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Published in:
70th International Institute of Welding Annual Assembly and International Conference, IIW 2017

Published: 01/01/2017

Please cite the original version:
Karvinen, H., Nordal, D., Galkin, T., & Santos Vilaca da Silva, P. (2017). Application of Hybrid Friction Stir Channeling (HFSC) technique to improve the cooling efficiency of electronic components. In 70th International Institute of Welding Annual Assembly and International Conference, IIW 2017 [III-1799-17]
Application of Hybrid Friction Stir Channeling (HFSC) technique to improve the cooling efficiency of electronic components

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1. Abstract

Hybrid Friction Stir Channeling (HFSC) is a new friction stir based method for producing internal, closed channels created simultaneously during welding of multiple metal plates. The channels are produced in a single step, with any path and constant or continuously modified shape along the path. Differently from the conventional Friction Stir Channeling, that is only able to produce channels in a monolithic component, the HFSC can be applied to complex structural systems involving different components with similar or dissimilar geometry and material. Thus, instead of the thick plates required for FSC, channels manufactured by HFSC can be created in structural systems involving multiple components of similar, or dissimilar, material, such as, preform base plates with overlapping ribs. The resulting channel has rough internal surface finishing, which is beneficial in heat transfer application. The irregular shape of the channels, with high surface to volume ratio, and the internal roughness of HFSC channels increases the cooling efficiency of the channel compared to other alternative cooling channels with smooth internal surface.

In this study, the cooling efficiency of HFSC is compared to a milled channel with similar shape. Microhardness testing and microstructural analysis of HFSC channels made of aluminum alloy AA5083 are presented to evaluate the features of HFSC. For the cooling efficiency testing, HFSC was applied to a liquid cooled heatsink designed for an electronic device containing multiple heat sources. Prototypes were tested in steady-state and transient-state conditions with total heat generation of 65 W and 30.7 W, respectively. The heatsink prototypes were produced with HFSC and milling having similar channel sizes and paths. The HFSC heatsink had 30 to 40 \% lower steady-state temperature than that of the milled version. However, the pressure losses in the HFSC were higher than in the milled channel. During the transient period, the maximum cooling rate for HFSC was 20 \% higher than that of the milled channel. Results show that HFSC is feasible and has potential to improve significantly the efficiency of liquid cooling of electronic components.

Keywords (IIW thesaurus): Other welding processes; Friction stir welding; Thermal properties; Hardness tests; Microstructure; Aluminium alloys

2. Introduction

Constantly developing electronics applications require improved cooling solutions to maintain operational temperatures of the components. Increasing power density limits usability of air cooling systems due to the low efficiency of convective heat transfer in air. Heat transfer coefficient of water in forced convection can reach 1000 W/m\textsuperscript{2}K whereas the heat transfer coefficient of air is around 5 W/m\textsuperscript{2}K in natural convection and 25 W/m\textsuperscript{2}K in forced convection [1]. Conventional passive and active air cooling solutions are not enough to dissipate heat from high local hot zones. Selecting materials with high thermal conductivity has a limited cooling effect because the heat transfer path affect the total thermal resistance [2]. Increased temperatures reduce the reliability of the electronics components and require large cooling structures, which prevents utilizing the miniaturization possibilities of novel electronics. Liquid cooling is already applied for electronics and electrical applications such as data centers [3], personal computers [4], frequency transformers [5] and electric motors [6]. The high efficiency of liquid cooling enable significant space savings since the components can be positioned close to each other and large air condition devices are not needed. Heat energy can also be recovered and reused to heat buildings or even generate electricity depending on the level of heat energy available.
Liquid cooling is already implemented and researched for cooling of enclosures of electronic devices [7] or direct cooling of the electronic chips by micro-channels [8]. Micro channels are channels with hydraulic diameters ranging 10 – 200 μm fabricated for example by micromachining, sawing or etching [9]. There are many methods to produce flow paths of fluid cooled applications within a single or multiple operations. These include but are not limited to drilling, milling, electric discharge machining, 3D printing, extruding, tubing, casting and welding of pre-manufactured profiles. Some methods are not suitable for complex channel paths such as drilling, EDM and extruding. On the other hand, milled channels require closing operations by welding, screwing, brazing or adhesives. Additive manufacturing enables production of very complex structures, but currently the manufacturing speed and expensive materials hinder implementing it for high series production. Use of tubes in a heatsink is a common solution, but it requires multiple operations and reduces the thermal efficiency of the system due to losses in the thermal resistive interfaces between the tubes and heatsink. The quality of the interfaces along the heat transfer path affect the cooling efficiency. Microgaps and macrogaps in the interface between two solids are commonly filled by substances (air, water, grease) whose thermal conductivities are much smaller than those of the solid metals [1].

