Foaming of friction stir processed Al/MgCO3 precursor via flame heating

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Abstract
In the recent years, metal foams have become promising candidate materials in the engineering sector owing to their light weight and excellent energy absorption properties. Friction stir processing (FSP) has emerged as a cost-effective route to fabricate metal foam precursors from bulk substrates. Although the short processing time in FSP is able to provide high productivity, the cost of the foaming agent, TiH2 in the case of aluminum foams is still high. This paper introduces flame heating to achieve localized foaming of aluminum alloy AA5754 to explore the possibility of using magnesium carbonate as a foaming agent stirred using multi-pass FSP. A specially designed slot based strategy using two plates arranged in lap configuration is devised to stir the foaming agent and understand the material movement after each subsequent pass. Microscopy techniques were carried out to evaluate the distribution of the foaming agent after each pass and the resulting microstructure of the processed plates as well as the morphology of the foamed sample. EDX results showed higher Mg and O content around the pore walls.

1. Introduction

Metal foams are porouss metallic structures wherein the process of foaming is responsible for their morphology [1]. The presence of a large number of pores gives rise to a unique set of properties to metallic foams. These include high acoustic and mechanical damping capabilities combined with excellent specific strength (low specific weight and high stiffness), absorption of high kinetic energy impacts, as suitable flame retardants with high heat dissipation ability due to a large surface area [2]; enabling metallic foams as promising contenders in the aerospace, automotive, marine, defense, power sectors encompassing a wide range of applications from foam core sandwich panels to foam filled load bearing members, crash absorbers, ballistic armor, heat exchangers and biomedical implants [1].

Traditionally, aluminum based metallic foams have been manufactured either via the melt based routes namely Alcan, Alporas, Gasar, and Formgrip or the powder based routes [3, 4]. In spite of the success of commercially available metal foams there exist a number of issues when assembling metal foams with bulk materials; as rather than in isolation, they are always interfaced with bulk materials. In light-weight structural applications, the sole and standalone use of metal foams is limited while the integration of foamed panels with sheets is a challenge. In such applications, producing components with localized foamed regions in bulk substrates would prove to be cheaper. On one hand the number of process variables involved in melt foaming is large, on the other hand the time and cost involved with powder based routes is high, thus hindering wide-scale adoption of metal foams in the industry.

A solution to this problem may be answered by the use of friction stir processing (FSP). FSP harnesses the heat input due to friction to soften the work material, subsequently deforming it plastically through a rotating and traversing tool (comprising of a shoulder and a probe of specified geometry) to modify a surface without
melting the base material [5]. The action of the rotating and traversing tool is known as stirring. To produce localized metal foams, a slot is machined on the plate’s surface and a foaming agent is filled in the slot. The foaming agent is then mixed and dispersed by the stirring action of the rotating and traversing tool within the bulk substrate to form a precursor. The powders can be also be stacked between two sheets or can be just sprinkled on the surface. The friction stir processed sheets are then held in a furnace for foaming to take place.

Unlike roll bonding [6] which is another solid-state process, the processing cycle of FSP is short, enabling a larger volume of material to be processed which translates into greater economy and productivity. FSP also has a distinction wherein the tool traverse area within the substrate can be controlled, and only a region of desired interest can be allowed to foam. Furthermore, multifunctional properties can be obtained using FSP, making it possible to produce a foamed region adjacent to a region of thermoelectric properties within the same substrate.

The concept of using FSP for the manufacture of metal foam through precursors was first realized by Hangai et al [7]. In their research, the authors have focused on tensile, compressive, dynamic drop tests, porosity, pore structure size and distribution and relative density to characterize the foam with the help of advanced x-ray computed tomography (CT scan) and FEM simulation. Using AA4045 as the base material it was shown that a porous structure could be fabricated using multi-pass FSP followed by furnace heating [7]. Their experiments have established that degree of porosity of the FSPed precursors is contingent upon both the number of passes and the tool rotation rate (referred to as the amount of stirring action) as it promotes effective mixing of the powders within the substrate which corresponds to evenly distributed pores [8]. Further, studies have revealed an optimum holding time to maximize the porosity of the foams. With an increase in the holding time, the tendency of the liquid films to hold the gases evolved due to the decomposition of foaming agent decreases, thus reducing the porosity of the foams. Also, an enhancement in the sphericity of the pores is observed with an increase in the number of passes. The stabilizing agent also has an effect on the circularity and distribution of the pores [9]. It has been observed that with a higher amount of stabilizing agent the ability of the precursor to hold the evolved gases in the liquid metal films is thus enhancing a more extensive space [4, 10].

