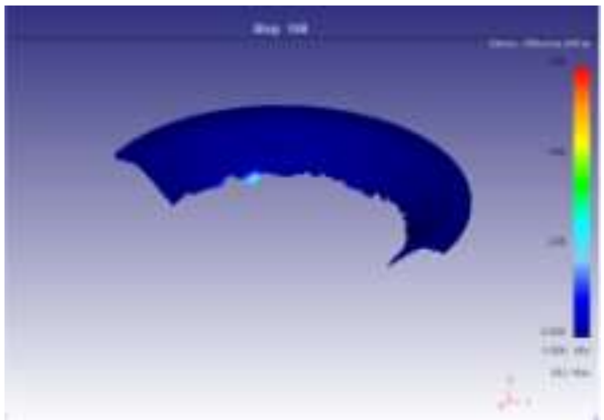

Fig 7. Damage, Strain, Stress for punch of C5 after tearing defect of deep drawing process of alumunium 7075

Chamfer 10 mm with the 30 Degress angles tool blank result of load prediction, damage, strain effective, and stress effective. The following is a Deform3D simulation for Alumunium 7075, which examines the load generated by the punch load via graphs and looks at the outcomes of damage, stain, and stress absorbed by the workpiece. These are the outcomes of the simulation.

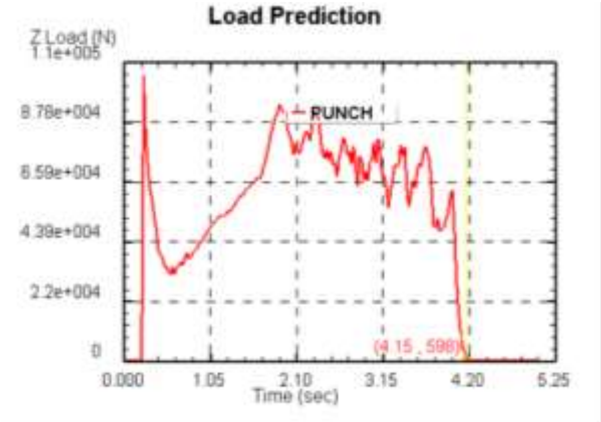

Fig 8. Load prediction for punch of C10 with the 30-degree angle tool blank of deep drawing process of alumunium 7075

The implementation of a 30-degree angle 10 mm chamfer on the blank and a matching chamfer on the punch in the deep drawing process of aluminum 7075 has produced noteworthy outcomes. The damage parameter, which registered at 0.797, indicates a successful outcome by suggesting minimum material damage during the deep drawing process. While the maximum stress effectiveness, measuring 0.00332 MPa at the ideal 200th step, suggests modest stress levels encountered by the material, the maximum strain of 1.22 mm/mm reflects a considerable level of deformation. Interestingly, the precise combination of a 30-degree angle and a 10mm chamfer has worked well to get the desired result. The workpiece's successful completion of the 200-step target without any flaws or tears highlights the beneficial effects of the selected parameters on the process as a whole. Do the angle and chamfer really have an impact on these outcomes? Yes, is the response. Choosing a 10-millimeter chamfer on the punch and blank that has a 30-degree angle has helped to keep stress levels low, minimize damage, and regulate strain throughout the deep drawing experiment. This implies that the performance of the deep drawing process for aluminum 7075 is greatly dependent on the selection of chamfer size and angle. The experiment will ultimately be successful in completing the specified number of steps when these criteria are carefully considered, as this helps to prevent flaws and ripping[30].