In 2005, Mishra proposed and patented Friction Stir Channeling (FSC) as a manufacturing method for small heat exchangers [10]. Mishra’s concept was based on reversing the material flow pattern from Friction Stir Processing, which enabled production of internally closed channel within a monolithic plate. In that concept all material extracted in the process is laid on a small clearance between the tool shoulder and workpiece. Therefore, the final surface is higher than the original surface. Later, in 2009, Balasubramanian et al. [11] presented the characterization of these channels. Rashidi et al. [12] reported similar FSC concept with modifications in the tool design and positioning. Instead of threaded tool probe as in Mishra’s concept, Rashidi et al. channeled aluminum with smooth cylindrical probe with tilt angle and non-threaded conical probe without a tilt angle and with a clearance between the shoulder and the workpiece [13]. In all these solutions, the size of the channels is limited because the material is not extracted from the processing domain in order to keep the channel closed. In 2013 Vilaça et al. [14] patented a new concept of the original FSC of monolithic components, which was based on a distinct material flow where controlled amount of processed material is extracted from the processed zone as self-detaching flash. In this concept, the tool shoulder is kept in contact with the surface of the workpiece. By adjusting process parameters, and tool features it is possible to produce channels with wide range of dimensions. These channels are addressed by Vilaça et al. [15] and extensively characterized by Vidal et al. [16-18].

The new HFSC was developed and patented by Vilaça et al. [19]. The HFSC enables producing simultaneously a weld joint and channel in a single action into multiple metal components. The channel can be produced in systems composed of multiple components involving similar, or dissimilar, materials and dimensions, namely, thin workpieces instead of the thick monolithic preforms required in previous FSC concepts. In this research, channels produced with HFSC are characterized and compared in terms of thermal efficiency with channels produced by milling. All the channels have with similar cross-sectional shape and dimension. Thus, the effect of the different channel finishing features is investigated envisaging the application in liquid cooling heatsinks. Analysis is based on the ability and efficiency of the heatsinks to cool a prototype of electronics device with multiple heat sources. The quality of the channels produced with HFSC is assessed with microhardness testing and optical microscopy. These testing techniques will address the changes in mechanical and microstructural properties due to the thermomechanical processing during the HFSC.

3. Features and Application of the Hybrid Friction Stir Channeling (HFSC)

The HFSC is a recently developed manufacturing method for internally closed channels created simultaneously during joining of multiple metal components within the thermomechanical processed zone. HFSC uses a non-consumable tool to generate and process a localized domain of visco-plasticized metallic material. The visco-plastic state of metal is also utilized in other friction stir based techniques to join materials by Friction Stir Welding (FSW) [20, 21], to deposit material layers on a plate by Friction Surfacing (FS) [22, 23], to modify material properties by Friction Stir Processing (FSP) [20] and to create internally closed channels into a monolithic plate by Friction Stir Channeling (FSC) [11, 24]. HFSC combines the benefits of FSW and FSC, leaving the processed surface at the same level, in a single-action stable process. With a dedicated design of the probe and shoulder, the material flow is used to mix and forge an interface of two or more metal components forming a weld and create an outward material flow, forming a channel. The shoulder design assures the closing of the roof of the channel and the generation of detachable flash, for any volume of material extracted. The channel and weld produced simultaneously with HFSC can have free path and the cross-sectional area of the channel is constant or
continuously modifiable along the path. The possibility to join components during channeling allows producing channeled structures from thin preforms. The tetragonal-like cross-section of the HFSC channels has internal irregular surface finishing that increases the surface area, promotes turbulent flow even at low flow rates and thus potentially improves heat transfer between solid material and fluid. In addition, HFSC does not require consumables or additional supporting chemicals in production, such as many other alternative machining techniques. No fumes or radiation are generated making HFSC a friendly process for the environment.

