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Gas Based Hot Forming of Micro-Channels for High Strength Aluminum Alloy Sheets

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Abstract. In carbon-free technologies, thin-walled components with microchannels from ultra-thin sheets, such as bipolar plates, cooling plates, and heat exchangers, are widely utilized. Using such components made of high-strength aluminum alloys further reduces the required wall thickness, thereby enhancing their lightweight potential. However, conventional forming methods for ultra-thin sheets, including elastomer-based deep drawing and hydroforming, are limited by process-induced phenomena such as springback, geometrical inaccuracies and reduced formability as well as localized thinning, which can necessitate a higher wall thickness or the use of a lower strength grade alloy. Gas-based hot sheet metal forming of high-strength aluminum alloys is introduced to improve formability and geometrical accuracy. In the present study, an isothermal, gas-based hot sheet metal forming process is developed for forming microchannels from AlMg3 alloy sheets with a thickness of 0.4 mm. A 100 mm × 100 mm blank is heated to 530 °C and formed under nitrogen gas pressure into a heated die featuring various channel geometries. The effects of blank-holder force, maximum gas pressure, wall angle, channel radius, and maximum channel depth on thinning and form filling are investigated. Additionally, the grain size of the final component is analyzed. A full form filling can be reached under a forming pressure of 200 bar. The thinning is dependent on the micro channel geometry and reaches a maximum of 29 % for a channel depth of 1 mm. The grain size increases during the forming process, dependent on the introduced strain into the material. The proposed method enables forming of components without fracture and with high geometrical accuracy.

Introduction

Thin-walled metallic components with integrated microchannel structures are widely employed as functional elements for heat and mass transfer, for example, as bipolar plates in fuel cells or as cooling plates for high-voltage batteries and power electronic systems [1]. In this context, aluminum alloys are particularly attractive, especially for mobile and aerospace applications, due to their favorable combination of high thermal conductivity, low density, and good chemical stability [2]. In recent years, the manufacturing of such aluminum components by sheet metal forming has been the subject of extensive research. Among the investigated forming technologies, Rubber-Pad-Forming (RPF), Flexible-Die-Forming (FDF), and hydroforming represent the most commonly applied processes.

In RPF, the sheet metal is formed into a rigid die by means of a compliant elastomer punch, whereas FDF utilizes a rigid punch in combination with a flexible die medium [3]. In hydroforming, the sheet is shaped by hydraulic pressure acting on one side of the material [4]. Within the field of RPF, several studies have focused on the fabrication of aluminum bipolar plates with complex channel geometries. The forming of Archimedes screw-shaped microchannels in AA1050 sheets with a thickness of 0.3 mm was systematically investigated with respect to the influence of process parameters on achievable channel depth and local thickness reduction. The results indicate that both channel depth and thinning behavior are strongly dependent on the hardness of the elastomeric forming medium [5]. In addition, failure mechanisms during the RPF of metallic bipolar plates are analyzed using fracture-mechanics-based criteria, enabling the prediction of crack initiation under critical forming conditions by means of the Cockcroft–Latham damage model [6]. To further reduce local thickness reduction, a modified two-step RPF strategy is proposed, demonstrating improved thickness distribution over the whole component thickness compared to conventional single-step forming [7]. For FDF, research activities have primarily addressed the influence of size effects on form filling and achievable channel depth when forming microchannels in thin aluminum foils. Investigations on Al 1100 foils reveal that the ratio of sheet thickness to grain size significantly affects material flow and limits formability at the micro scale [3]. Furthermore, an alternative FDF concept employing a polymer powder medium as a flexible die is introduced [8]. This approach provides a more uniform pressure distribution and improved form filling while maintaining low tooling complexity. Hydroforming-based studies have mainly concentrated on process understanding and quality control for the industrial production of metallic bipolar plates. Design rules and quality criteria were derived through systematic variation of key process parameters such as internal pressure and tool geometry, with particular emphasis on channel definition, thickness uniformity, and process reproducibility [4]. In addition, the surface integrity of hydroformed bipolar plates was investigated, demonstrating that forming conditions have a pronounced influence on surface roughness, which is relevant for both electrical contact resistance and fluid flow behavior [9].