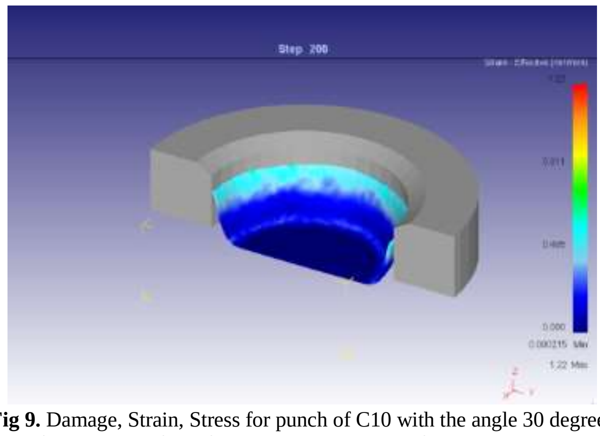

Fig 9. Damage, Strain, Stress for punch of C10 with the angle 30 degrees after tearing defect of deep drawing process of alumunium 7075

Chamfer 10 mm with the 45 Degress angles tool blank result of load prediction, damage, strain effective, and stress effective. The following is a Deform3D simulation for Alumunium 7075, which examines the load generated by the punch load via graphs and looks at the outcomes of damage, stain, and stress absorbed by the workpiece. These are the outcomes of the simulation. Figure 9 illustrates that in order for the punch tool to press 2 mm thick Alumunium 7075 material and reach the maximum yield strength phase, the material must harden within 0 seconds, requiring a load force of 70000 N.

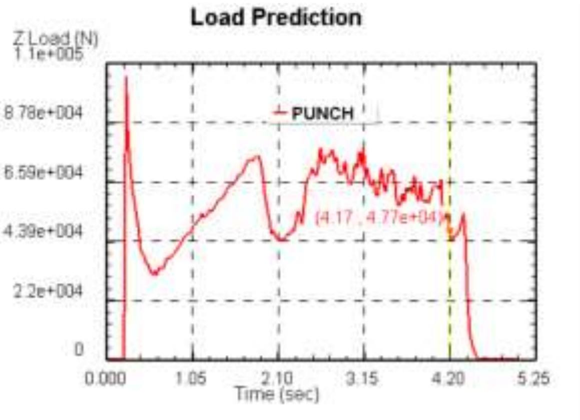

Fig 10. Load prediction for punch of 10 of the 45 degrees angle 5 blank of deep drawing process of alumunium 7075

When using a 10mm chamfer on the blank at a 30-degree angle in the deep drawing process using aluminum 7075, along with a matching chamfer on the punch, certain results have been obtained. At 0.756, the damage parameter shows that there was not much material damage throughout the deep drawing process, which is a good result. Likewise, a maximum strain of 1.03 mm/mm indicates a mild degree of deformation, and at the optimal 200th step, the maximum stress effectiveness measures 0.127 MPa, indicating controlled stress levels that the material experiences.

The findings highlight the efficiency of the selected parameters in reaching the intended result, as the workpiece successfully reached the target of 200 steps without any flaws or tears. Your inquiry, however, raises concerns regarding the differences that have been seen between the present results and the ones that were achieved with a 10 mm blank chamfer at a 30-degree angle. It is important to remember that the deep drawing process is extremely sensitive to many parameters, and that the material reaction can be significantly affected by even tiny changes. Variations in the distribution of stress and strain brought on by the particular chamfer angle and shape may be the origin of the variances in damage and strain between the two trials. In comparison to the preceding design, the 10mm chamfer with a 30-degree angle introduces distinct stress patterns and deformation characteristics that may result in variations in damage and strain. The outcomes of the deep drawing process are influenced by the selection of chamfer size and angle. The observed variations in strain and damage across trials with varying chamfer designs emphasize the need for a detailed comprehension of the ways in which each parameter affects the behavior of the material. To enhance comprehension of these impacts and

Journal of Evrimata: Engineering and Physics
Vol. 01, No. 02, Desember, 2023, p.70 – 77 e-ISSN: 3025-1265

optimize the deep drawing process for particular results, more investigation and testing are helpful.

