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Development of Technological Conditions and Applications of Friction Stir Channeling

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Dissertation for the Degree of Master of Science in Design and Engineering

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Afshin Hasani Aleni

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Abstract

This thesis investigates development of technical conditions of Friction Stir Channeling (FSC) with main focus on industrial Lithium battery cooling applications.

Conventional technologies - Electrical Discharge Machining (EDM), Drilling and Milling - have limitations in creating continuous straight or continuous curved internal channels and none of them are capable of producing continuous free-path internal channel in a single step.

FSC is an innovative method within solid-state manufacturing technologies which is able to produce continuous internal channels in monolithic plates in a single step. FSC is capable of producing both straight and curved channels in metal plates with control of technical parameters similar to that of Friction Stir Welding (FSW). However, FSC is in initial phases and still more research needs to be done in order to improve FSC tools for producing channels in more diverse metals.

This thesis designs and builds new tools for FSC with improved geometrical parameters, and by means of these new tools, performs experiments in order to investigate technical condition of FSC and its capability in various industries. This thesis produces various Friction Stir (FS) channel prototypes in aluminum alloy plates AA6082-T6 and AA5083-H111. This work performs thermal and flow analysis in order to evaluate capability of FSC for battery cooling.

Following conclusions are arrived at in this thesis:

The experimental results of this work shows that by means of our improved FSC tools and by selecting the right technical parameters, high quality of channel surface finish with low roughness is obtained using position control as opposed to forced control. Moreover, FS tool rotation and travel speed affect the channel size so that channel size increases by increasing travel speed and decreasing rotation speed. Pressure tests conclude that the FS channels produced in this work can endure high pressure levels.

Furthermore, investigation and analysis in this thesis concludes that FSC has high potential in heat exchanger industries and conformal cooling channels for mould industries, and results in high productivity and low cost of production. Moreover, our thermal and flow analysis concludes that FSC has a high potential to be applied for cooling of industrial Lithium-ion batteries.

Keywords

Friction Stir Channeling

Aluminum Alloy AA6082-T6

Aluminum Alloy AA5083-H111

Heat exchanger

Conformal cooling

Abstrakt

Magistritöös uuritakse hõõrd kanalite tegemise meetodi tehniliste parameetrite arendamist, et seda rakendada liitium-ioon akude jahutamisel.

Traditsioonilised tehnoloogiad - traat-erosioon, puurimine ja freesimine - seavad piirid sirgete ja kõverate kanalite loomisele ühe operatsioonina.

Hõõrd meetod kanalite valmistamisel on innovaatiline tootmistehnoloogia, milline võimaldab valmistada pidevaid kanaleid monoliitsetesse plaatidesse ühe operatsioonina. Tehnoloogia võimaldab luua nii sirgeid kui ka keerulisema kujuga kanaleid teatud tehniliste parameetrite abil sarnaselt hõõrdkeevitusele. Tehnoloogia on veel arengustaadiumis ja vajalik on täiendavad uuringud, et luua kanaleid erinevatesse materjalidesse.

Magistritöös projekteeritakse ja valmistatakse uued parendatud geomeetriliste parameetritega tööriistad hõõrd kanalite valmistamise tehnoloogiale. Uute tööriistadega viiakse läbi eksperimendid, et selgitada välja parimad tehnilised parameetrid erinevate tööstusrakenduste jaoks. Magistritöö raames loodi kanaleid alumiiniumi sulamitest AA6082-T6 ja AA5083-H111 valmistatud plaatidele. Töös on läbi viidud termiline - ja voolamisanalüüs kanalitele, et uurida tehnoloogia sobivust akude jahutamisel.

Töö tulemused:

Eksperimentaalsed tulemused näitavad, et parendatud tööriistade ja sobilike protsessi parameetrite korral on võimalik saavutada kõrge kvaliteediga kanaleid. Täiendavalt saadi teada, et tööriista pöörlemise ja edasiliikumise kiirus mõjutab kanali suurust nii, et kanali suurus suureneb liikumiskiiruse suurenedes ja pöörlemiskiiruse vähenedes. Surve testid näitasid, et töös valmistatud kanalite korral võis kanalites rakendada kõrgeid rõhkusid.

Täiendavalt võib märkida, et uurimustöös läbi viidud analüüsid näitavad tehnoloogia kõrget potentsiaali jahutuskanalite valmistamisel valuvormide tööstuses. Tehnoloogia on kõrge tootlikkuse ja madalate kuludega. Tehnoloogial on kõrge potentsiaal liitium-ioon akude jahutuse loomisel.

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Abbreviations

AA	Aluminum Alloy
A.S.	Advancing Side
BM	Base Material
CS	Channel Size
COB	Cooling of Battery
EDM	Electric Discharge Machining
FS	Friction Stir
FSC	Friction Steel Channeling
FSP	Friction Stir Process
FSW	Friction Stir Welding
R.S.	Retreating Side
TWI	The Welding Institute

1 Introduction

Producing continuous and curved internal channels in a single step is not possible by conventional technologies such as Electric Discharge Machining (EDM), Drilling and Milling. As an alternative innovative method, Friction Stir Channeling (FSC) has the unique capability of creating such internal channels with any desirable path and depth inside metal plates and only in a single step. FSC is an innovative technology based on converting ‘’wormhole’’ defect which generated during Friction Stir Welding (FSW) process into a manufacturing technique for creating internal channels in a monolithic plate. Continuous internal channel in a single plate can be achieved by selecting the right processing conditions and reversing the metal flow [1], [2].

In FSC, channels can be formed by combination of specific tool rotation and travel moves inside of metal plates. The visco-plasticized workpiece material is brought from inside of plate by profiled probe threads and the deformed material is constrained to close the channel ceiling by scrolled shoulder. The size and shape of channels can be controlled by tool geometrical features and process parameters. For producing continuous internal channels by deformation of workpiece material, FSC process relies to the frictional heat generation between tool and workpiece and heat energy generation from dissipation during plastic deformation and internal viscous dissipation during the material flow [3].

Related Work:

Research and development on FSC has only started in recent years and there are few scientific works on this topic. In 2009, the characterization of the Friction Stir (FS) channels has been done by Balasubramanian et al. and the relationship between the channel features and the processing parameters investigated [1]. In 2011, Pedro Vilaca and Catarina Vidal [4] developed FSC by promoting distinct material flow, where a controlled amount of material from the workpiece, flows out from the processed zone producing the internal channel. Thus, the material flowing from the interior of the solid workpiece is not deposited on the processed surface but directed outside of the processed zone in the form of toe flash.

Approach and Contribution of This Thesis:

According to [5], features and specification of tools play an important role in the FSC process, therefore this thesis designs and builds new tools for FSC with improved geometrical parameters. The FSC tools produced in this work, enable creating of improved continuous internal channels with desired size and with low roughness on the outer roof of the channel as seen on the workpiece surface.

Furthermore, this thesis experiments the produced tools on base metals of Aluminum alloy plates (Aluminum alloys AA6082-T6 and AA5083-H111). As a result of this experiment and investigation, optimal technological conditions (geometrical features and process parameters) required to produce the internal channel in each base metal are suggested.

Producing conformal cooling moulds and heat exchangers are high potential industrial applications of FSC. Therefore, another goal of this thesis is to investigate adapting the obtained FS channels for this application. More specifically, curved channels which are used to build cooling system for batteries are produced. In order to evaluate effectiveness of obtained channels, this work analyzes behavior of flow and heat transmitting of fluid inside channels produced by the FSC method.

Finally, this thesis investigates implementation capabilities of FSC in comparison to conventional methods.