The geometrical arrangement of the multiple components in the joint can be designed in an overlap joint, butt joint or a combination of overlapped with butt joint, as presented in Figure 1b. The Figure 1a shows the concept of HFSC applied on 3 overlapped components along a non-linear path. HFSC concept reduces the material requirements of channeled applications since only the material volume required to encompass the channel is added during processing. This also minimizes the post-processing since other geometrical features of the component can be produced before the HFSC. The probe of the HFSC tool creates a combined push-down and pull-up actions relatively to the shoulder. The geometrical features of the shoulder of the HFSC tool are kept in contact with the workpiece generating a combined pull-in and push-out actions to seal the roof of the channel and extract a variable amount of material as a flash. The processed final surface is at the same level of the original surface. The process is controllable and repeatable and is able to produce channels with wide range of dimensions. Geometries of conventional FSC and HFSC channel cross-sections made respectively by Afshin [25] and Nordal [26] at Aalto University, are shown in Figure 2. Figure 2a shows a FSC channel made in a monolithic 10 mm thick plate made of aluminum AA6082-T651. The Figure 2b presents a HFSC channel produced in an overlap of two AA5083-H111 plates with thicknesses of 5 mm (bottom) and 8 mm (top). Both channels have similar shape, with a smoother surface finishing at the shear/advancing side (AS) and bottom on the channel than those at the flow/retreating side (RS) and ceiling. The overall dimensions and cross-sectional areas of the channels are described in Table 1. Emphasis for the significant increase in size of the cross-sectional area of the HFSC [26] (over 30 mm²) when compared with others published based on the initial concepts of conventional FSC [11] (below 5 mm²).

![Figure 1. Concept of the application of the Hybrid Friction stir Channeling (HFSC): a) The HFSC applied to three overlapped components along a non-linear path; b) Schematic representation of alternative joints for HFSC.](image)

![Figure 2. Macrographs of channel cross sections: a) conventional FSC channel made in a monolithic 10 mm thick AA6082-T651 plate [25]; b) HFSC channel produced in two overlapped AA5083-H111 plates, with thickness of 8 mm (top) and 5 mm (bottom) [26].](image)

| Channeling technique | FSC [25] | HFSC [26] |
|----------------------|----------|-----------|
| Channel min/max width (mm) | 5.0/5.5 | 9.6/9.9 |
| Channel min/max height (mm) | 1.7/2.2 | 2.8/4.0 |
The study is concentrated on aluminum because the behavior of the solid-state material flow of aluminum is well-known, the aluminum can be processed with low cost tooling and aluminum alloys are good base materials envisaging application in thermal management solutions, one major potential field of application of these channels. HFSC as the other friction stir based techniques are sensitive to tool geometry and processing conditions. Since HFSC is based on mechanical processing of material, it requires firm clamping of workpieces during the process and machines able to produce the required processing forces. Clamping is especially important in HFSC concept where material ribs are joined on pre-manufactured workpieces that are not allowed to be deformed during the HFSC process.

4. Experimental methods

Material
All the cooling sink prototypes with channels produced by HFSC and milling were made of laminated aluminum alloy plates AA5083-H111. The AA5083 is used in automotive and marine applications due to its excellent corrosion resistance and strength although nominal magnesium content of 4.5 % reduces its strength at high temperatures [27]. The chemical composition (wt.%) of AA5083-H111 according is 4.0-4.9 Mg, 0.4-1.0 Mn, 0.05-0.25 Cr, ≤0.4 Fe, ≤0.4 Si, ≤0.25 Zn, ≤0.15 Ti, ≤0.1 Cu.

Manufacturing of the prototype with HFSC channel
The HFSC heatsink prototype was manufactured from overlapping 8 mm and 5 mm thick plates. The plates were strongly clamped on the worktable of an ESAB Legio FSW 5UT machine (Figure 3a). In the overlapping arrangement the 5 mm plate was on the bottom and the 8 mm plate on top. Three M5 screws were used to bolt the plates together near the starting point of the channel to prevent the separation between the two overlapped plates during the plunging of the probe, in the start of the HFSC cycle. The separation between the plates may occur if the plates are not clamped firmly against each other and the processed material is able to flow into the gap between them. The HFSC tool shoulder had an outer diameter of 24 mm. The HFSC tool probe had an outer envelope diameter of 10 mm and a total length of 10 mm, where the first 6 mm were dedicated for channeling and the last 4 mm, at the tip, for welding. The tool was plunged into 9.5 mm and the plates were channelled with position control. Tool rotation speed was 800 rpm during plunging and 300 rpm during travelling at 90 mm/min. Dwell time of 2 s was applied after plunging and before tool accelerated into travel speed. The resultant HFSC plate is presented in Figure 3b. The parameters implemented were selected for high stability of the HFSC process in complex paths, and the resultant channels do not correspond to the one presented in Figure 2b, which was made with parameters with the objective of maximizing the channel cross section. The resultant channel in the tested HFSC prototype are characterized in detail, in the analysis of the results.

