SIMULATION AND ANALYSIS OF HOT FORGING PROCESS OF 7075 ALUMINUM ALLOY FOR ULTRASONIC WELDING HORN

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Abstract - Traditional ultrasonic welding horns are primarily manufactured through CNC machining, which often leads to material wastage and non-uniform microstructure. This study explores an alternative hot forging-based manufacturing process for ultrasonic welding horns using 7075 aluminum alloy. The forming process, temperature variation, and microstructure evolution were simulated using finite element modeling (FEM) in QForm 10, considering key forging parameters such as temperature, deformation, and grain refinement. The results demonstrate that the proposed hot forging method significantly reduces material waste (by 58.41% compared to CNC machining), enhances grain refinement (from 250 µm to 60 µm), and improves mechanical properties. The study confirms the feasibility of using hot forging for mass production of ultrasonic welding horns while ensuring superior structural integrity and performance.

Key words - Hot Forging; Ultrasonic Welding Horn; Finite Element Method (FEM); Microstructure Evolution; Grain Refinement

1. Introduction

Ultrasonic welding technology has been widely adopted in various industrial applications due to its efficiency and effectiveness. However, the manufacturing process of ultrasonic horns remains largely dependent on machining methods, particularly CNC machining. The uniformity of the amplitude in ultrasonic horns is typically achieved by carefully designing the neck regions and step transitions at the input surface. Despite its precision, CNC machining presents several challenges, including high material waste, long processing times, and limitations in achieving optimal mechanical properties ([1] - [3]). These drawbacks highlight the need for an alternative manufacturing approach that enhances both production efficiency and mechanical performance.

In contrast, hot forging technology is recognized for its ability to produce parts with superior mechanical properties, minimal material waste, and enhanced durability. Unlike CNC machining, which involves subtractive manufacturing, forging reshapes the material through plastic deformation, significantly improving microstructure homogeneity and strength. While forging typically requires high initial tooling costs, it becomes economically advantageous for mass production due to its ability to maintain structural integrity and mechanical consistency [4]. Recent advancements in metal forming technology and simulation tools have further optimized the forging process, making it more adaptable to complex part geometries.

7075 aluminum alloy is widely used in aerospace and military applications due to its high strength-to-weight ratio and durability. However, its mechanical properties are highly dependent on heat treatment and hot deformation conditions [5]. The hot forging process for 7075 aluminum requires careful control of temperature and strain to optimize grain structure, reduce defects, and achieve desired performance characteristics [6]. A comprehensive understanding of hot deformation behavior and microstructural evolution is essential for the precise forming of complex components.

This study aims to develop a new manufacturing method for ultrasonic welding horns by employing hot forging as an alternative to traditional CNC machining. To achieve this, finite element modeling (FEM) is utilized to simulate the hot forging process, analyzing metal deformation and material flow. Additionally, the research evaluates the effects of heat treatment on the mechanical properties and microstructure of the ultrasonic horn after multiple forming operations. Furthermore, process parameters are optimized to enhance material efficiency, minimize defects, and improve overall product quality. By integrating hot forging with advanced simulation techniques, this study introduces a cost-effective and high-performance alternative for manufacturing ultrasonic welding horns, with the potential to revolutionize production processes in the industry.

2. Simulation Procedures

2.1. Geometry

In this study, the ultrasonic welding horn is designed and manufactured using metal deformation machining technology. The research is based on the study "Analysis of Process Parameters of Hypoeutectoid Steel Ultrasonic Horns with Different Heat Treatment Processes" by Thanh Hai Nguyen et al. [7], in which the authors utilized steel alloys for horn fabrication. While most ultrasonic horns are typically manufactured using specific grades of aluminum and titanium, some specialty applications also employ D2 steel and CPM steel [8]. However, this study proposes the use of 7075 aluminum alloy due to its superior durability and transmission performance compared to steel. The ultrasonic welding system was modeled using finite element analysis (FEA), and after modifications and re-simulation, the operating frequency of the ultrasonic horn remained at 28 kHz. The displacement distribution of the ultrasonic horn, following the material change, is illustrated in Figure 1a, with the maximum displacement occurring at the working surface of the horn.