To achieve above goals, following steps are performed in this thesis:

- Designing and building new tools for FSC and performing experiments using these tools.
- Creating channel prototypes using FSC to produce internal straight and curved channels.
- Suggesting optimal technological conditions to produce the internal channel in each base metal.
- Performing computational modelling to analyze thermal and flow behavior inside the channels.
- Implementation of channeling for cooling of batteries.
- Comparing FSC with alternative technologies.

Thesis Structure:

The rest of this thesis is structured as follows. Chapter 2 describes state of the art and shows how FSC was emerged and created from FSW. Chapter 3 investigates alternative and conventional technologies for channeling. Chapter 4 describes design of new FSC tools in this thesis, including their material characterization, different components and tool geometry. Chapter 5 presents the implementation of channeling and prototypes of channels using the tools designed in this work, and investigates effects of tool geometry in FSC process. Chapter 6 investigates capabilities of FSC in industrial applications with focus on cooling system for industrial Lithium-ion batteries, and performs flow and thermal analysis for this application. Chapter 7 presents comparison of FSC to alternative technologies.

2 State of Art

This section, firstly, explains the fundamental concepts of FSC and secondly, reviews initial and latest development of this technology.

2.1 Emersion from Friction Stir Welding

Friction stir welding (FSW) is a solid-state joining method, rapidly expanding based on pressure welding process. It was developed in United Kingdom by The Welding Institute (TWI) in 1991. In this process, high quality weld can be created using conventional milling machine by performing ordinary movement conditions of the machine, however, a different type of tool meeting certain requirements should be attached to the machine [6], [7], [8].

The tool used for FSW is a cylindrical shouldered tool with a profiled probe. This tool is rotated and plunged into the joint area between two pieces of sheet or plate material. Frictional heat between the wear resistant welding tool and the workpiece causes the latter to soften without reaching melting point, allowing the tool travel along the weld line. The plasticized material, transferred to the trailing edge of the tool probe, is forged through intimate contact with the tool shoulder and probe profile. Figure 1 shows principle of FSW process [9], [10].

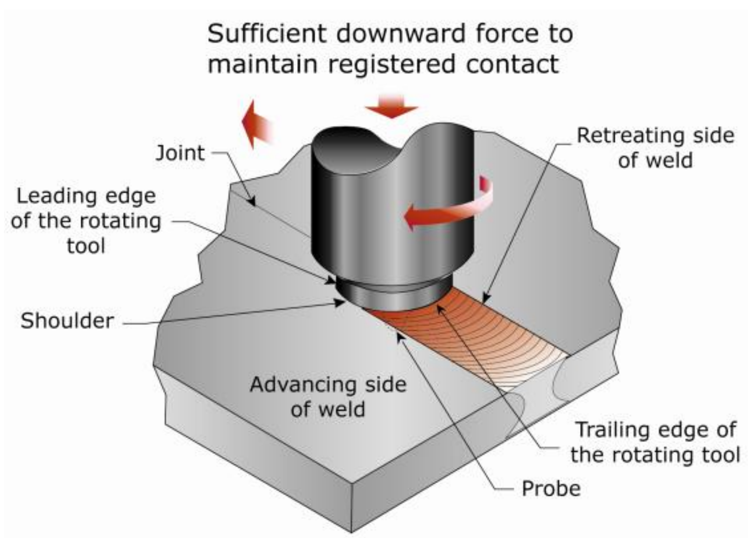


Figure 1 - Principles of FSW process [11].

According to [6], geometrical features of FSW tool plays very important role in this process. Tools consist of a shoulder and probe which can be integral with the shoulder or a separate insert possibility of a different material. The design of the shoulder and probe influences the quality of the weld. The probe of the tool generates heat and stirs material being welded and the shoulder provide additional frictional treatment as well as preventing the plasticized material from escaping from the weld region. Figure 2 shows various types of FSW tool and probe profiles depending on the application or desired result [6].

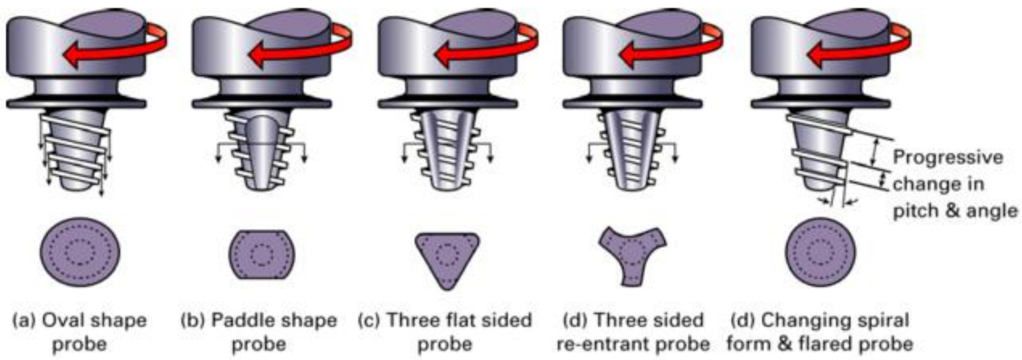


Figure 2 - Basic variants on the whorl ™ type probes tool [12].

In FSW, a defect called ‘’wormhole’’ is generated if the processing parameters and geometry of tool features are not optimal [13]. By converting this wormhole defect into a continuous channel, the friction stir channel is formed. Figure 3 presents heat zone region and wormhole defect in FSW processing.

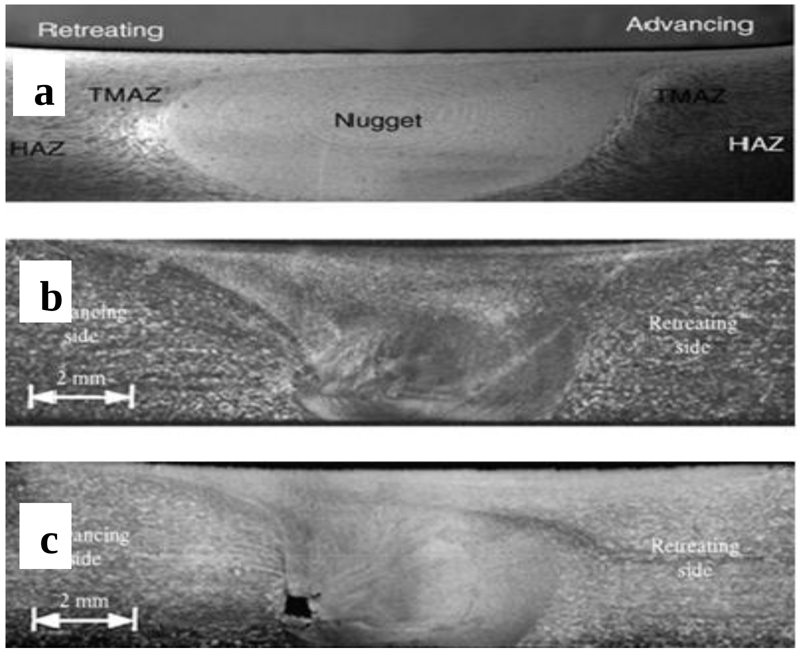


Figure 3 - a) Heat zone region b) Free of defect FWS c) Wormhole defect in FSW [13]

In 2005, R.S. Mishra from Missouri University [14] showed that it is possible to produce continuous, integral channel inside the metal plates in single step by reversing material flow of FSW and optimizing process parameters. Figure 4 shows schematic of FSC process and tool.