The channelled plate was then milled with a machining center to the final shape (Figure 3c) before assembling hose couplings, the heat sources, sensors and the top cover (Figure 3d). Hose couplings for the HFSC prototype were manufactured from M10 stainless steels screws with 5 mm hole through the screw and making 90° before entering the channel. The hose couplings were attached with a nut and washer plates (Figure 3e). The cross-sectional area of the HFSC channel was 26.1 mm².

Characterization methods applied to the channels produced by HFSC
Experimental analysis of the HFSC channels included microhardness testing and microstructural analysis of the processed zone. The samples for microhardness testing and optical microscopy were extracted from 210 mm long channels using a Beka-Mak BMSY 32CGL saw and a Struers Discotom-50 circular saw. Vickers microhardness testing was applied with a Struers Duramin-A300 hardness tester and 0.5 kg force (HV05). Indentation spacing was 1 mm and hardness was measured across the base material and the processed zone. Hardness of the unprocessed base materials were also measured. The indentation matrix was implemented in a box of 29 mm x 12 mm containing the entire thermomechanically-affected zone (TMAZ) and heat-affected zone (HAZ). The hardness mapping of HFSC is shown in Figure 4. Samples for microhardness testing and microstructural analysis were cold mounted using Struers VersoCit-2 Kit acrylic resin. Sample for hardness testing was ground
on a Struers LaboPol-21 machine using SiC papers to a 4000 grit finish and polished with 3 μm diamond compound on a Struers LaboPol-5 machine. Optical microscopy sample was further polished with a 1 μm diamond compound. The sample was etched using a 10% hydrofluoric (HF) acid. After microscopy analysis the channel was repolished to a 1μm finish and etched using modified Poulton’s acid. Etching procedure Microstructural investigation was carried out optically with a Nikon Epiphoto 200 microscope equipped with a Nikon DS-2Mv camera. The microscopic analysis focused on the weld stirred zone, channel ceiling and the four corners of the channel within the TMAZ. Some key-microstructural zones are schematically identified in Figure 4.

Optical microscopy sample was further polished with a 1 μm diamond compound. The sample was etched using a 10% hydrofluoric (HF) acid. After microscopy analysis the channel was repolished to a 1μm finish and etched using modified Poulton’s acid. Etching procedure Microstructural investigation was carried out optically with a Nikon Epiphoto 200 microscope equipped with a Nikon DS-2Mv camera. The microscopic analysis focused on the weld stirred zone, channel ceiling and the four corners of the channel within the TMAZ. Some key-microstructural zones are schematically identified in Figure 4.

Figure 3. Details on manufacturing of the prototype with HFSC channel: a) Clamping of the 8 mm (top) and 5 mm (bottom) plates for implementation of the HFSC process. b) Plates with weld and channel in as-HFSC condition. c) HFSC prototype after milling the shape of the device; d) Assembled prototype ready for testing. e) Illustration of the hose coupling used with HFSC channel.

Figure 4. Indentation matrix 30 x 13 (1 mm spacing) used in the hardness test (HV05) and schematic representation of the key zones of the HFSC processed region, including the channel ceiling and weld stirred zone.