In this process, only the metal-forming deformation of the outer profile of the horn will be simulated. The drawing of the outer profile of the horn is used for simulation shown in Figure 1b.

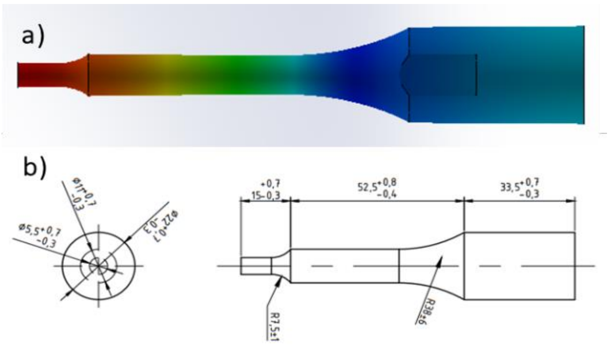

Figure 1. *Ultrasonic welding horn working at 28 kHz: (a) finite element analysis result, (b) drawing of outline profile*

2.2. Materials

The billet used in the simulation work is a solid round bar of 7075 aluminum alloy. The chemical composition of the workpiece is listed in Table 1.

Table 1. *Chemical composition of the sample (mass fraction, %)*

Element	Si	Fe	Cu	Mn	Mg	Cr	Ni
AA7075	0.1	0.19	1.53	0.07	2.55	0.18	0.0058

Element	Cr	Ni	Zn	Ti	Al
AA7075	0.18	0.0058	5.89	0.024	Rest

2.3. Heating Mode

Non-ferrous metals are often hot or cold die forging, rarely freely forged. When open forging or die forging, dies and tools need to be heated to 200÷250ºC. Metal heating mode before/during open forging and die forging includes determining basic quantities such as furnace temperature when inputting the workpiece into the furnace; workpiece heating temperature; holding time at a given temperature; total heating time; forging temperature range, etc.

Table 2. *Hot forging temperature range for different metals and alloys (ºC) [4]*

Metal or alloy	**Temperature Range (ºC)**
Aluminum alloys	400 - 500
Magnesium alloys	250 - 350
Copper alloys	600 - 900
Carbon and low-alloy steels	850 - 1150
Martensitic stainless steels	1100 - 1250
Austenitic stainless steels	1100 - 1250
Titanium alloys	700 - 950
Iron-base superalloys	1050 - 1180
etc.	

Hot forging is performed at a temperature above the recrystallization temperature of the metal. The recrystallization temperature is defined as the temperature at which new grains are formed, allowing the material to recover from work hardening. This high-temperature process is essential to prevent strain hardening during deformation [4]. According to the ASM Handbook Committee, Volume 14A, the recommended forging temperature range for AA7075 aluminum alloy is between 380ºC and 440ºC [9]. However, Yusuf et al. suggested that the forging temperature should fall between the solidus and recrystallization temperatures [10]. Additionally, it has been proposed that the recrystallization temperature for AA7075 ranges from 430ºC to 480ºC [11]. In this study, the selected forging temperature is 440ºC, while the initial heating temperature of the workpiece (considering air-cooling effects) is 460ºC, with a holding time of 120 minutes.

2.4. Forging Procedures

In forging, an initially simple part- a billet, is plastically deformed between two dies to obtain the desired final configuration. For understanding and optimization of forging operations, it is useful to classify this process in a systematic way [4].

In the hot forging simulation process of an ultrasonic horn, there will be 3 main operations: Pre-forming deformation step, Flash trimming & Heating and Final forging (*Die forging*). The category and parameters for hot forging procedures of an ultrasonic horn are shown in Table 3.