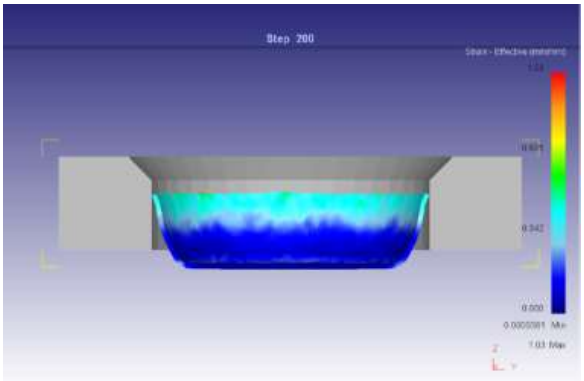

Fig 11. Damage, Strain, Stress for punch of C10 with the angle 45 degrees after tearing defect of deep drawing process of alumunium 7075

Chamfer 11 mm with the 60 Degress angles tool blank result of load prediction, damage, strain effective, and stress effective. The following is a Deform3D simulation for Alumunium 7075, which examines the load generated by the punch load via graphs and looks at the outcomes of damage, stain, and stress absorbed by the workpiece. These are the outcomes of the simulation. Figure 10 illustrates that in order for the punch tool to press 2 mm thick Alumunium 7075 material and reach the maximum yield strength phase, the material must harden within 0 seconds, requiring a load force of 70000 N.

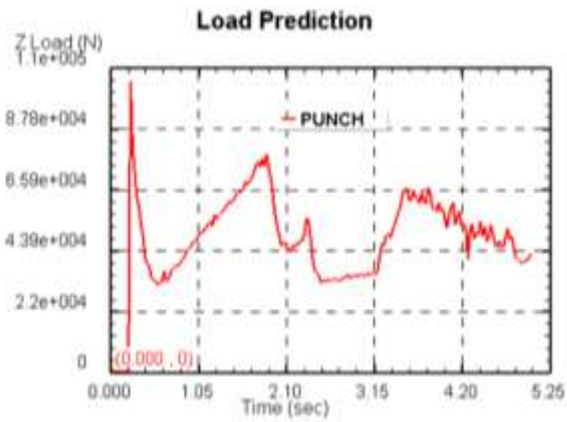

Fig 12. Load prediction for punch of 10 of the 60 degrees angle 5 blank of deep drawing process of alumunium 7075

Using a 10-millimeter, 60-degree-angled chamfer on the blank and a matching chamfer on the punch in the deep drawing process of aluminum 7075 has produced certain results. At 0.718, the damage parameter shows that there was not much material damage throughout the deep drawing process, which is a good result. Similarly, a maximum strain of 1.00 mm/mm indicates a modest degree of deformation, and at the optimal 200th step, the maximum stress effectiveness measures 277 MPa, indicating controlled stress levels that the material experiences. The fact that the workpiece made it to the 200-step mark without any flaws or tears highlights how well the settings selected worked to provide the intended result. Your query, however, brings up the point of the reported variations in strain and damage in relation to tests using a 10mm chamfer at various angles—namely, 30 degrees and 45 degrees.

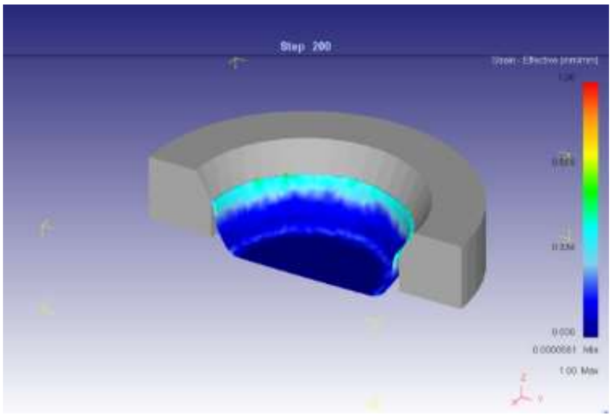

Fig 13. Damage, Strain, Stress for punch of C10 with the angle 60 degrees after tearing defect of deep drawing process of alumunium 7075