Functionally graded (FG) foams with multiple plateau stress and controlled deformation have also been fabricated using FSP. The ability of FSP to produce seamless joints between two different alloy precursors has been exploited to produce FG foams using alloys A1050-A6061 [11–13], ADC12 [14] and A1050-ADC12 [15] respectively. In the case of ADC12, FG foam precursors were fabricated by joining a set of plates with a foaming agent to those without a foaming agent, such that the porosity content varies along the length of the precursor.

In addition, the capability of FSP to manufacture foam cored sandwich panels has also been demonstrated. Unlike conventional sandwich panels where a high strength adhesive is used to bond the foam core and the solid sheets, Utsonomia and Hangai et al have devised a novel process in which mixing of the foaming agent and bonding takes place simultaneously. This includes sandwich panels comprising of ADC12 foam with ADC6 cladding [16]. Fabrication of Al-steel sandwich structures has also been reported [17]. Here, cladding between the Al precursor and steel sheet is achieved by FSP. Tensile tests have revealed a higher bond strength at the Al-steel interface [18]. FSP is also successful in the manufacture of foam filled tubes. Investigation of Al foam/Al tube [19], Al foam/steel [20] tube has demonstrated a strong bond of the precursor to the interior of the tube. Although, foaming of precursors as a result of frictional heating has been proved to be a viable option [21], the extraction of the foam, however, can be a problem.

Azizeh et al have used a slot based strategy followed by FSP to incorporate the foaming and stabilizing agent in Al alloy plates [22]. Here, the use of nano-sized alumina enabled a reduction in the amount of stabilizing agent. Papantoniou et al have adopted a similar strategy to find a suitable set of process parameters to obtain a high porosity content [23]. Lately, the authors have reported the fabrication of AA5083 based foams wherein multi-walled carbon nanotubes have been used for stabilizing the foamed structure [24]. Through friction stir incremental forming, a new layer of skin on the existing Alporas foam has been fabricated by Matsumoto et al [25].

In spite being a popular foaming agent, high cost and the risk explosion are some issues associated with the use of TiH2 [26]. Apart from hydrides, carbonates are now being considered as substitute foaming agents for aluminum [26–28]. The pore structure of carbonate based foams is quite different from titanium hydride, wherein the latter comprises of larger pores as compared to carbonate based foams [29, 30]. In the case of titanium hydride (TiH2), the hydrogen gas (H2) released on decomposition does not provide a stabilizing action to the melt [27]. Further, titanium forms brittle intermetallic compounds with the aluminum melt [29], leading to brittle fracture of the foams. While in the case of carbonate based foaming agents, the oxides formed on decomposition [3], help in stabilization of the pores, and the released CO2 reacts with the melt to make the melt viscous, while at the same increasing the volume of the nucleated pores [27, 30].

The aim of the present research is to fabricate locally foamed regions in aluminum sheets using MgCO3 as a foaming agent via the FSP route. As an alternative method to furnace heating, this research for the first time explores and presents the maiden use of flame heating to foam the FSPed samples in a cost effective manner. Flame heating is a well established process and has been exploited for applications involving heat treatment and
A concentrated flame directed on to the FSPed plates can bring down the foaming time, thus shortening the energy needed for foaming. Since the distribution of the foaming agent within the precursor material is critical, this study also aims to investigate the extent to which the foaming agent is dispersed within the precursor by the stirring action of the FSP tool. Therefore, a specially designed overlapping slot based strategy was devised to understand the material flow and the distribution of the foaming agent in the processed precursors, and the pore morphology of the foamed sample.

2. Methodology

The material used in the study is aluminum alloy AA5754, with its chemical composition given in table 1. AA5754 is a solid solution strengthened alloy, possessing high corrosion resistance and has good strength and ductility, finding applications in the marine industry. FSP was performed on a vertical milling machine (Bharat Fritz Werner (BFW), India) especially adapted to perform FSP. FSP was carried out with a tool made of H13 tool steel, comprising of a cylindrical pin, having a shoulder diameter of 18 mm, a pin diameter of 6 mm and a pin height of 4 mm as shown in figure 1.