Table 3. *Category and parameters for hot forging procedures of ultrasonic horn*

Category	1. Pre-forming deformation
Workpiece/Tool geometry	Shown in Figure 2(a)
Workpiece material	AA7075
Workpiece temperature	460°C
Machine type	Hydraulic press (100t - 6mm/s)
Tool/Dies material	H13 HRC50
Tool/Dies temperature	300˚C
Environment	Air 20˚C
Category	2.Flash trimming & Heating
Workpiece/Tool geometry	Shown in Figure 2(b)
Workpiece material	to be inherited,
Workpiece temperature	After Pre-forming is 351°C After flash trimming is 340°C
Machine type	Furnace
Tool/Dies material	None
Tool/Dies temperature	None
Environment	Air 440˚C
Category	3.Final forging
Workpiece/Tool geometry	Shown in Figure 2(c)
Workpiece material	to be inherited,
Workpiece temperature	440°C
Machine type	Hydraulic press (100t - 6mm/s)
Tool/Dies material	H13 HRC50
Tool/Dies temperature	300˚C
Environment	Air 20˚C

Some important notes of the process:

- Processing method: closed die forging (hot deformation - closed mold) because the precision and surface gloss of the part are high compared to open forging. The workpiece volume may not be exact but only changes the length of the product leg, which can be cut off during machining. In the pre-forming deformation step operation, the initial workpiece with dimensions of ϕ25x45 mm becomes a semi-finished product with dimensions of ϕ20x63. After the final forging operation, the resulting product will have the shape of the mold cavity.

- Cooling during machining: the project also takes into account cooling in the mold and in the air of the product during the technological process.

- Cooling after machining: is important because if cooled incorrectly, it can produce unwanted defects, causing mass waste. If cooled properly, it can prevent grain coarsening during recrystallization and improve the mechanical properties of the product. This parameter will be temporarily ignored in this topic and will be studied in detail in the following works.

- Mold structure: In this topic, this parameter is temporarily ignored to reduce simulation time, mainly focusing on the shaping ability of the material.

- Initial average grain size: To be able to follow the microstructural evolution through the whole technological process the simulation has been implemented starting from the pre-forming deformation step of the billet. The initial average grain size of the ingot was assumed as 250 µm according to manufacturer specifications [12].

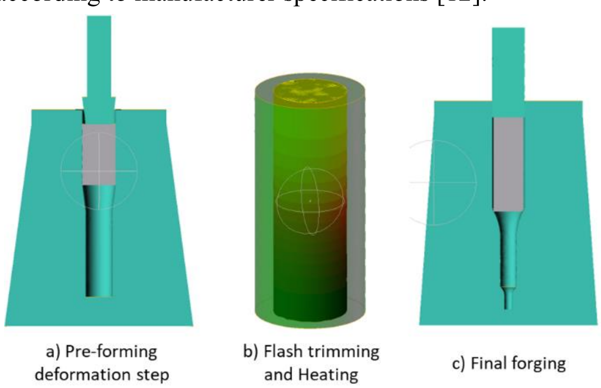

Figure 2. *Geometry for simulation: (a) Pre-forming deformation step, (b) Flash trimming & Heating, and (c) Final forging*

3. Simulation Results

3.1. Process characterization

Figure 3 shows the simulation results of the hot forging process, which includes the following stages: heating to forging temperature 460°C, pre-forming deformation step, flash trimming, reheating, final forging, second flash trimming, and cooling on air. Microstructure characterization and further FEM analysis have been carried out in certain cross-cut sections that are shown in Figure 4. The pre-forming deformation step operation aims to reduce the grain size of the part, helping to improve the micro-structure of the workpiece compared to deformation from a workpiece with a diameter of ϕ20 mm. If the grain is refined, the tensile strength, yield strength, and impact toughness will be increased. In addition, the grain size also helps to increase the resistance to fatigue cracking and reduce the risk of stress corrosion cracking. The goal of the article is to improve the microstructure of the entire workpiece volume, but it may not need to be uniform across the entire part (Figure 5).