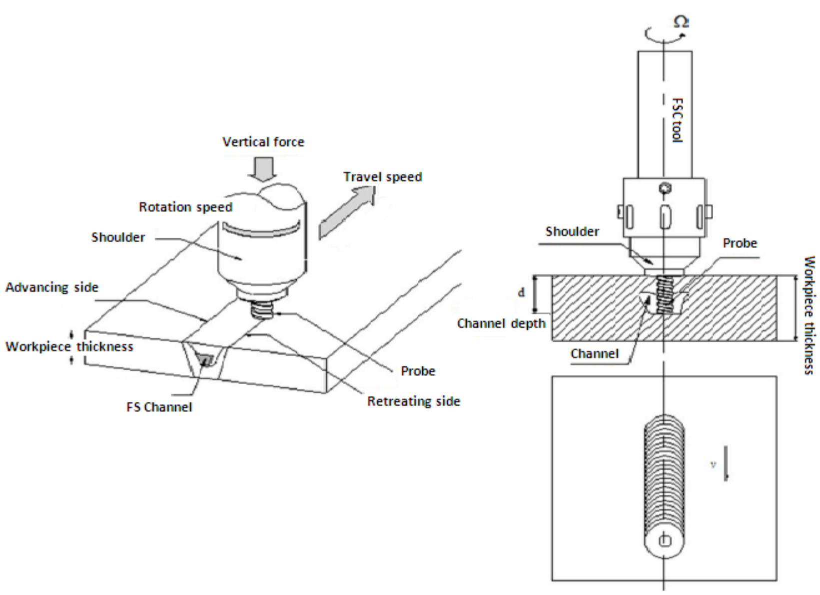


Figure 4 - Schematic of FSC tool and process [14]

2.2 Initial development of FSC

After FSC was emerged, a few efforts started in order to further develop and improve FSC, and convert it into an applicable technology.

In 2009, the characterization of the Friction Stir (FS) channels has been done by Balasubramanian et al. [1] and the relationship between the channel features and the processing parameters investigated in their work, the main aspects of FSC are included in:

a) The rotation of profiled tool such that the material flow is upwards towards the tool shoulder.
b) Providing an initial clearance between the shoulder and the workpiece, where the material from the base of the probe is deposited.
c) Adjustment of distance between the tool shoulder and the workpiece to control the shape, size and integrity of the channel.

For forming a channel, the material must be removed from the base of the probe to upward under the shoulder. This is depends on the probe threads and the direction of the tool rotation. The removed material is deposited on the surface to close the ceiling of the produced channel by the shoulder. The main difference between FSC and FSW is the gap between shoulder and workpiece where the back of shoulder touches the workpiece to produce free defect welding by generation the forging action required. In the channeling, by rotating a right hand threaded tool along clock wise direction or left hand threaded tool along counter clock wise direction an upward force is generate. Because of the separation of the plasticized material around the probe from the plasticized material at the base of the probe, a channel is formed. Also authors of [1] found that the size and the shape of the channels can be controlled by varying the following parameters: the gap between the shoulder and workpiece, the tool design, the tool rotation speed and the tool travel speed [1].

Balasubramanian et al. [1] proposed an experimental procedure of FSC and performed experiments on commercial 6061 Al alloy using three different tools with cylindrical probes and left-handed threads. The tools were rotated in the counter clock wise as seen from the top of workpiece. The authors tried to use those parameters to obtain channels with maximum size and free of visible surface defects. Moreover, the authors concluded through their experiments, that in order to achieve the desired channel size, it is necessary to set specific values for process parameters of travel speed, tool rotation speed and plunge depth. The experimental tool specification is shown in Table 1.

Table 1 - Balasubramanian experimental tools specification[1]

Tool	Shoulder Diameter (mm)	Probe diameter, (mm)	Probe length (mm)	Thread pitch (mm)	Thread angle	Depth of cut (mm)
1	16	5	4	1.25	60°	0.4
2	16	5	4	1.25	60°	1
3	16	5	4	1.25	75°	1.6

Figure 5 shows different regions of the cross-section in the resulting channel [1]. Regions A and B are referred to as the stir zone. Region C is unprocessed parent material, and region D is the channel. Region E exposes deposited material from the channel nugget region above the surface of the plate under shoulder. Layer surrounds the nugget, referred to a thermo-mechanically affected zone that is not clear in Figure 5. Advancing side represents the side of channel where the velocity vector of the tool rotation has the same direction as the travel direction. Retreating side is opposite the advancing side and represents the flow side of FS process.

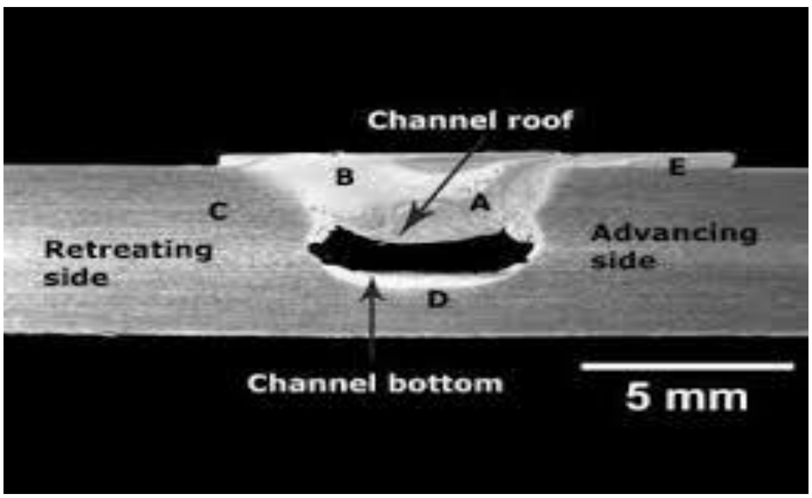


Figure 5 - Cross section of channel showing the different regions: (A and B) channel nugget (C) parent material (D) channel and (E) material from channel nugget deposited on the surface [1].

2.3 Latest Developments of FSC

Vidal et al. [15] and [16] developed FSC by promoting distinct material flow, where a controlled amount of material from the workpiece, flow out from the processed zone producing the internal channel. Thus, the material flowing from the interior of the solid workpiece is not deposited on the processed surface but directed outside of the processed zone in the form of toe flash. In addition, there is no gap between the shoulder and workpiece unlike the earlier works of [1] and [14] explained in previous section.

The selected probe for experiments of [16] was a conical probe with 5 mm bottom diameter and the threads of probe was left-handed along the probe length and also they used two spirals striates scrolling an angle of 360˚. The outer diameter of shoulder was 20 mm and the inner was 9 mm. The depth of probe penetration was 5.5 mm. Table 2 shows the variable parameters used.

Table 2 - FSC variable parameters [16]

Channel ID	Tool rotation speed (rpm)	Tool travel speed (mm/min)
a	600	80
b	600	150
c	800	80
d	800	150

Table 3 shows the obtained channel areas in experiments of [16]. Channel area decreases with increasing tool rotation speed, and for the same tool rotation speed increases by increasing tool travel speed. Figure 6 shows shapes of the obtained channels.

Table 3 - Geometric parameters of channels [16]