Manufacturing of the prototype with milled channel
The open groove corresponding to the channel in the milled prototype was machined in a single AA5083-H111 plate with thickness of 11 mm. The channel had a cross section of 23.3 mm², corresponding to a rectangular groove with 9.3 mm x 2.5 mm (Figure 5a). The milled rectangular groove having the same path as the HFSC channel was covered with 2 mm thick aluminum plate. The thickness of the lid is similar to the thickness obtained for the channel ceiling of the HFSC. Thus, both HFSC and the milled prototype have dimensions that are very close, enabling the comparison of the different finishing without interference of other geometrical effects. The lid was sealed with forty-seven M3 screws and Hylomar® M jointing compound (Figure 5b). Conventional straight hose spindles attached with R 1/8 pipe threads were used with the milled channel. The final prototype with milled channel is shown in Figure 5c.
Procedure for cooling efficiency testing

Cooling efficiency of the HFSC channels was measured with a prototype of liquid cooled heatsink representing an enclosure of a small electronics device. The envelope dimensions of the prototype were 170 mm x 140 mm x 60 mm. Two heatsink prototypes were made with one containing a HFSC channel and the other containing a milled channel with a screwed lid to seal the roof of the channel. The cooling channel in both prototypes had the same 465 mm long flow path with similar shape and cross sectional area. In addition to the heatsink, the prototype assembly included a printed wiring board (PWB), thermal interface materials, six power resistors as heat sources and a plastic top cover to prevent air flow over the resistors. The channel path was designed considering the heat power source distribution, leaving for last the most powerful heat power source in order to maximize the heat extraction. The distribution and location of the power sources is discussed later and the channel path is depicted in Figure 7a.

Cooling performance was measured with steady-state and transient conditions. Steady state condition was measured with fixed total heat power of 65 W at different volume flow rates: 0.3; 0.5; 0.8; 1.0; 1.5; 2.0 and 2.5 l/min. The Reynolds number (1) was used to enable the adimensional comparison between the two similar, but not equal, channels produced by HFSC and milling.

\[ Re = \frac{\rho VL}{\mu} \]  

(1)

In equation (1) the \( \rho \) is the density (kg/m\(^3\)) of the fluid, \( V \) is the flow velocity (m/s) of the fluid, \( L \) is the wetted perimeter (m) of the channel and \( \mu \) is the viscosity (kg/(m.s)) of fluid. In practical terms, the wetted perimeter is the perimeter of the channel in contact with the fluid. The flow is laminar at small Reynolds number and the heat is transferred by molecular conduction between fluid particles. At large Reynold number, the flow becomes turbulent and the particle are mixed, which increases heat transfer [28]. The value of the wetted perimeter \( L \) for the HFSC and milled channel are 0.0244 m and 0.0236 mm, respectively. The parameter \( L \) for HFSC channel is calculated with image processing software. The coolant fluid used was water-ethylene glycol mixture which have an approximated density of 1.023 kg/m\(^3\) and dynamic viscosity of 0.001 kg/(m.s).

Steady-state condition was considered when the temperature in measurement locations varied less than 0.5 °C during 1000 s. At heat power 65 W, three measurements were made at each flow rates.

Transient cooling condition tests were made at 30.7 W heating power. The prototype was heated to steady-state condition without flow rate. After stable conditions, liquid cooling was turned on with a fixed flow velocity of 0.56 m/s for both type of cooling channels. The temperature was measured and logged until conditions were stabilized.

The closed flow circuit in the test consisted of a 7 l liquid container, pump, hoses, digital flowmeter, analog pressure gauge and a heat exchanger transferring the heat from the system into the air at atmospheric room conditions. The system kept the inlet temperature of the liquid approximately at 22 °C. Illustration and components of the system are shown in Figure 6.

Six ARCOL HS25 power resistors were used as heat sources representing actual electronic components, such as, processors and flash memories (Figure 7a). Similar heat source arrangement was prepared for both prototypes. One resistor was attached with two M3 screws to the liquid cooled heatsink and five resistors were screwed with M3 screws to a printed wiring board (PWB). Thermally conducting silicon paste was used to seal the interface when attaching the resistors. Silicon filled Al\(_2\)O\(_3\) gap pads were used to secure the contact between the PWB and...
the heatsink (shown as blue rectangles in Figure 7b). Tests were run with heat power level 65 W in steady-state testing and 30.7 W in transient testing.

Four K-type thermocouples (Labfacility Z2) were used to measure temperature of heatsink, liquid inlet, liquid outlet and ambient. The thermocouple in the heatsink was attached by gluing into a 2 mm x 2 mm groove under the 22 Ω resistor. Horizontal and vertical locations of the thermocouple in the heatsink is depicted in Figure 7. The heat flux of the resistor was 5.0 W/cm² at the steady-state testing and 2.2 W/cm² at the transient testing. During steady-state testing, temperature was logged at 0.1 Hz frequency. In transient testing, temperature was logged with a frequency of 1 Hz.

| Part                      | Model/type                  |
|---------------------------|-----------------------------|
| Pump                      | Seaflo SFDP1-045-040-41     |
| Flow meter                | IFM SM6000                  |
| Liquid to air heat exchanger | Nissens 71442 + 4 electric fans |
| Coolant                   | 20 % ethylene glycol + 80 % water |

Figure 6. Test setup for liquid cooling applied to both heat sink prototypes, i.e., with HFSC and milled channel: a) Schematic representation; b) Description of main components in the system.