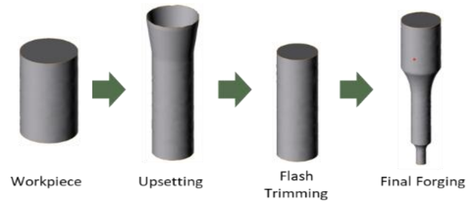

Figure 3. *The sequence of forming process of the part*

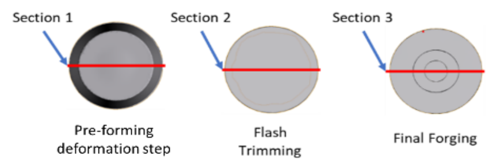

Figure 4. *The scheme of crosscut sections in the part*

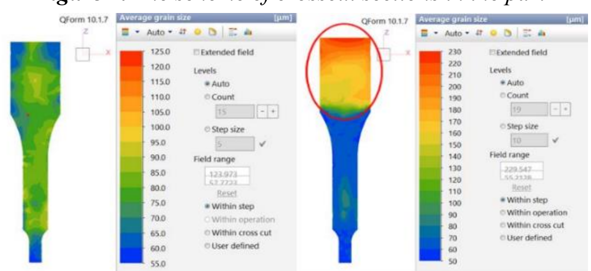

Figure 5. *The microstructure in the process has pre-forming deformation step operation with single-step deformation*

3.2. Material saving coefficient of metal forming method with machining method

We will calculate each method by using Eqs. (1) according to the following formula:

$$\text{Material Waste Ratio (MWR)} = \frac{V_{billet} - V_{product}}{V_{billet}} \text{x}100\% \quad (1)$$

where: + V_{billet} is the initial billet volume.

+ $V_{product}$ is the final product volume.

The initial billet sizes were determined based on the target product geometry plus the allowance for material loss. For the CNC machining baseline, the billet size (Φ24 mm × 105 mm, V_{Billet} = 47,500 mm³) was selected to fully encompass the final horn shape, including extra stock for machining tolerances. For the forging process, the billet size (Φ25 mm × 45 mm, V_{Billet} = 22,090 mm³) was chosen to achieve near-net shape filling, with an estimated 10-15% excess volume to compensate for flash formation and trimming losses. The author has taken into account the selection of workpiece size for CNC machining and hot forging, which will be presented in future experimental studies.

The product volume of the horn is automatically calculated by using SOLIDWORKS (V_{Prod} = 19755 mm^3), as shown in Figure 6. For the machining method, in order to manufacture the outer profile shape of the welding horn, the metal volume is wasted nearly 58.41%. While with the metal forming method, the metal waste is only about 10,58%. Therefore, the closed die forging is very metal-saving, helping to reduce the cost of the product much.

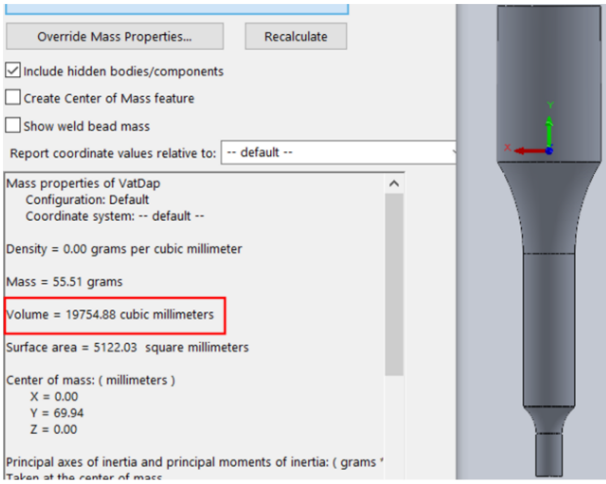

Figure 6. *Volume of the outer profile of the part*

3.3. Microstructure evolution

To be able to follow the microstructural evolution through the whole technological process, the simulation has been implemented starting from the pre-forming deformation step of the billet. The initial microstructure of the sample is 250 µm. The resulting grain size distribution in the deformation zone after pre-forming deformation step is shown in Figure 7. Except for the tip of the bar (where it contacts the tool), the average grain size is almost uniform throughout the bar and the value of the average grain size is about 83 µm. Then, this burr will be removed in the second operation.