For conventional forming processes conducted at room temperature, the predominant research focus lies on formability, commonly quantified by the maximum achievable channel depth, and on minimizing local thickness reduction. These inherent limitations have motivated the development of advanced forming processes that incorporate controlled thermal energy input in order to extend the forming limits of thin aluminum sheets. Among these approaches, hot forming processes such as high-speed blow forming and hot metal gas forming (HMGF) have gained increasing attention. A defining characteristic of these processes is that the primary forming step is performed at elevated temperatures, resulting in reduced flow stress and enhanced forming limit. In the context of HMGF, the forming of metallic bipolar plates from AA8111 aluminum blanks with a thickness of 0.2 mm under isothermal conditions at approximately 500 °C is investigated [10]. The influence of gas pressure, channel width, and fillet radius on form filling was systematically analyzed. It was shown that form filling increases with gas pressure, reaching a maximum of approximately 80 % at a pressure level of 4 MPa for a holding time of 15 minutes. Complementary studies addressed the fabrication of microchannel components from AA1070 sheets with a thickness of 0.1 mm using HMGF at temperatures between 300 °C and 400 °C [11]. By varying the channel depth-to-width ratio and fillet radius, optimal geometric conditions for maximum formability were identified, with the highest formability observed for a fillet radius of 7.5° and a depth-to-width ratio of 0.5. Numerical investigations of the HMGF process applied to pin-shaped bipolar plates manufactured from 0.2 mm thick AA8111 blanks demonstrated that both gas pressure and fillet radius have a significant influence on thickness reduction and die filling behavior [12]. Further studies on AA6063 revealed that increasing the forming temperature leads to enhanced formability and promotes a more homogeneous grain size distribution due to thermally activated microstructural mechanisms [13]. In addition to experimental work, numerical process modeling has been addressed [14]. Suitable finite element discretization strategies for gas-based hot sheet metal forming were proposed, demonstrating that refined through-thickness discretization is required to accurately capture coupled thermal and mechanical gradients. Building on these findings, a hybrid hot forming process was developed that combines conventional hot deep drawing with subsequent gas-based forming, thereby exploiting the advantages of both approaches within a single process chain [15]. Finally, the evolution of microstructure and mechanical properties during gas-based hot sheet metal forming was investigated for the heat-treatable aluminum alloy AA6010. The results show that although deformation at elevated temperatures promotes grain growth, the final mechanical properties after artificial aging are not adversely affected. This indicates that gas-based hot forming can be effectively integrated into manufacturing routes for high-strength aluminum components [16].

While the production of microchannel components from high-strength aluminum alloys by means of HMGF has been investigated primarily with regard to the influence of geometrical tool design on form filling and thickness reduction, the associated microstructural evolution has received considerably less attention. In particular, deformation at elevated temperatures is known to promote grain growth in aluminum alloys, which may significantly affect the final mechanical performance of thin sheet metal components. To date, the interplay between die geometry, local thinning, and grain size development during HMGF has not been systematically addressed for thin aluminum alloy sheets. To address the existing gap in the current literature, the present study proposes an HMGF-based process for the manufacture of microchannel components from thin aluminum alloy sheets and aims to investigate the influence of die geometry on both thickness reduction and grain size evolution during the forming process.

Experimental Setup

For the experimental investigations, square blanks of an AlMg3 alloy with a thickness of 0.4 mm and dimensions of 100 mm × 100 mm were used for HMGF under uniform temperature conditions. The forming experiments were conducted using a servo-hydraulic press (Schenck) with a maximum nominal press force of 630 kN, Fig. 1 a). The forming tool insert consists of a die and a blank holder, Fig. 1 b). Both components are heated by an integrated heating ring and thermally insulated by an insulation plate and a cooling plate, respectively. The tool temperature was controlled and maintained at a constant value of 530 °C throughout the forming experiments. The blank holder force was applied by the servo-hydraulic press and simultaneously served as the sealing force for the gas-based forming process. The forming pressure was applied using nitrogen gas, supplied from an external gas cylinder, with a maximum available pressure of 25 MPa. The die features a circular overall contour with a diameter of 70 mm and a depth of 0.5 mm, as shown in Fig. 2 a) and b). Microchannel grooves were machined into the die surface within this contour. The geometric parameters of the microchannels were varied in terms of channel depth d, wall angle α, and lower corner radius, as defined schematically in Fig. 2 c). A sectional view of the die, depicted in Fig. 2 d), illustrates the spatial distribution of the microchannel geometries. Each microchannel groove is equipped with dedicated gas outlet holes, allowing residual air between the blank and the die to escape during forming and thereby promoting complete form filling. The gas outlets of each groove can be closed individually. This design enables continued forming of the remaining microchannels without loss of forming pressure in the event of local material rupture.