The tool rotational speed was kept at 900 rpm and a welding speed of 80 mm min$^{-1}$ was provided. The tool plunge depth was set at 0.1 mm. These parameters were chosen after rigorous trial experimentation so as to obtain defect-free FSPed surface and a good particle distribution. Furthermore, the tool head was tilted at an angle of 2°. Plates with dimensions 170 mm × 54 mm × 3 mm were used in the investigation. Plates arranged in lap configuration are shown in figure 2. Two slots with dimensions 3 mm × 1 mm × 125 mm were made in two plates with a 3 mm carbide end mill cutter (refer figure 2). These slots were filled with MgCO$_3$ (particle size <50 μm) and aluminum foil was used to cover the filled slots. Figure 3 shows a scanning electron micrograph of the foaming agent (MgCO$_3$) used in the study.

A set of four FSP passes were made in total. The tool rotation was in such a manner that the slot in the top sheet was on the retreating side for all 4 passes. Figure 4 represents the scheme of FSP pass sequence. The fixed parameters and pass sequence strategy was chosen based on past experience [34–36] on particle distribution coupled with trial experimentation. For the first pass, the tool was plunged at the center of the slots. In pass 2, the tool axis was offset by 0.5 mm to the left of the center. Next, the plates were flipped followed by pass number 3 at the center. Finally, the tool was again offset by 0.5 mm to the left. The FSPed sheets were machined to remove burrs/flash before applying the third and fourth passes. The length of passes was 140 mm in each case. The amount of foaming agent added corresponded to 15% volume fraction of the pin stirred volume. (Slot made in plate 1, i.e. the plate on top, will be referred to as slot 1 while the slot in plate 2 will be called slot 2 in the paper from now on.)

Table 1. Chemical composition of Al5754.

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Others | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|--------|-----|
| %       | 0.25| 0.27| 0.08| 0.39| 3.1 | 0.28| 0.2 | 0.1 | <0.15  | Balance |
In order to achieve foaming of the stirred plates, flame heating using an oxy-acetylene gas torch was utilized for localized foaming of the sample. The outer blue feather of the neutral flame was traversed along the top face of the stirred region, which led to foaming of the sample within a time span of 3 min. The torch was traversed at a
traverse speed of 50 mm min$^{-1}$. Foaming of the substrate began on the upstream side as the flame was traversed. This procedure was carried out by a skilled operator, ensuring the distance between the torch tip to the surface of the plates was maintained at 80 mm. These parameters were carefully chosen through extensive trial by a skilled welder under the supervision of the authors. After foaming, a metallographic study was carried out for which specimens were polished sequentially with increasing grit size (100 to 2500 grit). After polishing, a fine mirror finish was achieved by using a velvet cloth and diamond paste. Samples were etched with the help of a modified version of Poulton’s reagent.

Microstructure of the four FSP passes and the foam was examined via optical microscopy (QS Metrology, New Delhi, India) and a scanning electron microscope (Zeiss, Jeol JSM-6380LV). Elemental analysis of the FSPed and foamed samples was performed with the help of energy dispersive x-ray spectroscopy (Oxford Instruments). Optical micrographs were stitched using an open source image stitching program (Image Composite Editor 2.0, Microsoft Corporation). Porosity of the samples was determined via image analysis (ImageJ), taking into account the volume of the precursor before and after foaming.

3. Results and discussion

3.1. Distribution of MgCO$_3$ after FSP

Figure 5 shows the macrostructure of the FSPed region after each of the four passes. From these macrographs, well-defined stir zones (SZ), as well as the movement of MgCO$_3$ in the vicinity of the machined slots, can be seen. The macrographs show distinct advancing sides (AS) for pass 1 in figure 5(a), pass 2 in figure 5(b), pass 3 in figure 5(c) and pass 4 in figure 5(d). The remnants of pass 1 and 2 can still be observed in plate 1 while pass 3 and pass 4 were applied. Note that passes 3 & 4 exhibit a sharper transition between the SZ and the thermo-mechanically affected zone (TMAZ).