A key element affecting the process's integrity and performance is the effect of blank geometry on the mechanical characteristics of stresses and strains during the deep drawing process utilizing aluminum 7075 at 50°C. Differential chamfer dimensions (1mm, 5mm, 10mm) and radii (1mm, 5mm, 10mm) at various angles (30°, 45°, and 60°) result in unique distributions of stress and strain. While distinct stress patterns are created by varying chamfer angles, larger radii often provide smoother deformations. The fact that 200 steps were successfully completed without any faults at different angles (30°, 45°, and 60°) with a radius of 10 mm and a chamfer of 10 mm emphasizes the significance of striking a compromise between limiting stress concentrations and obtaining the required shape. Reduced angles could result in more concentrated stress points and sharper features, which could tear while deep drawing. The arrangement that was selected appears to be successful in lowering the likelihood of tearing, which highlights the necessity of carefully optimizing blank geometry to guarantee both formability and structural integrity throughout the deep drawing process.

Table 1. The comparison of difference of blank geometry defeorm properties result

No.	Blank Geometry	Damage Result	Strain Effective Result (mm/mm)	Stress EffectiveResult (Mpa)
1	C1 (Fold Step 88th)	5.87	3.46	360
2	C1 (Defect Step 1150)	5.88	3.47	211
3	C5 (Fold step 88th)	2.71	5.48	401
4	C10-30	0.797	1.22	0.00332
5	C10-45	0.756	1.03	0.121
6	C10-60	0.718	1.00	277

Source: Data Analysis

The mechanical properties of strains and stress in the deep drawing process employing aluminum 7075 at 50°C are greatly influenced by the choice of blank shape. Stress distribution and material behavior are affected by variations in chamfer dimensions (1mm, 5mm, 10mm) and radii (1mm, 5mm, 10mm) at varying angles (30°, 45°, and 60°). The fact that 200 steps were completed flawlessly with a 10 mm chamfer at three different angles (30°, 45°, and 60°) emphasizes how crucial it is to create a balanced design in order to minimize stress concentrations and obtain the required shape. Sharper features can cause tearing, and smaller angles might make this more likely. To sum up, in order to guarantee the material's formability and structural integrity during the deep drawing process, blank geometry optimization is essential.

5. CONCLUSIONS

Conclusions drawn from multiple deep drawing simulation results, including damage, effective strain, and effective stress on the ALUMUNIUM 7075 workpiece and load on the punch tool, indicate that objects with these values produce workpieces free of defects; this is dependent on the geometric shape of the blank and the duration of the simulation process. Therefore, engineers using deep drawing processes should consider the state of the material, the shape of the blank, and the duration of the process to achieve the best possible production outcomes. If the engineer wishes to use a lengthy process, similar to the one described above, engineers are advised to use

6. ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to all those who contributed to the successful completion of this research. Our heartfelt thanks to mechanical engineering head departments for their invaluable guidance, expertise, and support throughout this study. We also extend our appreciation to the Politeknik Negeri Malang for providing the necessary resources and facilities for conducting this research. Special thanks to Muhammad Fakhruddin, Michamad Muzaki, and Hilmi Iman Firmansyah for their contributions and collaboration.

7. AUTHOR CONTRIBUTIONS

- Conceptualization: Muhammad Fakhruddin.
- Data curation: Adjie Yoga Pratama, Auzini Widyasari.
- Formal analysis: Adjie Yoga Pratama.
- Funding acquisition: Muhammad Fakhruddin.
- Investigation: Auzini Widyasari.
- Methodology: Muhammad Fakhruddin.
- Project administration: Mochamad Muzaki, Hilmi Iman Firmansyah.
- Resources: Muhammad Fakhruddin.
- Software: Adjie Yoga Pratama, Auzini Widyasari.
- Supervision: Muhammad Fakhruddin.
- Validation: Mochamad Muzaki, Hilmi Iman Firmansyah.
- Visualization: Adjie Yoga Pratama, Auzini Widyasari.
- Writing – original draft: Adjie Yoga Pratama, Auzini Widyasari.
- Writing – review & editing: Muhammad Fakhruddin.