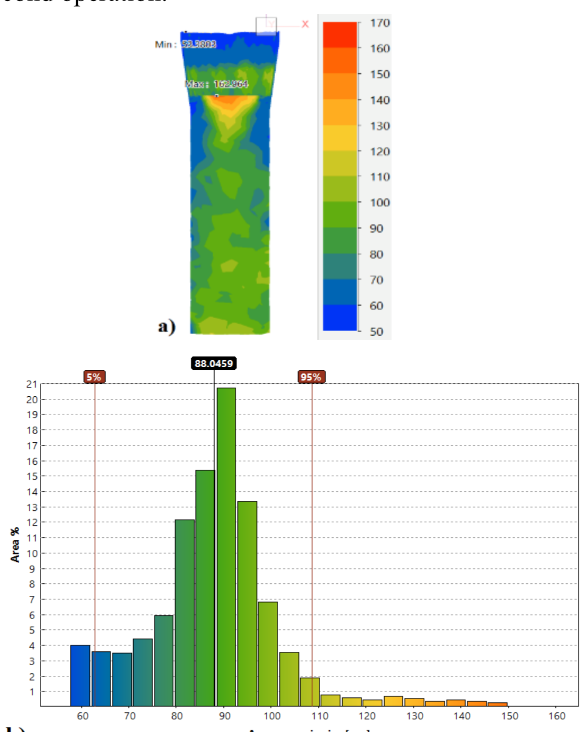

Figure 7. *The crosscut section (a) and the scheme (b) of grain size of the part after pre-forming deformation step*

After heating the bar to 440°C, we can see that the grains do not grow in size during this entire operation and these size grains are to be used for the next operations, i.e. final forging. As seen in Figure 8, the ends of the billet after the forging operation keep the initial grain size as it was in the pre-forming deformation step because they are not subject to deformation larger than the critical strain. Meanwhile, the pressing process with a large ratio of deformation in the closed die pressing operation helps to significantly reduce the average grain size (the average grain size in this operation is about 75 µm), especially in the ϕ5.5-dimension part has a grain size of about 60 µm.

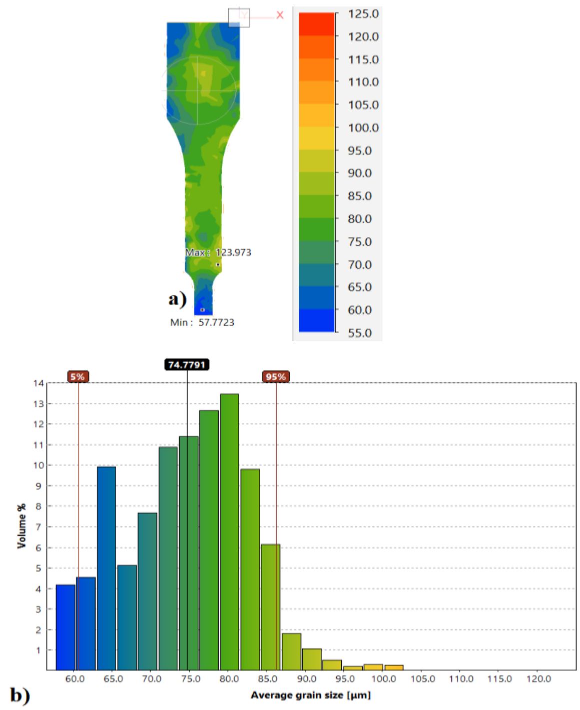

Figure 8. *The crosscut sections (a) and the scheme (b) of grain size of the part after final forging*