With each pass the assimilation of the foaming agent within the Al alloy substrate increases. The foaming agent (which has light grey/off-white appearance) when mixed more evenly in the precursor appeared in a dark shade and can be seen in figures 5(b)–(d). During the first pass, the foaming agent was not thoroughly mixed in the alloy, as a result no blackish appearance was observed. From figure 5(a), it can be seen that the geometry of the slots in the top and bottom plates is deformed due to the downward force exerted and the stirring action of the rotating tool. Slot 1 retains most of its powder and can be seen as tapering towards the SZ, while slot 2 gets flattened and the foaming agent contained in this region is dragged towards the SZ. These can be observed as light and dark bands, with a central elliptical zone formed at the center. On applying an offset of 0.5 mm towards slot 2 in pass number 2 (figure 5(b)), an appreciable amount of MgCO$_3$ is drawn into the stir zone, which can be seen as a long dark region in the SZ. Since the interaction of the tool with slot 2 is more, an additional arm is produced at the bottom of the stirred region. Compared to pass 1, the mixing of the foaming agent in this pass increases by many folds.

When pass 3 is applied, the processed zone which was considered as the AS in passes 1 & 2 now becomes the retreating side (RS). This change from AS to RS leads to spreading of the powder. In addition, the tool spreads the powder filled in slot 1, which was earlier less affected by previous passes (refer to figure 5(c)). The introduction of the offset in pass 4 towards slot 1 facilitates widening of the powder processed zone. This pass tends to move the foaming agent further out towards the faces of the plates, relatively more skewed towards plate 2 (figure 5(d)).
The heat generated due to the interaction between the tool and the plates is below the decomposition temperature of the foaming agent, but is sufficient enough to mix the MgCO$_3$ in the base alloy.

Another feature that can be identified from the figure is that all passes suffer from the hooking defect typically found in lap configuration of FSP. Hooking is a common feature in lap joints [37–39]. Here, the AS curls towards the nugget forming a hook, while the RS rises up, leading to a reduction in joint efficiency in lap joints. Although the lifting of the plates in the case of regular lap welds is of the order of a few microns, in the present case a pronounced gap can be observed. Leaving aside the process parameters that may affect the extent of hooking, the presence of a machined slot and the aluminum foil used for packing the foaming agent can be responsible. Even though the powder was tightly packed within the slots, it still occupies a lesser volume compared to the volume of material removed from that slot. This coupled with the inherent unevenness of the aluminum foil leads to a deficiency in the amount of material that needs to be fed during stirring. Thus, near the end of the 4th pass, this shortage of material becomes significant as a result a tunnel can be observed as shown in figure 5(d). The degree of hooking after each pass will be discussed in later sections.

The microstructure of the processed region after the first pass can be seen from figure 6(a). As seen from the micrographs, the powder filled machined slots undergo deformation. Slot 1, being on the RS (figure 6(c)) gets pulled upwards as a result of hooking. As a consequence, a slight gap is seen to be created at the root of the slot and faying surfaces (refer to the arrow in figure 6(b)). At the throat of slot 1, the foaming agent can be seen to be drawn towards the processed zone. The shape of slot 1 which originally comprised of a rectangular cross-section has deformed to the shape of a wedge after the pass. Slot 2, on the other hand, gets elongated in the shape of a shoe due to the tool pressure and the intense mixing involved. The flow of material in the vicinity of slot 2 towards the processed zone also leads to the creation of a gap as indicated by the arrow in figure 6(b). At the center of the processed zone, an onion-ring shaped movement of the foaming agent can be observed. Since the tool is in contact with slot 2 to a greater extent, significantly higher amount of MgCO$_3$ is dragged towards the SZ. This is clearly evident from the light and dark lamellae which are substantially higher in concentration in between the slot 2 and the SZ. These dark clusters signify MgCO$_3$ rich areas, which can also be seen as rising along the AS and TMAZ boundary as shown by the arrow in figure 6(a). Moreover, the aluminum foil present between the faying surfaces gets incorporated in the processed region.

On applying an offset of 0.5 mm towards slot 2, the resulting FSPed microstructure of the plates is shown in figure 7. Since the pin comes closer to slot 2, a large portion of the foaming agent is advanced towards the SZ. This can be seen as the dark area branching into 3 new sectors. A part of the powder is fed into the center of the SZ and beneath the slot, while a large portion is dragged into the region below the SZ. These regions, which lie below the pin experience a limited radial material flow leading to the formation of a quiescent zone where intermixing of lamellae is restricted [40, 41]. While in the region just above slot 2, dune-like material movement...
can be observed just like in the previous pass. Also, this pass is successful in spreading the material throughout the width of the SZ since an increase in the number of lamellae can be observed on both the AS and the RS. Considering that an appreciable amount of material mixed by pass 1 gets agitated again by the tool in pass 2, multiple onion-ring shaped projections one on top of the other can be detected in the SZ. The shift of the tool shoulder to the left also creates a compression field which closes the gap on the AS previously present after pass 1. On the contrary, the throat of slot 1 gets elongated due to hooking and since the tool shoulder is no more present to consolidate the material near the root of slot 1, an increase in the gap between the plates can be seen.