Channel ID	Area (mm^2)
a	13.49
b	14.01
c	12.75
d	12.88

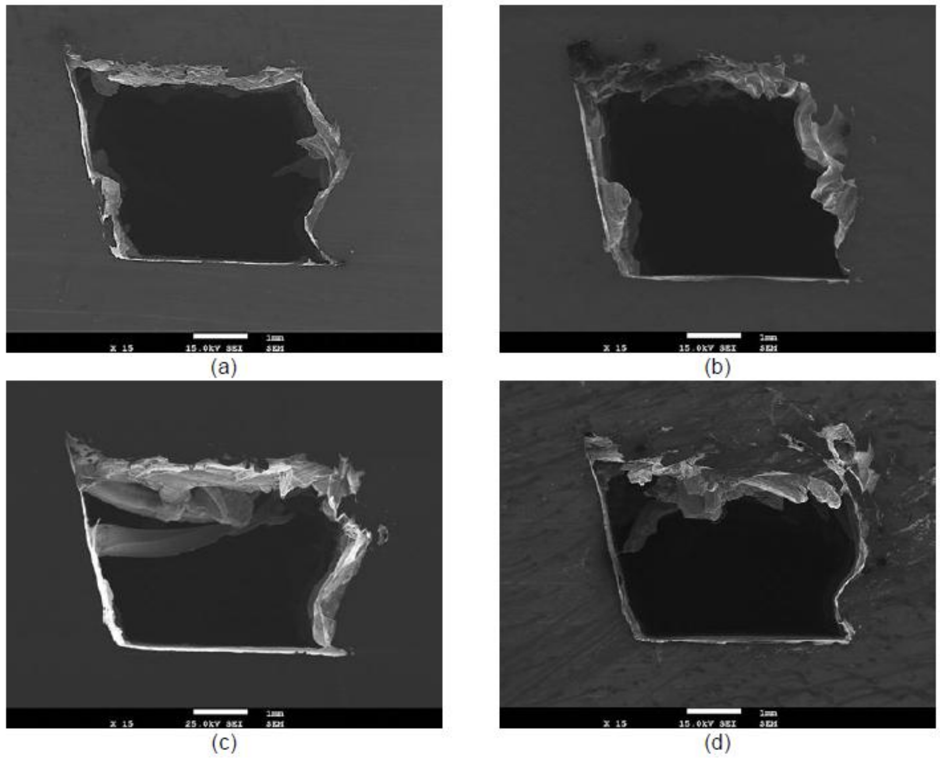


Figure 6 - Cross-section macrograph showing the channel geometries at different FSC processing parameters: (a) 600 rpm, 80 mm/min., (b) 600 rpm, 150 mm/min., (c) 800 rpm, 80 mm/min. and (d) 800 rpm, 150 mm/min. [15].

3 Alternative technologies

FSC is capable of creating internal channels in a single step with desired paths inside the metal plates and it has a high potential to be introduced in various industries. However, FSC has some advantages and disadvantages. Alternatively, continuous internal channels can be produced by conventional technologies. Main methods are *Drilling*, *Milling* and *EDM*. The named technologies have their own advantages and disadvantages that need to be studied.

3.1 Drilling

One of the most common operations in workshops is drilling. About 40% of all metal-cutting operations in industry are performed using drilling. Many industries such as aerospace, automotive, railway and construction involve a large number of drilling process [17].

In this process, either the holes are initiated in a solid block or existing holes are enlarged. The cutting tool called the ’drill’ is fed into the work while rotating. The rotary and feed motions are performed by the machine called the ‘drill press.’ Drilling is an operation to create an initial hole which is used either directly itself, or as a preliminary to reaming, boring, counter-boring, counter-sinking and tapping. Drilling is one of the most economical methods of removing metal [18]. Drills are normally made of high-speed steel (HSS). There are various drills which enable making holes and channels inside different metals with different alloys [19]. Producing channel by drilling is easy and economical. It is possible to achieve smooth path by drilling and reaming.

However, drilling process is suitable for making the desired channel comprised of straight holes, although with a limited hole depth due to the limitations on the tool length. Because of the straight shape of tools and its inflexibility, it is not possible to manufacture curved holes for conformal cooling channels using the drilling method. As illustrated in Figure 7, the production of the channel by drilling requires extra holes and pipe plugs. In addition, the fluid pressure in the channel bends is reduced due to their sharp angle [20]. To sum it up, drilling has above limitations and FSC can be the solution to tackle them. FSC can produce a hole with any desired straight or curved path.

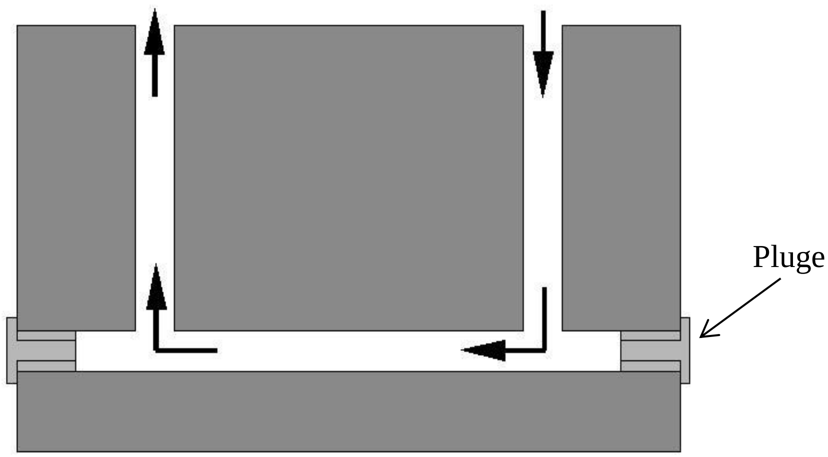


Figure 7 - Produced straight channel by drilling

3.2 Milling

Milling is a process that removes metal from the workpiece by feeding it past a rotating multipoint cutter. The cutter rotates at a high speed and because of having several cutting edges, removes metal quickly. Therefore, surfaces can be machined much faster than with single-point tools, and often with a better finish. The work is mounted on the table of the machine or clamped in a vice or fixture which is, in turn, mounted on the table. The work moves past or into the rotating cutter mounted on the spindle, and acquires the required shape or surface [18].

As stated by Schulze et al., circular milling and wobble milling are better alternatives to drilling as they cause less damage to the machined surface. To achieve lower levels of surface damage, these methods focus the process forces towards center of the workpiece, and also reduce the feed rate to a low value [21].

Milling process allows creating channel with different shapes and depths and with desired smooth paths on the metal plates but the main disadvantage of milling process for channeling is that it is impossible to create internal channels with ceiling. In addition, due to the reduced feed rate, milling has a low productivity compared to other technologies.

3.3 EDM

Electrical discharge machining (EDM) is a machining method used for hard metals or those that are impossible to machine with traditional techniques. Metals which can be machined with EDM include hardened tool-steel, titanium, tungsten carbide, monel and inconel. This method is also called "spark machining" because it removes metal by producing a rapid series of repetitive electrical discharges. These discharges are passed between an electrode and the piece of metal being machined. The small amount of material that is removed from the workpiece is flushed away with a continuously flowing fluid. The repetitive discharges create a set of successively deeper craters in the workpiece until the final shape is produced. Figure 8 shows schematic of the EDM hole drilling process [19].

Drilling has great difficulties in creating holes inside uneven and angled (e.g. circular) surfaces. EDM drilling is a solution for these difficulties. In EDM drilling, the rotating electrode never touches the surface that is being cut. This contact-less feature of the tool in the machining process eliminates the tool pressure while drilling on the surface. The rotating electrode causes concentricity, an even wear, and improves the flushing process [22], [23].

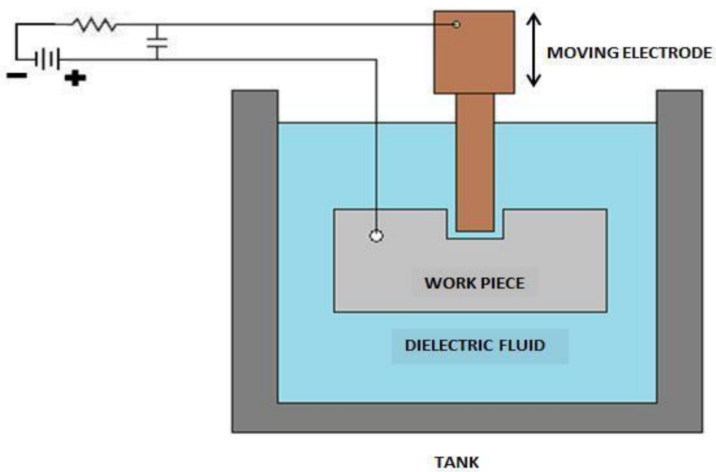


Figure 8 - Schematic of the EDM hole drilling process [19].