Prior to forming, each 100 × 100 mm² blank was coated with a thin layer of boron nitride spray, which served as a high-temperature lubricant. The blank was then manually positioned between the die and the blank holder. Subsequently, the tool was closed using the servo-hydraulic press to ensure full contact between the tool surfaces and the specimen. During a holding period of 60 s, the blank was heated to the forming temperature of 530 °C. After reaching the target temperature, a blank holder force of 250 kN was applied. The forming process was initiated by opening the gas valve, resulting in a gradual increase in forming pressure. A maximum gas pressure of 20 MPa was reached after a forming time of 5 s. Upon completion of the forming step, the gas valve was closed, the tool was opened, and the formed specimen was manually removed from the die. The specimens were subsequently air-cooled to room temperature and prepared for further evaluation. For geometrical characterization, the formed specimens are first cleaned using cold water and isopropyl alcohol. Subsequently, the samples are sectioned perpendicular to the channel direction, as illustrated in Fig. 3 a). The sectioned samples are embedded and metallographically prepared by grinding and polishing. Geometrical measurements were then carried out using an optical microscope (Keyence VHX-7000). To characterize the grain size evolution, the embedded samples were electrochemically etched using a Barker-type electrolyte at an applied voltage of 20 V for 120 s. Grain size measurements were subsequently performed under polarized light using the Keyence VHX-7000 optical microscope. The grain size was quantified using the linear intercept method in accordance with ASTM E112.

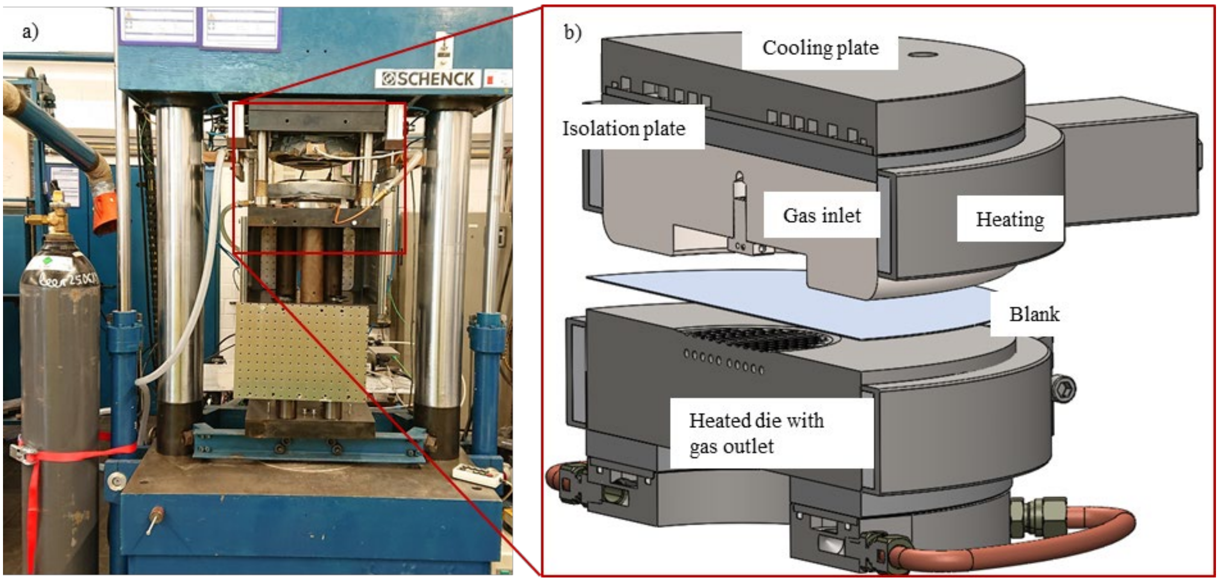

Fig. 1. a) Schenck hydraulic press with HMGF tool insert b) CAD design of tool insert.