The microstructure of the plates after applying pass 3 is shown by figure 8. With the application of pass 3, the extent of spreading of the powder has grown by many folds. By looking at the regions marked with white triangles, one can see the homogenization of the foaming agent in the alloy substrate. These are the regions which were previously dominated by dune-like lamellae. The region marked by the black circle represents the MgCO₃ rich zone in the vicinity of slot 2. As opposed to accumulated powder in the previous pass, thin lamellae can be observed here. Due to the intense churning produced by the rotation of the tool, the powder nearer to the probe/pin is drawn to the center of the stir zone, while the portion away from it advances in the direction of the tool shoulder. This pass is also effective in broadening the expanse of the foaming agent filled in slot 1, which was left unattended by passes 1 and 2. As can be seen from the region marked by a white circle on the micrograph, the powder rich sector is stretched till the processed zone. It can be noted that it is easier to spread the powder rich zone which was processed earlier [42]. Since the powder is discrete and loose as opposed to the base material, it is difficult to move. But once it gets integrated with the alloy, it becomes possible to sweep it further to a greater extent. Thus, it is easier to spread the powder rich zone which was processed earlier. Though the gap at the root of the slots seems to be closing, slot 2 being on the RS experiences a rise at the base due to hooking.

Microstructural changes after pass 4 can be viewed from figure 9. The engagement of the tool with slot 1 is seen to increase significantly with the application of the offset. Since the material in circle marked area (location A) lies in the SZ in all 4 passes, good mixing of the powder is observed. The foaming agent present in slot 2 disperses up to the TMAZ boundary, forming a dark C shape with its edge close to the tool shoulder. The lamellae of MgCO₃ and the base alloy at the root of slot 2 can also be seen. The powder rich region of slot 1, which

Figure 7. Microstructure of FSPed plates after Pass 2.

Figure 8. Microstructure of FSPed plates after Pass 3.
was extended by pass 3, continues to expand as fine lamellae. Some of the unstirred powder in slot 1 is also pushed further away from the processed zone as a result of tool pressure. The movement of the foaming agent can be understood by white arrows marked in the SZ. Here slot 1 seems to act as a powder rich reservoir which feeds additional foaming agent in the direction marked by the arrows. A change in hue from black to grey along this path indicates an increase in the mixing of powders as one moves away from slot 1. As a consequence of hooking, the gap at the AS increases (region marked by white triangle) which elevates the shortage of material near the end of the pass. The square marked area is a tunnel as a result of the deficit created at the end of the pass. On the whole, the fourth pass broadens the reach of the foaming agent within the alloy.

Scanning electron microscopy at location A is shown in figure 10(a). Foaming agent particles can be identified from black dots in the micrograph. Thin lamellae are formed as a consequence of rigorous mixing in the common zone. Through spectrum analysis (figure 10(b)) the major elements identified in the zone are Al, O and Mg. The presence of foaming agent is the major contributor of O and Mg.

Figure 11 gives a clear idea of the extent of stirring after each pass. The stirred foaming agent has been given a white shade in figure 11(a), which represents the stirring produced after the first pass. The black solid line is the location of the pin which disperses the foaming agent from the slots. The dispersion of powders is more prominent on the side closer to slot 2 with a higher presence of light and dark bands of lamellae. The area of the plates that is left uninfluenced by the tool is indicated by a blue shade as no significant microstructural changes can be observed in the region. The unaffected zone lies beneath the heat affected zone (HAZ), wherein only the temperature rise during the stirring action is responsible for the alteration of the microstructure.