By this process, materials of different hardness can be machined without burrs on machined surface. One of the main advantages of this process is that thin and brittle components can be machined without distortion and also complex internal shapes can be machined with a suitable quality. However, EDM has some limitations as well. Firstly, this process can only be used in electrically conductive materials, and secondly, material removal rate is low and the process is slow compared to conventional machining processes. Internal channels manufactured by EDM method are similar to the ones manufactured by drilling method. The main difference is that in EDM channeling process it is possible to create deep holes with different diameters because the depth and diameter depend on the shape of electrode. Channels produced by EDM are L-shaped straight channels with sharp corners similar to channels produced by drilling (as previously shown in Figure 7). The problem is that producing curved channels inside the metal plates by this method is difficult due to the non-flexible tools.

In order to tackle the problem of L-shaped curved channels, authors of [20] designed and produced a tool which is capable of making curved channels. As illustrated in Figure 9 [20], in their experiments they utilized electrode with required diameter of hole in the end of helical compression spring. They controlled the motion of electrode by wires during the process to create curved channel. However, this process has the disadvantage of slow removal rate of material due to vibration of the electrode during the machining, and also it is impossible to create U- shaped or continuous curved internal channels.

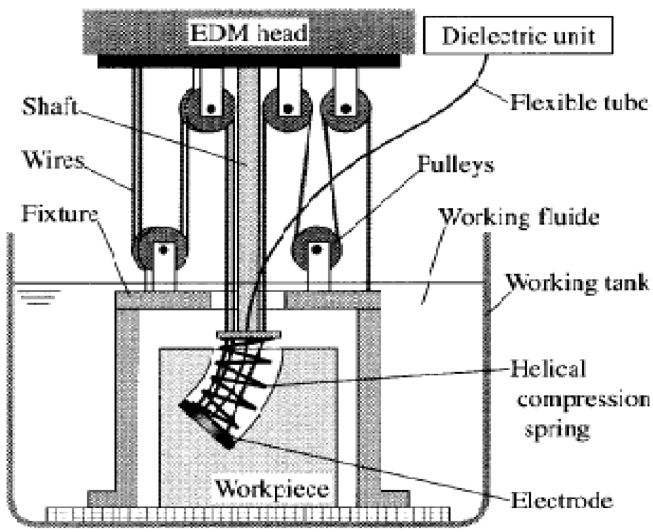


Figure 9 - Structure of an electrode curved motion generator for curve hole machining [20].

4 Designing and Producing New FSC Tools

As explained before, tools play an important role in FSC. Therefore, in this thesis, new FSC tools with improved geometrical parameters are designed and built. Highlight of this work is that the FSC tools produced, enable creating of improved continuous internal channels with desired size and with low roughness on the outer roof of the channel as seen on the workpiece surface. Such results were not achieved with previous FSC tools and methods. In this work, two probes of different size and three shoulders of different scroll and pitch are designed. The design was performed using SolidWorks software.

4.1 Tool Material

In this work all parts of FSC tool has been made from hot work tool steel H13. According to AISI classification Chromium hot-work tool steels belong to group H. Special mechanical properties of this steel makes it appropriate to produce FSW and FSC tools for the aluminum alloys workpiece [6]. Table 4 and Table 5 show the chemical composition and mechanical properties of H13 tool steels, respectively.

Table 4 - Chemical composition of H13 Tool Steel [24].

Element	Content (%)
Chromium, Cr	4.75-5.50
Molybdenum ,Mo	1.10-1.75
Silicon, Si	0.80-1.20
Vanadium, V	0.80-1.20
Carbon, C	0.32-0.45
Nickel, Ni	0.3
Copper, Cu	0.25
Manganese, Mn	0.2-0.5
Phosphorus, P	0.03
Sulfur, S	0.03

Table 5 - Mechanical properties of H13 Tool Steel [24].

H13 Tool Steel- Mechanical properties	
Tensile strength, ultimate	1000-1380 MPa
Tensile strength, yield	1200-1590 MPa
Modulus of elasticity	215 x 10^3 MPa
Poisson's ratio	0.27 - 0.3

4.2 Tool Components and Geometrical Features

Geometry of tool plays an important role during FSC process. Material flow and the shape of channels can be defined and controlled by geometrical features of probe and shoulder. For the present work, new probes and shoulders with different geometry and profiles are designed. FSC tool consist of three parts: Tool Body, Probe and Shoulder. Following sections give detailed explanation of these components.

4.2.1 Tool Body

Figure 10 shows the tool body. Due to fact that probe and shoulder are mounted on the tool body, this part must withstand of torsion moment and mechanical stresses during FSC process.

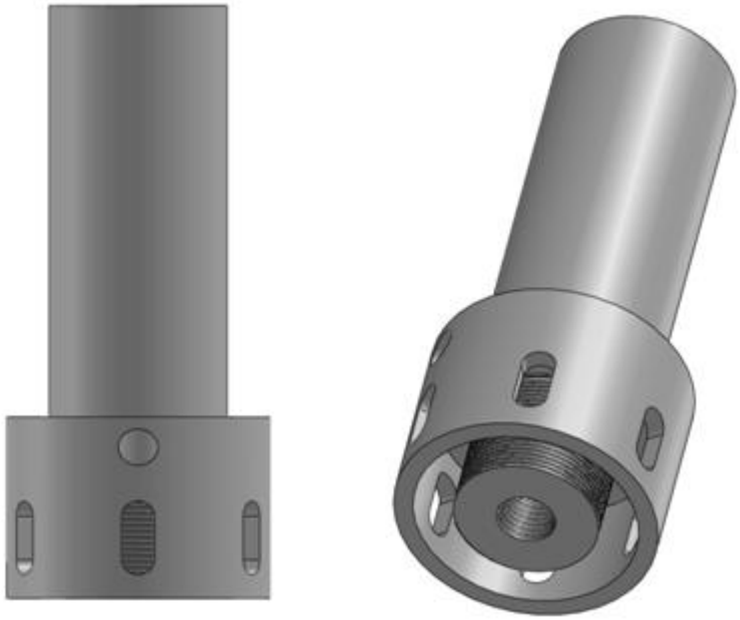


Figure 10 - Tool body

4.2.2 Probe

The role of probe in the FSC process is to remove material from inside of workpiece to outside under shoulder. Two different lengths of cylindrical probes with special trapezoid profile have been designed and used. Figure 11 shows the probes and thread profile created in this work and Table 6 shows its technical specification.

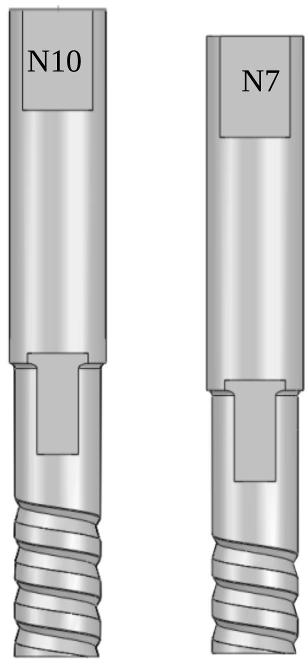
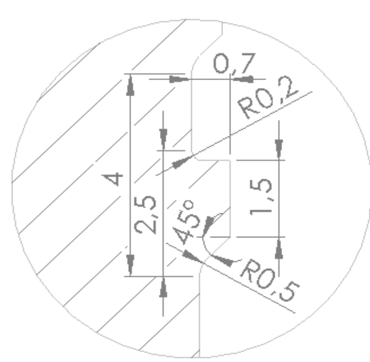


Figure 11 - Two designed probes (N10, N7)

Table 6 - Technical specification of designed probes

<table>
<tr><th>Probe ID</th><th>N7</th><th>N10</th></tr>
<tr><td>Probe length</td><td>61 mm</td><td>64 mm</td></tr>
<tr><td>Probe thread length</td><td>13 mm</td><td>16 mm</td></tr>
<tr><td>Thread profile</td><td colspan="2">
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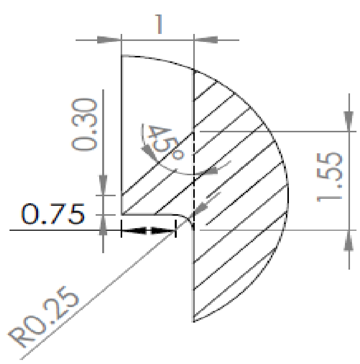
4.2.3 Shoulder

The shoulder is responsible to close the ceiling of the channel by constraining the formed material. The scrolls control amount of material which is brought out from the inside of the metal workpiece to outside by the probe [5]. Figure 12 shows three different shapes (A, B and C) of scroll and pitch of shoulders designed and manufactured in this work. Table 7 shows the technical specification of the designed shoulders.