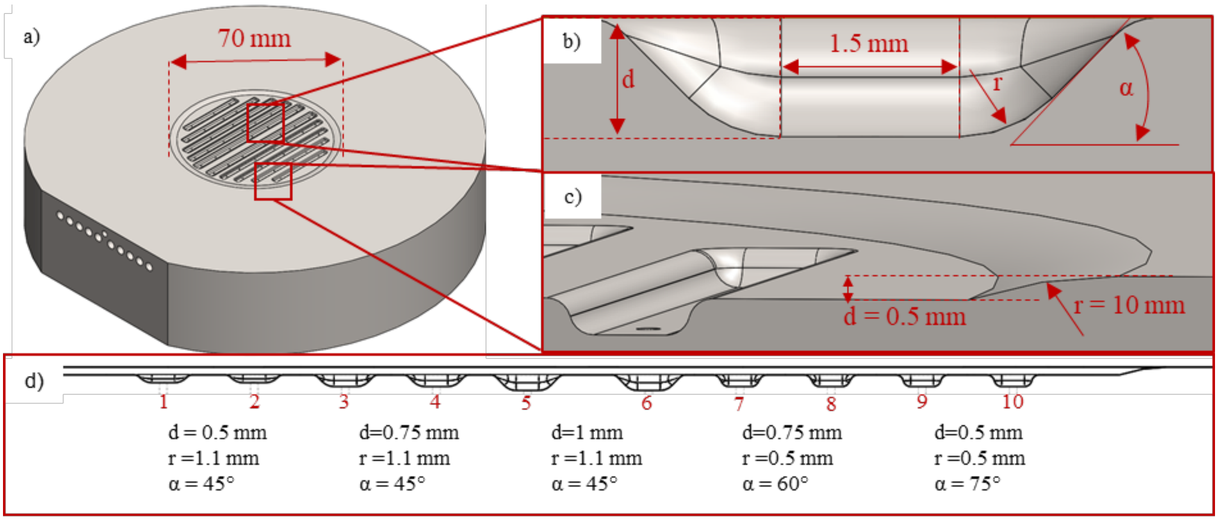

Fig. 2. a) Die with micro channels b) sectional view of one die contour with geometrical values defining the micro channel c) sectional view of die and dimensions d) sectional view of all micro channels and geometrical dimensions.

Results - Shape and Dimension Analysis

In total, five specimens were produced and evaluated. The following geometrical parameters are determined, as defined in Fig. 3 b): Channel depth d, wall thickness t_w, lower thickness t_l, and upper thickness t_u. For each of the investigated channel geometries, thickness reduction was evaluated as an average over all five specimens, with two channels analyzed per specimen. The resulting average thinning values for the three characteristic thickness locations are summarized in Fig. 3 c). The results indicate that the highest thickness reduction occurs in the channel wall region (t_w). For channel depths of 0.5 mm and 0.75 mm, the wall thinning ranges between 16 % and 18 %, whereas a significantly higher thinning of approximately 29 % is observed for channels with a depth of 1 mm. A qualitative comparison of the different channel geometries is presented in Fig. 3 d). In the transition region between the upper fillet radius and the channel wall, localized necking is observed for channels numbered 1 to 6, which are characterized by a wall angle of 45°. In contrast, channels 7 to 10, featuring steeper wall angles of 60° and 75°, do not exhibit visible necking in this region. Despite the occurrence of necking in channels with smaller wall angles, a direct comparison of wall thinning values does not indicate a pronounced increase in thickness reduction for geometries with similar channel depths d. The thickness reduction in the lower channel region (t_l) ranges from 7 % to 8 % for channels with a wall angle of 45° and from 6 % to 7 % for channels with steeper wall angles, suggesting a weak correlation between bottom thickness reduction and wall angle. In contrast, the upper thickness (t_u) shows a slight increase of approximately 1 % to 2 % relative to the initial blank thickness. This effect can be attributed to measurement uncertainty and is therefore considered negligible. Based on the geometrical evaluation, it can be concluded that microchannels with a depth of 1 mm and a width of 1.5 mm can be successfully manufactured with a maximum thickness reduction of approximately 28 %. For smaller channel depths, lower thickness reductions can be expected. Furthermore, steeper wall angles tend to result in slightly reduced wall thinning, which can be attributed to a decreased tendency for necking in the upper fillet region. However, these findings do not permit any conclusions regarding defect sensitivity.