3.4. Temperature

After taking into account cooling during deformation (cooling in air and cooling in mold), the temperature of the bar is 446°C (meeting the requirements for forming temperature range of AA7505 alloy). The results of the temperature distribution at the cross-section and the entire volume of the bar (represented via a scheme) after pre-forming deformation step are shown in Figure 9. It can be seen that the temperature of the bar after deformation is distributed in a decreasing direction from top to bottom, with an average value of 351°C. The maximum temperature is 384°C, and the smallest temperature is 313°C, still within the temperature range where aluminum is in the solid phase.

After flash trimming, it is mandatory to heat the bar to 440°C (deformation temperature range). In the closed die forging operation, the temperature of the bar after deformation has an average value of 365°C. The maximum temperature is 429°C, and the smallest temperature is 322°C, still within the temperature range where aluminum is still in the solid phase (Figure 10). The deformed workpiece emits heat energy, which contributes to the increase in workpiece temperature, especially for operations performed at high deformation rates.

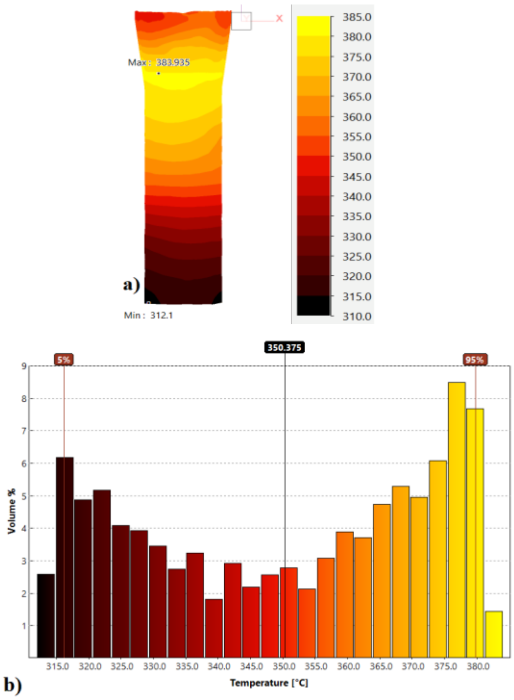

Figure 9. *The crosscut sections (a) and the scheme (b) of the temperature of the part after pre-forming deformation step*

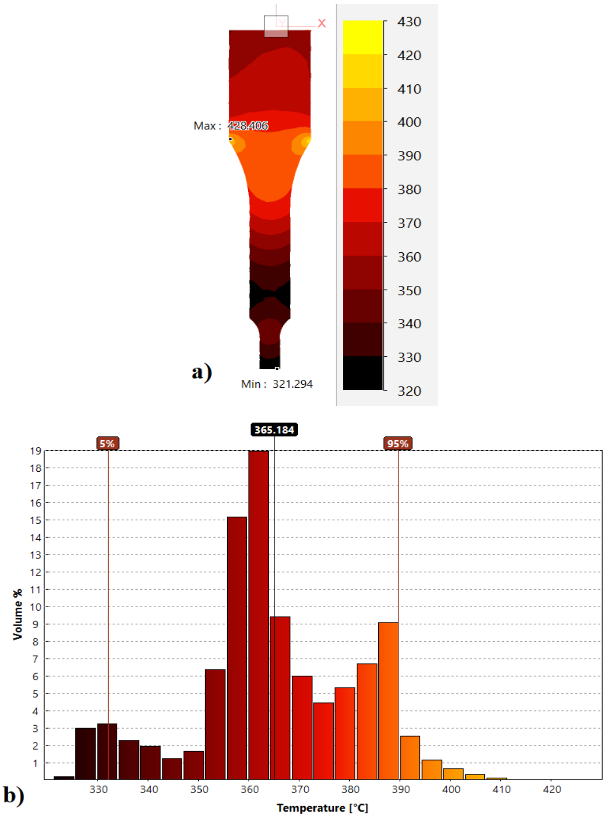

Figure 10. *The crosscut sections (a) and the scheme (b) of the temperature of the part after final forging*