Table 7 - Technical specification of designed shoulders

Shoulder Type	**1 scroll pitch 1**	**1 scroll pitch 2**	**2 scroll pitch 2**
Inner diameter	8 mm	8 mm	8 mm
Outer diameter	20 mm	20 mm	20 mm
Scroll profile			

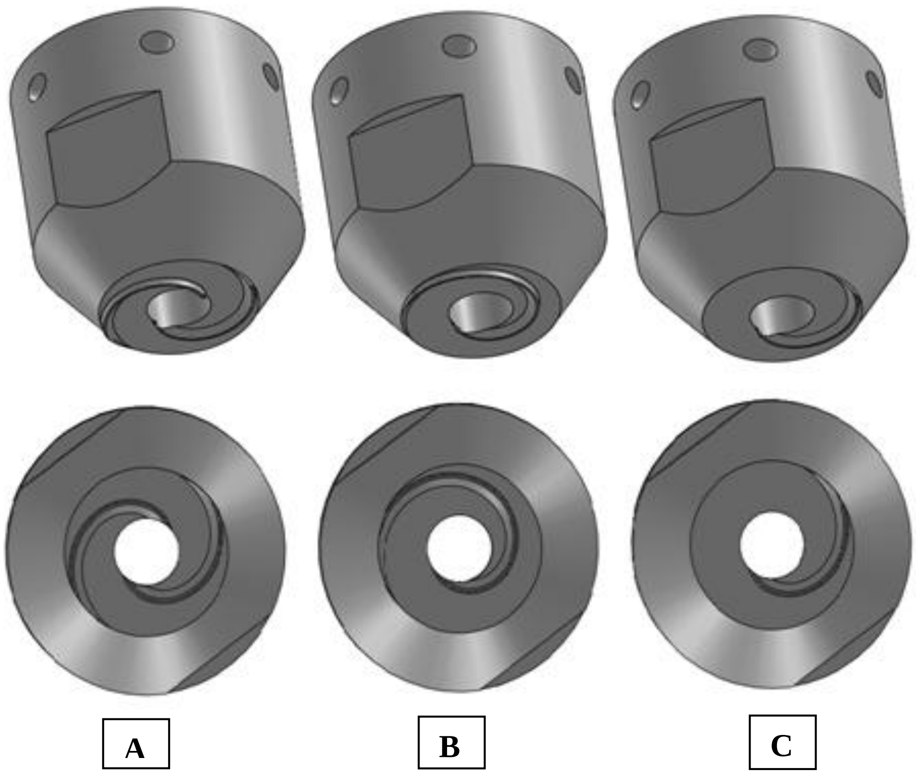


Figure 12 - Shoulders (A) 2 scroll pitch 2 (B) 1 scroll pitch 1 and (C) 1 scroll pitch 2

4.3 Tool Hardening

Heat treatment of steel is one of the hardening methods to increase the hardness of the outer surface while the core remains relatively soft. The combination of a hard surface and a soft interior is greatly valued in modern engineering because it can withstand very high stress and fatigue. In this work, all probes and shoulders were hardened by pre-heating in two steps and finalized according to Table 8.

Table 8 - Hardening condition [25]

Temperature ˚C	Soaking *time minutes	Hardness
1025	30	53±2 HRC
1050	15	54±2 HRC

* Soaking time = time at hardening temperature after the tool is fully heated through

4.4 Tool Assembly

This section briefly explains assembly of components of FSC tool together. As the Figure 13 shows, the shoulder and probe are fastened to the tool body and allow adjusting probe and shoulder by moving into the body in order to achieve desired probe length and FS channels depth. The screws fix probe and shoulder into the body to prevent it from rotation during processing. Figure 13 illustrates tool assembly model and section view of tool that is used in this work.

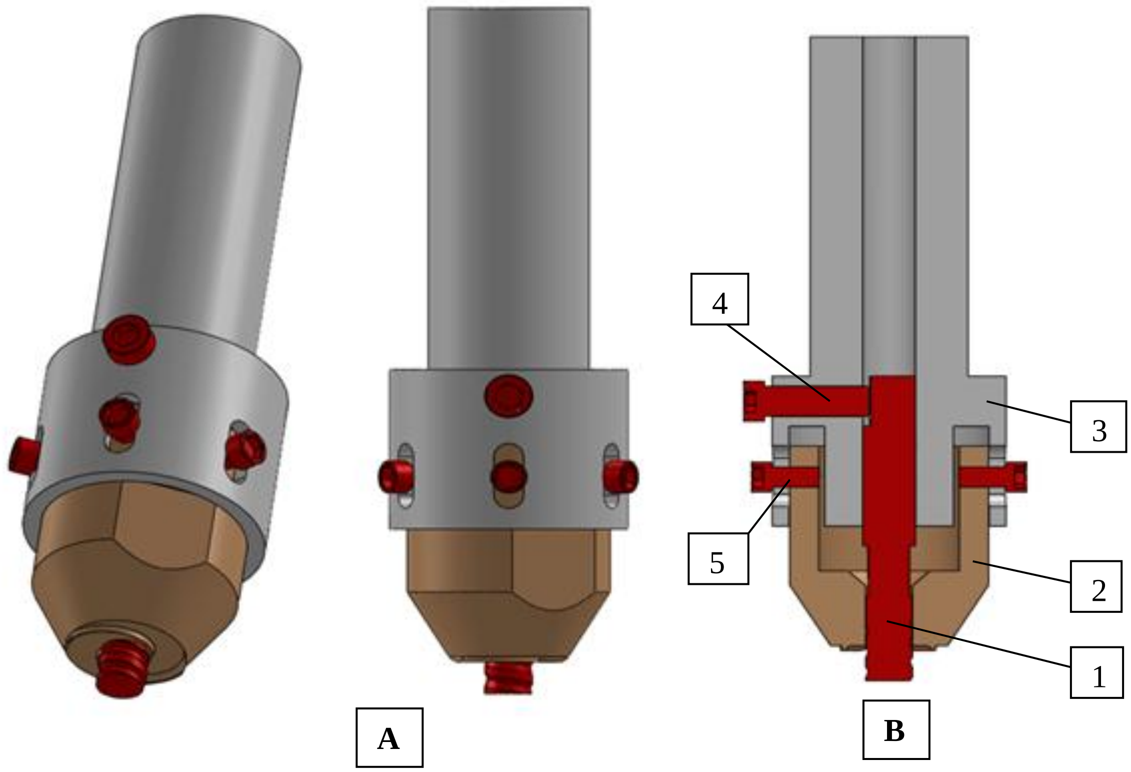


Figure 13 – FSC tool: (A) Assembly views, (B) Section view: 1-Probe 2-Shoulder 3-Body 4-Probe lock screw 5-Shoulder locks screws.