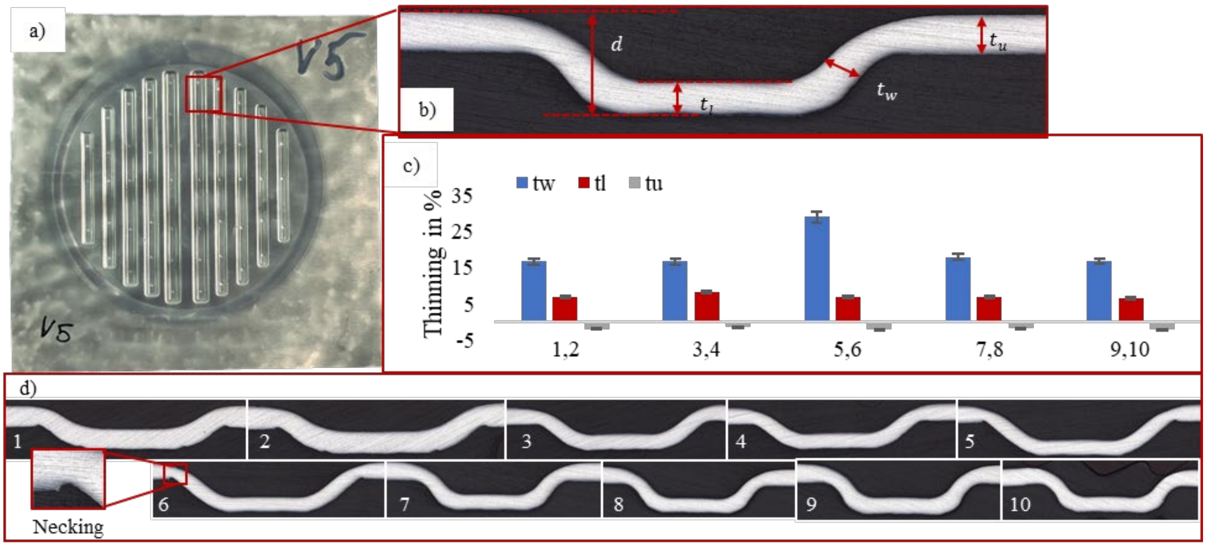

Fig. 3. a) Formed specimen b) microsection of formed specimen channel and areas of measurement c) thinning for measured areas for different geometrical dimensions d) close up of all microchannels of specimen no. 5.

Results - Microstructural Investigation

Measurements were conducted separately in the upper region, the lower region, and the wall region of the microchannel. The resulting grain size distributions are presented in Fig. 4. Overall, a pronounced increase in grain size is observed as a consequence of the forming process. The initial average grain size of 12.8 µm increases to 24.5 µm in the upper region of the microchannel and to 31.9 µm in the lower region. In contrast, the wall region exhibits a substantially larger increase in grain size, reaching an average value of 182.9 µm. In several cases, individual grains extend across nearly the entire wall thickness, as illustrated in Fig. 4 d). Considering the local wall thickness after forming, the ratio of grain size to wall thickness in the wall region approaches unity for these outliers. This indicates that the microstructure locally transitions from a polycrystalline to a quasi-columnar or single-grain-dominated state across the thickness. In comparison, the upper and lower regions remain clearly polycrystalline, with grain sizes that are small relative to the local sheet thickness. The pronounced grain growth in the wall region can be attributed to a combination of factors inherent to the HMGF process. First, the wall region undergoes increased local plastic deformation during the forming operation increasing the dislocation density, which promotes dynamic recovery and grain boundary mobility, as also observed for 2XXX grade alloys in [17,18]. Second, prolonged contact with the heated die in this region leads to increased local thermal exposure compared to the upper and lower channel regions. The superposition of high level of localized strain and extended dwell time at elevated temperature provides favorable conditions for abnormal grain growth. From a materials perspective, such localized grain coarsening is expected to influence both the mechanical and functional properties of the formed component. A grain size approaching the local wall thickness may result in reduced yield strength and altered strain hardening behavior, as well as increased anisotropy. In addition, coarse grains can affect corrosion behavior and surface stability, which are relevant aspects for microchannel components used in electrochemical or thermal management applications. In the context of process design, these results indicate that while HMGF enables the successful formation of microchannel geometries in thin aluminum alloy sheets, the associated thermo-mechanical history can lead to pronounced microstructural inhomogeneities. Consequently, the control of local temperature exposure, forming time, and die-sheet contact conditions appears critical to limit excessive grain growth in highly strained regions. This finding motivates a more detailed consideration of die geometry and process parameters not only with respect to form filling and thickness reduction, but also with regard to microstructural stability.