5. Analysis of Results

The heat and material flow in the processed zone affects differently the original material properties. In the particular case of the friction stir based processes, the TMAZ encompasses material undergoing elasto-plastic and visco-plastic deformation, with a significant dissipation of the mechanical energy into heat. The combination of all these effects result in a complex distribution of microstructural and mechanical properties. As in the other friction stir based processes, also during the HFSC processing the different zone of the base materials undergo thermal and thermomechanical processing, resulting in the HAZ and TMAZ, respectively. However, differently from the other friction stir based processes (e.g. FSW and FSP), because a relevant part of the processed material
is extracted from the stirred zone, the material near the channel surfaces are not forged under closed die condition, resulting in four distinct free-shape surfaces, with irregular finishing and less consolidated solid-state joining mechanisms. Additionally, in the HFSC, the channel and weld zones, undergo through distinct material flow histories within the TMAZ.

**Microhardness**

The microhardness map (HV05), obtained from the cross-section of the HFSC sample, is shown in Figure 8. In this figure, it is possible to identify several sub-zones and features of the HAZ and TMAZ processed zones, resulting in a complex distribution of mechanical properties. The HAZ is distinct, but emphasis should be given to the different sub-zones within the TMAZ of the HFSC, mainly the ones resulting from the formation of the weld and the channel. As term of comparison, the measured average hardness of the 5 mm and 8 mm thick unprocessed base materials were 98 and 98.5 HV0.5, respectively. As support for the analysis, some lines were added to the microhardness map. The horizontal linear horizontal line represents the overlap joint interface between 5 mm and 8 mm plates. The HAZ (dashed line) and the TMAZ (solid line) are also qualitatively identified. There is no physical meaning for some of the very low values of hardness (dark blue) plotted. Namely: i) near the overlap joint interface; ii) near the perimeter of the channel; and iii) inside the channel. These values correspond to indentations in empty, or semi-empty, zones of metallic material.

Within the TMAZ, the weld stirred zone has higher values than base material, and channel ceiling. The TMAZ, the values are slight higher in the retreating side (RS) comparing to the advancing side (AS), at both weld stirred zone and channel ceiling.

The results at the HAZ are important. Around the weld stirred zone the values of the hardness at the HAZ are lower at the retreating side (RS) comparing to the advancing side (AS). In opposite arrangement, around the channel zone, the hardness at the HAZ is lower at the advancing side (AS) comparing to the retreating side (RS). These results are reach in information, because for these Al-Mg alloys the lower hardness is typically associated with higher peak temperature and eventually of higher cooling rates [29] Further investigation needs to address the different role of the shoulder in this wide and deep penetration level of the whole processed zone, and the quite different patterns of material flow deep inside the joint interface and at the vicinity of the channel zone. In a global analysis, the average hardness of the HFSC sample was 106 HV0.5, with maximum value of 125 HV05, and minimum value of 98 HV0.5.

![Microhardness mapping](image)

*Figure 8. Microhardness mapping (HV0.5) at the cross section of the HFSC heat sink component, with support lines identifying the TMAZ, HAZ and original location of the overlap joint line.*

**Microstructural characterization**

Macroscopic image of the HFSC processed zone is shown in Figure 9. Figure 9a shows the whole processed zone and Figure 9b shows a detailed view of the weld stirred zone. Comparing the AS and RS interface zones reveals a significant difference in transition between grain size and orientation. The AS has a very narrow and well-defined boundary or transition zone observed as a crisp boundary between the dynamically recrystallized region and the TMAZ. On the RS this region is much larger and less well defined, because the transition from the base material’s large grain structure to the stirred processed zone’s small recrystallized grain structure takes place slowly. This increased size in the transition zone is caused by the nature of the material flow that finds in the RS
a flow domain of most of the material that is separated at the sharp shear layer in the AS. The heat input is typically higher at the RS in FSW, because of the material flow transports a significant amount of heat with it [Ref.s]. But as presented in the Figure 8, for the complex material flow during the HFSC, this fact is true around the weld stirred zone, but not at the channel ceiling, where the lower hardness at the AS indicates a higher peak temperature, that maybe influenced by the close distance to the shoulder.