4.5 Tool Adjustment

To achieve desired probe length, it is not necessary to disassemble the tool from FSC machine. Different lengths of probe can be obtained by screwing probe in the body and supplanting shoulder into the sliding holes in the body. Figure 14 shows various positions of the shoulders with different length of probe by moving on the tool body.

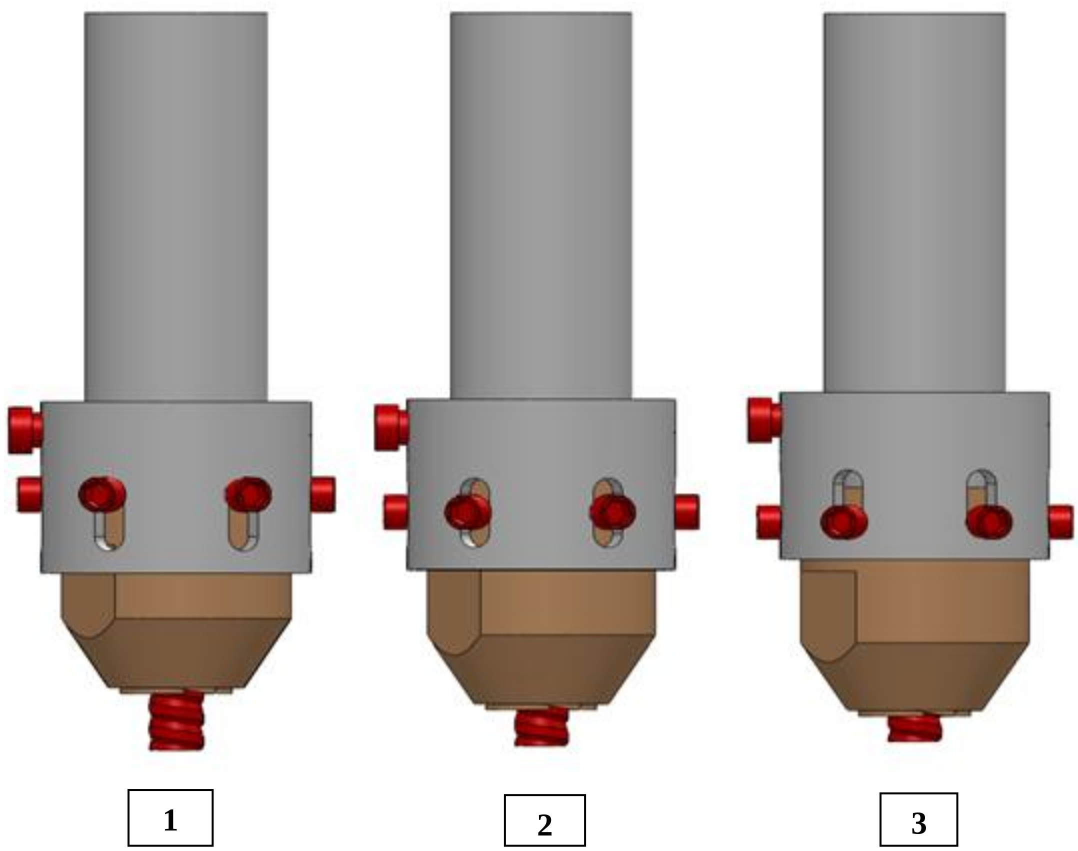


Figure 14 – Different Adjustments of Probe Length: (1) Maximum length of probe, (2) Nominal length of probe and (3) Minimum length of probe.

5 Experimental Results and Analysis

This chapter performs experiments using the tools produced in previous chapter (including the designed probes and shoulders) on base metals of Aluminum Alloy plates (Aluminum Alloys AA6082-T6 and AA5083-H111) and explains the resulting FS channels.

Explanations are given as follows. Firstly, it explains the preparation, settings and conditions employed during our experiments (material for workpiece sample, tools, equipment and clamping). Secondly, it explains the resulting samples and presents analysis and conclusion on the results. Optimal technological conditions (geometrical features and process parameters) required to produce the internal channel in each base metal will be suggested as a result of this experiment and investigation.

5.1 Material Characterizations

AA6082-T6 (Al-Mg-Si) and AA5083-H111 alloys were used in this work as base material with 10 mm thickness. Table 9 to Table 14 below show the properties of these materials.

Table 9 - Chemical composition of AA6082-T6 [26]

Chemical composition of AA6082-T6 (%)							
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.7-1.3	0.0-0.5	0.0-0.1	0.4-1	0.6-1.2	0.0-0.25	0.0-0.2	0.0-0.1

Table 10 - Physical properties of AA6082-T6 [26].

Physical properties of AA6082-T6	
Density	2.7 g/cm^3
Melting point	555˚C
Thermal expansion	24 x 10^{-3} 1/K
Modulus of elasticity	70 GPa
Thermal conductivity	180 W/(m.K)
Electrical resistivity	0.038 x 10 $^{-6}$ Ω.m

Table 11 - Mechanical properties of AA6082-T6 [26].

Mechanical properties of AA6082-T6	
Tensile strength	290 MPa
Yield strength	260 MPa
Elongation	10 %
Vickers Hardness	70 HV

Table 12 - Chemical composition of AA5083-H111 [26]

Chemical composition of AA6082-T6 (%)							
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.0-0.4	0.40	0.10	0.4- 1	4- 4.9	0.05-0.25	0.0-0.1	0.05-0.25

Table 13 - Physical properties of AA5083-H111 [26]

Physical properties of AA6082-T6	
Density	2.65 g/cm^3
Melting point	570 ˚C
Thermal expansion	25 x 10^{-6} 1/K
Modulus of elasticity	72 GPa
Thermal conductivity	121 W/(m.K)
Electrical resistivity	0.058 x 10^{-6} Ω.m

Table 14 - Mechanical properties of AA5083-H111 [26]

Mechanical properties of AA6082-T6	
Tensile strength	275-350 MPa
Proof Stress (Minimum)	115 MPa
Elongation	10 %
Hardness Brinell	75 HB

5.2 Final Conditions of Shoulder and Probes

For experimental work, two different shoulders with outer and inner diameter 20 mm and 8 mm with 1 scroll pitch 1 and 1 scroll pitch 2 and one probe were used. The probe diameter was 8 mm and the length of thread was 13 mm. Figure 15 shows the shoulders, probe and the assembly of them. The plunge length of probe after final tool set up was 7 mm.

Figure 15 - Shoulders, Probe and assembly of the tool

5.3 Equipment

Straight and curved friction stir channeling prototypes were produced by STROJTOS Universal knee types milling machine (Figure 16) and FS Welding machine ESAB LEGIOTM FSW 5UT (Figure 17), respectively. These machines are used in the Design and Production Engineering Department workshop of Aalto University for research and development.

As presented in Figure 16, the head of machine still stands while the workpiece that is fixed on the machine table can move in directions X,Y and Z. Table 15 shows the technical specification of STROJTOS Lipnik milling machine and Table 16 shows the technical specification of Friction Stir Welding machine ESAB LEGIOTM FSW 5UT.

Figure 16 - CNC milling machine used for producing straight FS channel.

Table 15 - Technical specification of Strojtos Lipnik milling machine.