3.5. Fill capacity

The cross-sections of the steps in Figure 4 are intended to clearly demonstrate the filling process of the billet in the mold cavity, especially in the welding horn head region and the radius region. In the final forging step, it can be seen that the aluminum almost fills the entire mold, there is no area where the billet cannot be filled, and there are no serious metal flow defects. QForm 10 has a feature that can analyze the metal flow defects when simulating the forging process, and with this simulation weren't be found any metal flow defects. This will be analyzed in more detail in future experimental studies.

4. Conclusions and Discussion

4.1. Conclusions

In this study, the hot forging process of 28 kHz ultrasonic welding horns was simulated using finite element modeling (FEM). The horns were made of 7075 aluminum alloy, and the following key findings were obtained:

- This research demonstrates a promising approach for the design, simulation, and manufacturing of ultrasonic welding horns through a closed die forging process, leveraging digital technology to optimize fabrication.

- Second, forging temperature: 450°C, this high-temperature process is essential to prevent strain hardening during deformation, as well as according to the suggestion of other authors that the forging temperature should be between the solidus and recrystallization temperatures. The Workpiece dimensions: Φ25 mm × 45 mm; and Initial grain size of 250 µm was refined to approximately 60 µm after the forging process, confirming effective dynamic recrystallization under optimized conditions. The proposed hot forging process offers substantial material savings compared to conventional CNC machining. The material waste ratio was reduced from 58.41% to 10.58%, achieving approximately 47.83% material savings. This improvement in material efficiency delivers both economic and environmental benefits.

- The proposed forging method enhances microstructural uniformity, resulting in a smoother, more refined grain structure. This grain size reduction can improve the mechanical properties of the aluminum alloy, minimize internal defects in the welding horn, and enhance its hardness and durability after deformation.

- The temperature distribution of the workpiece after the entire forging process follows a gradual decrease from top to bottom. A proper heat treatment regime is recommended to further improve mechanical properties, limit grain coarsening, and prevent material defects. The maximum and minimum temperatures of the workpiece remain within the range where aluminum is in the solid phase, reducing the risk of deformation-related defects.

4.2. Discussion

Although the present study provides valuable insights into the hot forging process of 7075 aluminum alloy of ultrasonic welding horns, several limitations should be acknowledged.

First, the simulation focuses on the forging stage and does not model the post-forging heat treatment process. In precipitation-hard enable alloys like AA7075, cooling rates critically affect precipitation kinetics (e.g., $MgZn_2$ phase formation) and ultimately influence mechanical properties. Therefore, the predicted grain refinement presented here may not fully represent the final thermomechanical state of the material.

Second, the simulation does not account for detailed mold structure features such as fillet radii, venting channels, or die surface texture. These factors can significantly affect material flow behavior, local friction conditions, and complete mold filling, potentially leading to minor inaccuracies in predicting flash formation and cavity filling percentages.

Third, the current study assumes uniform initial material properties and neglects potential billet inhomogeneities (e.g., segregation, prior texture), which could influence actual forging behavior in industrial applications.

Fourth, while the simulation predicts significant grain refinement during forging, no experimental validation of the final mechanical properties (e.g., tensile strength, and fatigue resistance) has been conducted at this stage. Thus, improvements in mechanical performance are expected based on grain size reduction but require future experimental confirmation, including post-forging heat treatment studies.

Despite these limitations, the simulation results provide a solid foundation for process design optimization and highlight the promising potential of hot forging as an alternative manufacturing route for ultrasonic welding horns. Future work will address post-forging cooling modeling, precipitation evolution analysis, detailed mold structure effects, and experimental validation of mechanical properties.

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