The wavy line shown in weld stirred zone is the dislocated original interface between the overlapped plates. The oxide layers of the aluminum plates are strong and stable and they need to be broken and mixed efficiently to produce strong welds. Lack of deformation and mixing of the oxide layers can result in a weak weld in which the interface continues into to the channel. The RS is more prone to alignment of particles such as hook effects. The AS is more prone to contain weak joining, because it is at the AS that the material flowing around the tool probe has to be consolidated with solid state joining mechanisms. The quality of the consolidation of the joint will depend on the local temperature and forging pressure. It can be seen in Figure 9b that the oxide interface and material is more mixed as it approaches the AS. Other critical zones of the processed region were observed in the corners of the channel and they are marked as rectangles in Figure 9a. These zones, the channel ceiling and the weld stirred zone are depicted in detail in the micrographs of Figure 10.

Along with the Figure 9a, the Figure 10 helps to understand the material flow and mechanisms of formation of the channels during the HFSC processing. The AS is sharply sheared (Figure 10e) from the base material with very narrow evidence of a stirred zone, in fact, the Figure 10e shows a very narrow recrystallized region adjacent to the channel surface. The thin recrystallized region does correlate to the increased shear deformation enacted on the AS of the channel during channeling operations. In the opposite side (RS), the Figure 10d shows a distinct thick layer of flow of dynamically recrystallized stirred material. The bottom of the channel has a relatively well-defined geometry, resulting from the separation of the flow, upwards against the shoulder, and downwards to forge the weld stirred zone. Anyway, this surface is less precise in geometry when compared with the same surface resulting from a conventional FSC [24], where the surface is defined by the tip surface of the tool probe. From the four corners of the channels, the most relevant for the quality of the channel are the ones located at the AS, presented in Figure 10c (top) and Figure 10e (bottom). In this case, there are evidences of good consolidation of the solid-state joining mechanisms along a wide length. The evidences are the high gradient of vertical packed layers of stirred material against the sheared wall of the AS. This fact is more evident in the Figure 10e encompassed already by the weld stirred zone. In both corners (Figure 10c and Figure 10e), only a small amount of overlapped flash is visible. The Figure 9a, shows some free flash within the channel, coming from the ceiling surface. The Figure 9a and Figure 10b show a channel ceiling with fully dynamically recrystallized small size grain structure, with distinct orientation given by the multi-influence of the material flow induced by the probe and shoulder. A quite different material flow pattern is exhibited at the RS and AS. The channel corners located at the RS, Figure 10a (top) and Figure 10f (bottom), also show evidence of the complex material flow. This fact is mainly visible in the non-recrystallized grain structure of the TMAZ, with severe grain deformation. Some flash overlap is more visible in Figure 10f (bottom), than at the Figure 10a (top).

![Figure 9](image_url)

*Figure 9. Microstructure of the processed zone by HFSC, containing the channel and the weld (etched with 10 % HF): a) Macrograph of the overall cross-section with identification of the key-zones targeted in the micrograph analysis; and b) Closer perspective of the microstructure in the weld stirred zone of the HFSC.*
More detailed examination of the channel ceiling (Figure 10b) and weld stirred zone (Figure 10g) reveals significant grain refinement due to dynamic recrystallization. The weld stirred zone contains a higher level of grain refinement observed by the finer grain structure although overall difference is small. This suggests a higher forging pressure in the weld stirred zone over the channel ceiling promoting a finer grain formation. With the weld located in the center of the plates arrangement it will experience a slower cooling rate than the channel ceiling further supporting the findings of the finer grain structure in the weld stirred zone and somewhat higher hardness (Figure 8).