8. REFERENCES

[1] J. Cao *et al.*, “Manufacturing of advanced smart tooling for metal forming,” *CIRP Annals*, vol. 68, no. 2, pp. 605–628, Jan. 2019, doi: 10.1016/j.cirp.2019.05.001.

[2] C. Wang, R. Ma, J. Zhao, and J. Zhao, “Calculation method and experimental study of coulomb friction coefficient in sheet metal forming,” *J Manuf Process*, vol. 27, pp. 126–137, Jun. 2017, doi: 10.1016/j.jmapro.2017.02.016.

[3] N. Park, H. Huh, S. J. Lim, Y. Lou, Y. S. Kang, and M. H. Seo, “Fracture-based forming limit criteria for anisotropic materials in sheet metal forming,” *Int J Plast*, vol. 96, pp. 1–35, Sep. 2017, doi: 10.1016/j.ijplas.2016.04.014.

[4] D. R. Cooper, K. E. Rossie, and T. G. Gutowski, “The energy requirements and environmental impacts of sheet metal forming: An analysis of five forming processes,” *J Mater Process Technol*, vol. 244, pp. 116–135, Jun. 2017, doi: 10.1016/j.jmatprotec.2017.01.010.

[5] O. M. Ikumapayi, E. T. Akinlabi, P. Onu, and O. P. Abolusoro, “Rolling operation in metal forming: Process and principles - A brief study,” in *Materials Today: Proceedings*, Elsevier Ltd, 2019, pp. 1644–1649. doi: 10.1016/j.matpr.2020.02.343.

[6] V. L. Hattalli and S. R. Srivatsa, “Sheet Metal Forming Processes-Recent Technological Advances,” 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings2214-7853

[7] W. Zhou, J. Lin, D. S. Balint, and T. A. Dean, “Clarification of the effect of temperature and strain rate on workpiece deformation behaviour in metal forming processes,” *Int J Mach Tools Manuf*, vol. 171, Dec. 2021, doi: 10.1016/j.ijmachtools.2021.103815.

[8] W. E. King *et al.*, “Simulation and modeling of the metal powder bed fusion additive manufacturing process,” 2014.

[9] B. J. Ralph, A. Schwarz, and M. Stockinger, “An implementation approach for an academic learning factory for the metal forming industry with special focus on digital twins and finite element analysis,” in *Procedia Manufacturing*, Elsevier B.V., 2020, pp. 253–258. doi: 10.1016/j.promfg.2020.04.103.

[10] J. M. P. Martins, J. L. Alves, D. M. Neto, M. C. Oliveira, and L. F. Menezes, “Numerical analysis of different heating systems for warm sheet metal forming,” *International Journal of Advanced Manufacturing Technology*, vol. 83, no. 5–8, pp. 897–909, Mar. 2016, doi: 10.1007/s00170-015-7618-9.

[11] M. Sigvant *et al.*, “Friction in sheet metal forming: Influence of surface roughness and strain rate on sheet metal forming simulation results,” in *Procedia Manufacturing*, Elsevier B.V., 2019, pp. 512–519. doi: 10.1016/j.promfg.2019.02.169.

[12] M. P. Shisode, J. Hazrati, T. Mishra, M. de Rooij, and T. van den Boogaard, "Modeling mixed lubrication friction for sheet metal forming applications," in *Procedia Manufacturing*, Elsevier B.V., 2020, pp. 586–590. doi: 10.1016/j.promfg.2020.04.180.

[13] I. Mashudi, M. Fakhruddin, and A. Hardjito, "The effect of strain hardening on the limit forming ratio on the single-step incremental hole flanging process on aluminium plates," *IOP Conf Ser Mater Sci Eng*, vol. 1073, no. 1, p. 012079, Feb. 2021, doi: 10.1088/1757-899x/1073/1/012079.

[14] V. Paunoiu, M. A. Saadatou, D. Nedelcu, and M. Octavian, "Experimental and numerical investigations of sheet metal circular bending," 2015.

[15] S. Bruschi *et al.*, "Testing and modelling of material behaviour and formability in sheet metal forming," *CIRP Ann Manuf Technol*, vol. 63, no. 2, pp. 727–749, 2014, doi: 10.1016/j.cirp.2014.05.005.