In figure 11(b), the white shaded region shows the degree of mixing after the application of pass 2. The tool pin which was offset by a distance of 0.5 mm towards slot 2 is (shown by a yellow solid line) is successful in dispersing the foaming agent towards the center of the pin. An increase in the movement of MgCO₃ towards the region left to slot 1 can be seen. The reason for this can be attributed to the transport of the foaming agent residing in slot 2 which is picked up and deposited on the other side layer by layer. The reminiscence of pass 1 in pass 2 is shown by the area highlighted by a magenta hue. Since the movement of material due to a cylindrical geometry of the pin takes place in layers perpendicular to the axis of the tool, a majority of the material stirred by pass 1 gets agitated again by pass 2. It is only beneath the pin, that the agitation is less severe, such that a portion
of the area stirred by pass 1 is not affected by pass 2 owing to the offset provided. Moreover, the expanse of the unaffected region gets shortened as can be seen from the receding area highlighted in blue.

In figure 11(c), the section highlighted in red depicts the spread of the powder after pass 3. The pin location in this pass can be identified by the solid blue line. By flipping the plates, a marked increase in the amount of mixing of the powders is observed. In the common region which lies in the intersecting area stirred by the tool during pass 1, pass 2 and pass 3, a high extent of homogenization can be noted. In the vicinity of this common area, the thinning of previously formed lamellae, as well as the formation of new lamellae by integrating powder clusters with the base alloy can also be detected. The reason for an enhancement in material mixing can be attributed to the change in location of the tool from pass 2 to pass 3 which reverses the material flow direction leading to a vigorous agitation of the powders in the alloy matrix. Reminisce of pass 2 in pass 3 is depicted by the region highlighted in blue in which microstructural changes occur due to the influence of the tool in pass 2. As can be noted, the effect of pass 1 does not linger till the third pass.

The solid red line in figure 11(d) is the pin position in pass 4. Rest of the dashed lines indicates the previous locations of the pin. The white highlighted area represents the stirred foaming agent. The section only affected by pass 2 (shown in blue) recedes backward by a small amount, while the zone influence only by the previous pass 3 can also be seen in orange (refer figure 11(d)). Formation of additional lamellae with the disintegration of powder clusters is carried out by the tool pin in this pass. Since the powder present in slot 2 is spread to a greater extent as compared to slot 1 by the previous three passes, the stirred powder near slot 2 moves more readily by the pin in pass 4 as can be identified by the curving of the lamellae near the base of the tool shoulder. This flow of material is further assisted by the shift the MgCO$_3$ cluster sitting in slot 1 towards slot 2 and the tool shoulder.

The transition of the movement of the foaming agent from pass 1 to pass 2 is seen from figure 12(a) in which pass 2 is superimposed on top of pass 1 with opacity of 50%. The black hue of the foaming agent in pass 1 in contrast to the white hue of the stirred powder in pass 2 makes it discernable to identify the movement of material as they are stirred. The clusters of powders with a black and grey hue are those moved by pass 1. Whereas the regions with a white hue show the extent of spreading of the foaming agent produced after pass 2. Clearly, the second pass spreads the foaming agent way further than pass 1. The spread is more dominant below the onion ring-shaped pattern and the shoe-shaped projection of slot 2 seen after pass 1.

From figure 12(b), the transformation in the movement of the foaming agent from pass 2 to pass 3 can be recognized. Pass 2 with its spread powder highlighted in white is set as the base layer, on which pass 3 with its
distributed powder highlighted in red is superimposed. The opacity of 50% of the superimposed layer makes the extent of spreading after the two passes recognizable. The section with a pink hue is the distribution of MgCO₃ after pass 2, while the additional spreading shown in red is that induced by pass 3. The section predominantly affected by pass 3 is the region on the left side of slot 1, where a large portion of the foaming agent from slot 1 is dragged into the processed zone.

Figure 12(c) represents the change of material flow from pass 3 to pass 4. Here, pass 4 with the stirred powder highlighted in white is superimposed on to pass 3 in which a red hue is used to highlight the powder stirred region. The region in the figure marked by a pink hue is the common region to both pass 3 and pass 4. The white section depicts the additional stirring of the MgCO₃ after the 4th pass. As mentioned above, the MgCO₃ rich lamellae are forced towards the tool in pass 4, resulting in the more identifiable changes in the microstructure of pass 4.