![Figure 10. Micrographs of some key-zones of the microstructure resulting from the HFSC processing: a) RS – channel ceiling interface; b) Channel ceiling; c) AS – channel ceiling interface; d) RS of the channel; e) AS of the channel; f) RS – weld stirred zone interface; g) weld nugget and h) AS – weld nugget interface.](image)

**Cooling efficiency**

Both production methods, i.e. the HFSC and the milling resulted in heatsinks with admissible distortion and easy to assemble to the chassis containing the electronic components. The Figure 11a shows the temperature of the heatsink as a function of the Reynolds number. Temperatures are shown as a difference from ambient temperature, so the lower the difference the better result. Temperature at the liquid inlet was at the ambient level. The HFSC keeps the temperature of heatsink lower at all the tested flow rates. The temperature of the heatsink responses accurately to the changes in the inlet temperature. This can be seen in the results for milled channel where the heatsink temperature seems to stabilize or increase around Reynolds number 2500. At steady-state conditions, temperature difference between the heatsink and ambient was 30 – 40 % lower in HFSC than in milled heatsink prototype. The difference obtained between the HFSC and milled heatsink prototypes increased with increasing flow rate.
Results of the transient-state testing are shown in Figure 11b. The cooling rate of the HFSC is 20% higher than that of the milled prototype. Maximum cooling rate of the HFSC and milled prototypes are 2.2 °C/s and 1.83 °C/s, respectively, which represents 20% higher cooling rate for the HFSC. The high cooling rate is important for cooling systems that need to be responsive for changing conditions. High responsive cooling system can effectively cool sudden increases in heat fluxes and increase service life of electronics.

The shape and surface finishing of the channel of the HFSC increase flow resistance compared to that of milled channel, which can be seen in the mechanical power requirement presented in Figure 12a. The mechanical power $P_{\text{Mech}}$ is calculated with equation (2).

$$P_{\text{Mech}} = p \cdot \dot{V}$$  \hspace{1cm} (2)

Where the $p$ is the pressure of the flow (Pa) and $\dot{V}$ in volume flow rate ($\text{m}^3/\text{s}$). More mechanical power is required for HFSC at all flow velocities and the difference increases with increasing flow velocity. At Reynolds number 2000 the difference is not significant, but at Reynolds number 6000 the pressure in HFSC is 50% higher than in milled channel. By comparing the requirement for mechanical power and Reynolds number, the HFSC prototype requires more energy to operate the flow (Figure 12a). Anyway, when analyzing the temperature drop of the heatsink and the mechanical power, the HFSC heatsink cools the electronic components more efficiently at low mechanical power level than the milled heatsink (Figure 12b). For example, at the power 0.5 W the temperature difference between the HFSC heatsink and ambient is 30% lower than that between the milled heatsink and ambient. By increasing the flow velocity, the power requirement increases significantly but does not improve cooling.
6. Conclusions
The following conclusions can be drawn from the evaluation of the channels produced with the HFSC to be used as heatsink of electronic components:

- The HFSC showed to be a feasible technique to produce heatsinks with closed internal channels of large dimensions, with complex path, while joining two overlapped plates of AA5083. All in one action only;
- The microhardness map showed that the weld stirred zone have higher mechanical resistance than the channel ceiling. But these values are close to the hardness values of the base material;
- The critical lowest values of the hardness are located at the HAZ, but in different positions along the thickness of the HFSC processed zone. The low hadness of the HAZ are located at the RS around the weld stirring zone and at the AS around the channeled zone;
- Based on the optical microscopy, workpiece materials are subjected to severe deformation and recrystallization in the channel ceiling, around the channel, mainly at the RS and in the weld stirred zone.
- The high gradient of vertical packed layers of stirred material against the sheared wall of the AS, of the channel is evidence of good consolidation of the solid-state joining mechanisms along a wide length.
- The weld stirred zone contains a higher level of grain refinement observed by the finer grain structure although overall difference is small;
- The heatsinks produced with HFSC presented in overall, better cooling performance when compared with similar channels produced by milling;
- During the transient cooling period the HFSC based solution presented a faster cooling rate. The fast cooling response reducing the peak temperatures represents a feature of high importance for extending the life of electronic components that undergo complex and demanding heat loading cycles during service;
- At steady-state conditions, temperature difference between the heatsink and ambient was 30 % to 40 % lower in HFSC than in milled heatsink prototype. The differences in the operative temperature during steady-state condition are perceptually relevant for the two different heatsinks emphasizing the effect of the surface finishing also at stable temperature operation conditions.

7. Acknowledgements
The authors acknowledge the support from The Finnish Funding Agency for Innovation (TEKES) via the program: New knowledge and business from research ideas – TUTL.
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