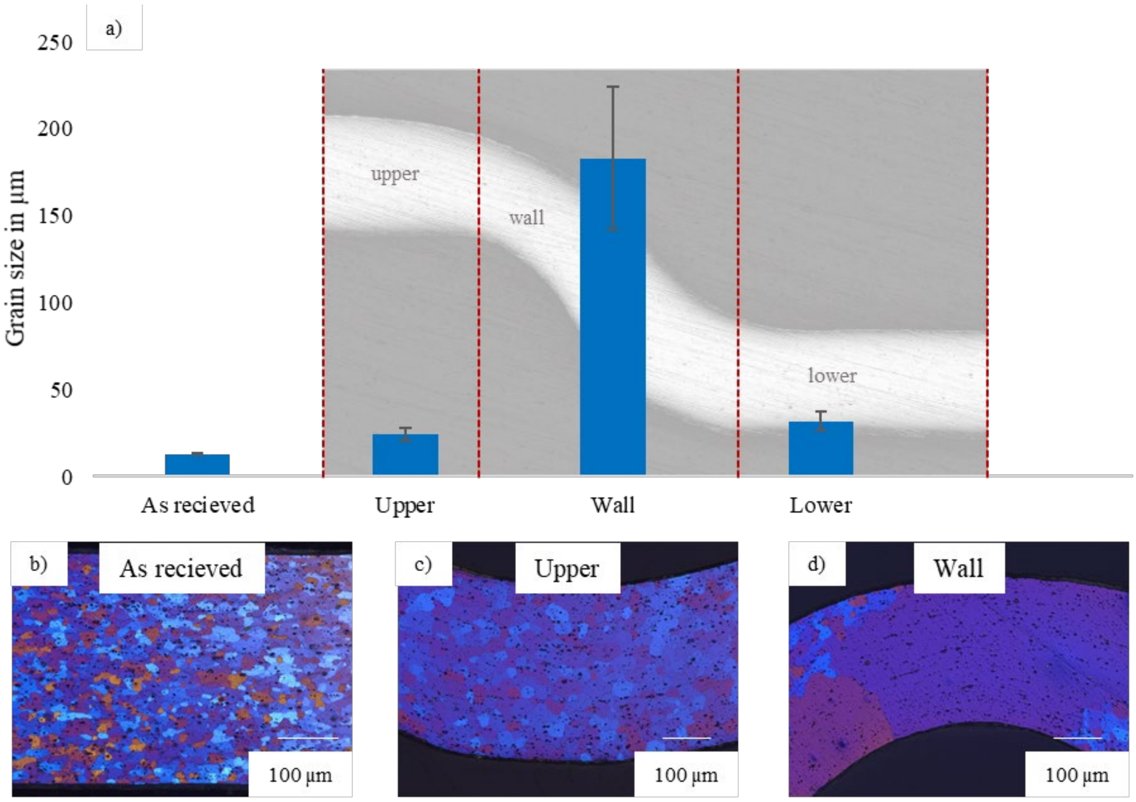

Fig. 4. a) Grain size evaluation over all specimens and micro channels depending on the location of measurement b) microsection of initial blank as received c) microsection of final component in upper area d) microsection of final component in wall area.

Conclusion & Outlook

HMGF was successfully employed to manufacture thin-walled aluminum components with integrated microchannels from 0.4 mm thick AlMg3 sheets at a forming temperature of 530 °C. Microchannels with a depth of up to 1 mm were produced with complete die filling using a maximum forming pressure of 20 MPa applied for 5 s. The magnitude of thickness reduction is primarily controlled by channel geometry, particularly channel depth and wall angle, and reaches a maximum of approximately 29 % for a channel depth of 1 mm. Regions subjected to the highest local thinning exhibit pronounced grain growth, with grain sizes locally approaching the remaining wall thickness. These results indicate that, while HMGF enables the reliable forming of microchannel structures in thin aluminum sheets, careful control of process parameters is required to limit excessive grain coarsening in highly strained regions. Future work will therefore focus on optimizing the thermal–mechanical process conditions and die design to improve microstructural stability and ensure consistent mechanical performance of the formed components.

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