3.2. Foamed sample
Traversing a concentrated oxy-acetylene flame on the top of the processed region for a span of 3 min led to softening and near melting of the base metal as well as decomposition of MgCO₃ stirred in the substrate. As the temperature rises, the rate of decomposition of MgCO₃ into magnesium oxide (MgO) and CO₂ increases. This promotes higher pressure of the evolved CO₂, which pushes the softened aluminum boundaries further out, creating large porosities within the material. Uniformity in the rise of the foamed region via current route can be observed from figure 13, which represents the resulting foam after flame heating. In spite of the fact that the traversing flame is considered as a moving point heat source, the rise in the foam column is even for the entire length of the sample. Figure 14(a) shows a macrograph of a section of the foamed sample wherein foaming was realized. Since the region stirred by the first two passes was directly exposed to the flame, a convex shaped bulge is formed, while the opposite side remains fairly straight. The majority of the foaming takes place in the upper region of the stirred sample as seen from the figure.

Ellipsoidal pores of larger diameter can be seen near the flame heated zone while the interior consists of smaller voids of round as well as irregularly shaped morphology. The presence of larger voids near the surface can be attributed to the coalescence of smaller voids. Due to a higher temperature near the surface, the viscosity of the melt is relatively low, as a result, the pressure inside the void is sufficient enough to break the liquid metal film around it and merge to form larger voids. As the volume of the evolved gas near the surface increases, a temperature gradient is developed, preventing the formation of larger pores in the middle of the plates. A
portion of the gas leaks out along the gap created between the plates as a result of hooking. These can be observed as flat voids near the root of the slots.

The microstructure of the foam is shown in figure 14(b). Closed cell pores with pore sizes ranging from the smallest pores of size 0.1 mm to a maximum pore diameter of 2.8 mm can be observed. Sites A and B are the location of slot 1 and 2 respectively before the passes were applied. The area in between A and B is the powder stirred zone. During pass number 4, a portion of the foaming agent was pushed away from the location of slot 1, which on decomposition has created a large irregular shaped void at site A. Moreover, a long narrow channel below this region can also be observed. This channel can be caused by thermal expansion combined with the deficiency of material created in this region during FSP. The hill shaped region left to sight B is formed as a consequence of hooking. The distribution of the pores exhibits a pattern, with the location of the slots acting as epicenters in dispersing the foaming agent. Pores can be seen to emanate from these two areas and move towards a region of higher temperature as shown by white arrows.
From the micrograph, it is quite evident that foaming has occurred only in the upper half of the stirred region. The heat supplied was not sufficient enough to penetrate the entire depth of the plates. This can be confirmed by the white oval shaped zone marked in the micrograph, which encompasses the powder stirred sector of slot 2. The darker contrast indicates this powder stirred zone does not participate much in foaming. Thus, limiting the porosity of the foam so obtained to 54%. Heating the opposite side can help enhance the porosity content.

Since pores in the core of the foamed sample experience a higher thermal gradient, elongation along the direction of higher temperature can be observed in the middle of the sample. The extent of elongation or irregularity is dependent on the nucleation of pores in the vicinity. The location of the pores marked in the red and violet regions is set closer to the gas torch; as a result, the decomposition rate is high which promotes the nucleation of larger pores around a central pore. These peripheral pores having a higher amount of evolved gas exert a pressure from all directions on the central pore resulting in a spherical morphology. While the pores marked inside the black oval are spaced further from the torch, a higher temperature gradient results in nucleation of fewer pores place beneath this region. Therefore the pores are only influenced by the pressure column of gas above it, making it relatively easier to expand towards the bottom, creating an elongated morphology of pores.

The distribution of pores in the foamed sample has a correlation with the distribution of the foaming agent after the fourth pass. Figure 15(a) shows a superimposed micrograph of the stirred MgCO$_3$ distribution after pass 4 on to the foamed micrograph. The white highlighted region indicates the location of the foaming agent in the substrate prior to foaming. In order to reveal the pores beneath the superimposed layer of the foaming agent, a transparency of 60% was applied to the top layer. The white dashed lines represent the width of the sample before the flame was traversed. It can be noted that the majority of the foaming agent present in the upper half of the stirred region participates in the formation of pores. When the flame is traversed, the nucleation of pores is
high in plate 1, which can be confirmed by the presence of a large number of porosities extending the white powder stirred region in the upper half, causing a substantial volumetric rise. On the other hand, voids in the lower plate can only be seen in those areas where the concentration of the foaming agent is high. The pores nucleate under the heat of the flame and the stirred lamellae get spaced further apart as the voids start expanding. In areas having a higher concentration of the foaming agent, such as the original location of the slots (marked as A and B in figure 14(b)), large voids emanate which space the two plates apart. The spacing between the plates is more prominent on the right side owing to less stirring of powder present in slot 1 compared to slot 2 (refer figure 9, figure 11(d)).