[16] Z. Lai *et al.*, "A comprehensive electromagnetic forming approach for large sheet metal forming," in *Procedia Engineering*, Elsevier Ltd, 2017, pp. 54–59. doi: 10.1016/j.proeng.2017.10.737.

[17] Z. Gronostajski *et al.*, "Recent development trends in metal forming," *Archives of Civil and Mechanical Engineering*, vol. 19, no. 3. Elsevier B.V., pp. 898–941, May 01, 2019. doi: 10.1016/j.acme.2019.04.005.

[18] A. E. Tekkaya, P.-O. Bouchard, S. Bruschi, C. C. Tasan, and P.-O. Bouchard, "Damage in metal forming," *CIRP Annals-Manufacturing Technology*, vol. 2020, no. 2, pp. 600–623, doi: 10.1016/j.cirp.2020.05.005ï.

[19] C. V. Nielsen, P. A. F. Martins, and N. Bay, "Modelling of real area of contact between tool and workpiece in metal forming processes including the influence of subsurface deformation," *CIRP Ann Manuf Technol*, vol. 65, no. 1, pp. 261–264, 2016, doi: 10.1016/j.cirp.2016.04.126.

[20] M. Fakhruddin and M. Agus Choiron, "The Influence of Process Parameters toward Collar Height on Incremental Backward Hole-Flanging Process," *JEMMME*, vol. 2, no. 1, 2017.

[21] H. Güler and R. Özcan, "Comparison of hot and cold stamping simulation of Usibor 1500 prototype model," 2014.

[22] A. A. Petunin and C. Stylios, "Optimization Models of Tool Path Problem for CNC Sheet Metal Cutting Machines," in *IFAC-PapersOnLine*, Elsevier B.V., 2016, pp. 23–28. doi: 10.1016/j.ifacol.2016.07.544.

[23] I. Mashudi, M. Fakhruddin, and A. Hardjito, "Forming parameters effect toward flange height on single-step incremental backward hole flanging process," in *AIP Conference Proceedings*, American Institute of Physics Inc., Apr. 2023. doi: 10.1063/5.0126731.

[24] K. Dohda, M. Yamamoto, C. Hu, L. Dubar, and K. F. Ehmann, "Galling phenomena in metal forming," *Friction*, vol. 9, no. 4. Tsinghua University, pp. 665–685, Aug. 01, 2021. doi: 10.1007/s40544-020-0430-z.

[25] W. Wang, Y. Zhao, Z. Wang, M. Hua, and X. Wei, "A study on variable friction model in sheet metal forming with advanced high strength steels," *Tribol Int*, vol. 93, pp. 17–28, Jan. 2016, doi: 10.1016/j.triboint.2015.09.011.

[26] L. Ben Said, J. Mars, M. Wali, and F. Dammak, "Effects of the tool path strategies on incremental sheet metal forming process," *Mechanics and Industry*, vol. 17, no. 4, 2016, doi: 10.1051/meca/2015094.

[27] H. Zhang, M. Diehl, F. Roters, and D. Raabe, "A virtual laboratory using high resolution crystal plasticity simulations to determine the initial yield surface for sheet metal forming operations," *Int J Plast*, vol. 80, pp. 111–138, May 2016, doi: 10.1016/j.ijplas.2016.01.002.

[28] A. Al-Tamimi, R. Darvizeh, and K. Davey, "Experimental investigation into finite similitude for metal forming processes," *J Mater Process Technol*, vol. 262, pp. 622–637, Dec. 2018, doi: 10.1016/j.jmatprotec.2018.07.028.

[29] D.-Y. Yang *et al.*, "Title: Flexibility in Metal Forming Flexibility in Metal Forming." [Online]. Available: www.elsevier.com/locate/cirp

[30] V. Mugendiran and A. Gnanavelbabu, "Analysis of formability and twist angle in AA5052 alloy by single point incremental forming process," 2018.