Figure 15 is an enlarged view of the lower half of the foamed sample. On the examination of the overlapping crescent-shaped region it can be seen that in spite of a higher concentration of the foaming agent present in this area, the presence of pores is less. Unlike the expansion in plate 1, the decomposition rate of the foaming agent here is low. A close comparison with figure 14(b) can reveal the probable retention of the foaming agent seen as a dark patch at this location. Two reasons can be given for the lower foamability of the lower plate. First, the pores in the top plate create a large thermal barrier, which restrict the amount of heat reaching the lower plate, making it less favorable for the MgCO3 to decompose. Secondly, the large portion of CO2 evolved on decomposition escapes through the cavity between the abutting plates (clearly seen in figure 14(a)), thereby limiting the porosity in the lower plate. As a consequence, there are fewer voids above the location of the machined slots. By increasing the value of the offset applied in passes 2 and 4, the expanse of the powder within the alloy plates can be widened and a more homogeneous mix in the substrate can be created which can help avoid leakage of the evolved gas during foaming.

A close examination of the pores as seen from figure 16 reveals a preferential migration of elements. Pore walls exhibit higher amount of oxygen (O) and magnesium (Mg). This migration is consistent with the findings with the case of carbonate based foaming agents, wherein the oxides produced on decomposition provide stability to the melt [27, 30]. In the present case, the MgO produced on decomposition of MgCO3 tends to preferentially sit along the periphery of the pores, thickening the melt without the need for additional stabilizing agent.

4. Conclusion

In the study, an aluminum foam precursor comprising of magnesium carbonate as the foaming agent was fabricated by the help of multi-pass FSP. By adopting a sandwich based slot strategy wherein the foaming agent was filled in slots between two Al 5754 abutting plates, the processed region was widened and good mixing of the
foaming agent within the alloy matrix was observed. The movement of the foaming agent after each of the four passes was studied in detail with the help of optical microscopy. Foaming of the stirred substrate was achieved via a foaming method which involved the use of an oxy-acetylene flame to foam the powder stirred region. Flame heating allowed foaming to take place within a span of 3 min, which translated into reduction in energy consumed as well as an enhancement in productivity. With a porosity of 54%, the morphology of the pores of the foam can be exploited in applications requiring deformation of selective zones of the foam. The following can be concluded from the experiment:

1. The extent of assimilation of the foaming agent in the alloy increases as more number of passes are applied. With the churning action of the rotating tool, broadening of the powder stirred region is observed. An appreciable enhancement in the mixing of the powders is experienced on flipping the plates since the AS becomes the RS and vice-versa, leading to vigorous mixing of the foaming agent.

2. The mixing of magnesium carbonate in the base alloy takes place via the formation of lamellae and with subsequent passes the width of the lamellae can be seen to reduce. Homogenization of the foaming agent occurs in those areas which fall in the stir zones of the previous passes. During the initial stages of mixing, the movement of the powder is slow owing to its discrete nature, but as the powder and the substrate integrate, the powder can be maneuvered to a greater extent.

3. In passes 1 and 2 the engagement of the tool is higher in the vicinity of slot 2, as a result the formation of powder rich lamellae is higher near slot 2. When passes 3 and 4 are applied, these lamellae are further broken up, accompanied by the formation of new lamellae near slot 1. Thus at the end of the four passes, the distribution of the stirred foaming agent is skewed towards slot 2.

4. The foam is characterized by a closed cell structure where the morphology of the pores changes as one moves away from the flame, towards the cooler end. Foaming of the upper half of the stirred region takes place and the resulting pores create a thermal barrier such that foaming in the lower half is restricted.

5. In the region closer to the flame, coalescence of the pores takes place, as a consequence large round pores are observed. Beneath these large pores lie a cluster of round pores of roughly the same size around a larger central pore. In the middle of the foamed sample, pores elongated along the direction of heat gradient can be seen.

6. The pore walls are rich in oxygen (O) and magnesium (Mg), which suggests the stabilizing action of MgO in preventing the cell walls from collapsing.

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