Spindle Taper	ISO 50
For milling machine motor power output	7 KW
Maximum torque	900 Nm
Distance of vertical axis of spindle from upright Ways at machine stroke	120-520 mm
Distance from spindle end face to clamping surface of table at machine stroke	100-550 mm

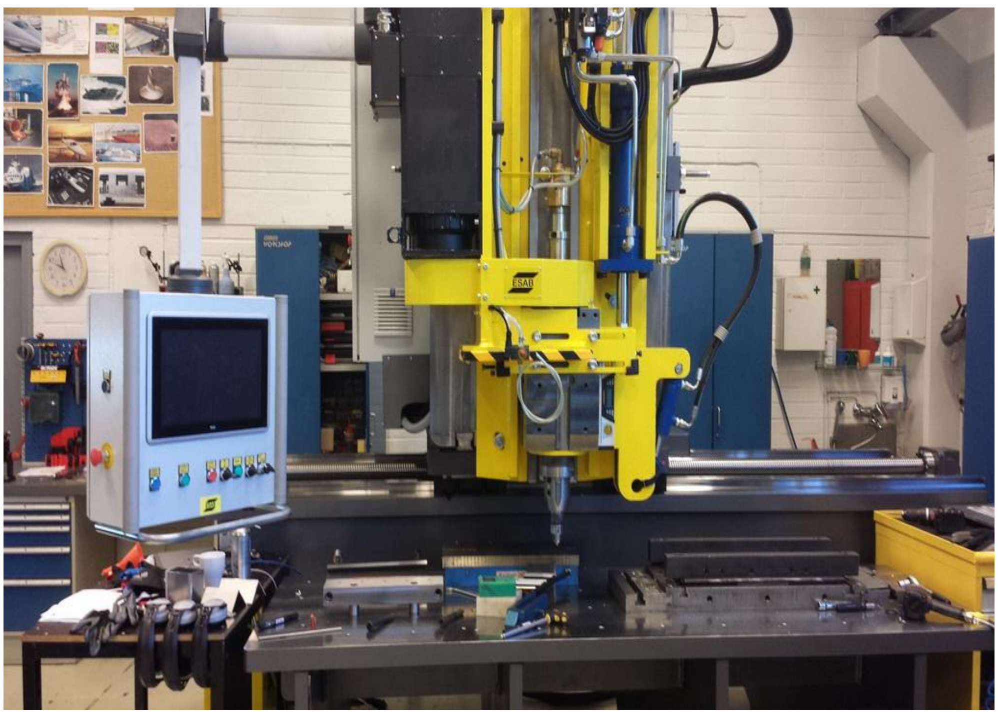


Figure 17 - Friction Stir Welding machine for producing curved FS channel.

Table 16 - Technical specification of ESAB LEGIOTM FSW 5UT.

Z-axis Control	**Position + Speed + Force**
Maximum Forces	Fz_max = 100kN (Fx_max = Fy_max = 40kN)
Maximum Welding Travel Speed	Vx_max = Vy_max = 4m/min
Maximum Spindle Power	30kW
Maximum Spindle Speed	Ωmax = 3000rpm
Work Envelope (x ; y ; z)	2000mm x 400mm x 300mm
Special focus on the application to	HSSteels, SSteels, Al, Cu and Ni based alloys

5.4 Clamping

For fixing workpiece on the table of machine, two solid blocks were used. The dimensions of blocks were 670 x 40 x 60 mm and the blocks were fixed on table by four M16 bolts. Figure 18 shows fixing of workpiece on the table of machine.

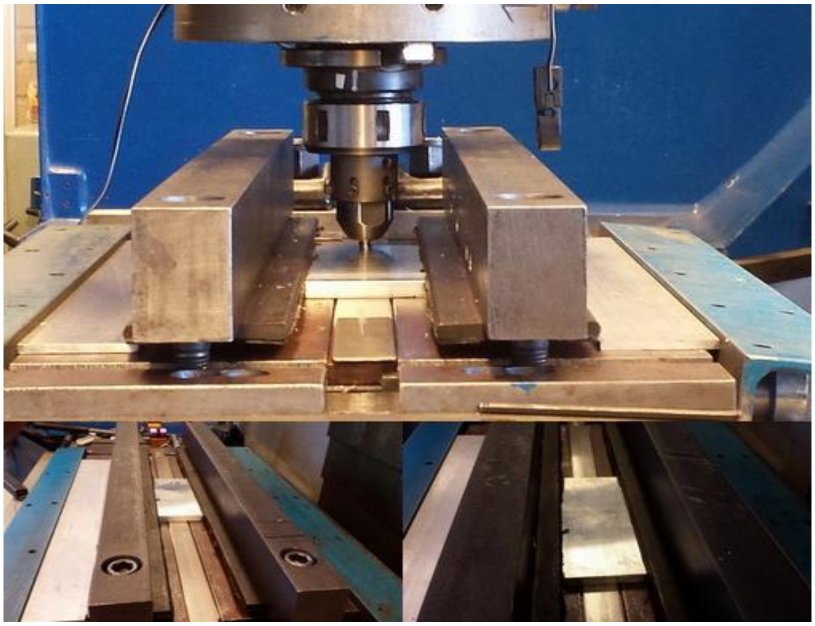


Figure 18 - Clamping of workpiece on machine table.

5.5 Results and Analysis

This section demonstrates achieved results, analyzes them and compares technical specifications of straight and curved channels produced in this work.

5.5.1 Technical Analysis of Straight Channel

Figure 19 shows obtained straight channels with the aluminum alloy AA6082-T6 base metal by different technical parameters and tool geometries. As Figure 19 shows, the channel (B) has a high quality of the final surface in comparison with channel (A), but the size of the channel (A) is about two times bigger than other one. After producing channels, transect and longitudinal done on the samples for investigation of channels shape and size.

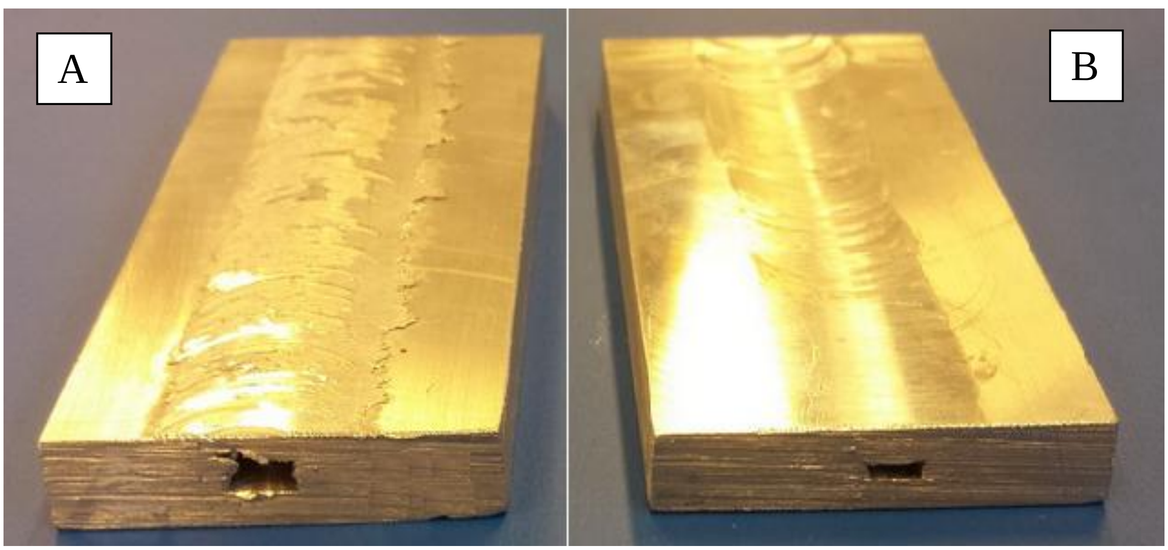


Figure 19 - Straight channels with aluminum alloy AA6082-T6 base metal. (A) 800 rpm, 120 mm/min, (B) 1000 rpm, 90 mm/min

5.5.1.1 Comparison of Channel Size

Figure 20 illustrates the channels shape which produced by two different technical parameters. By comparing above channel shapes, it is possible to understand that, the channel size increase by increasing travel speed and reducing rotation speed. As Table 17 shows, the channel (A) area is two times bigger than channel (B), (30.66 mm² vs 14.05 mm²). It means that for producing big channel size, it is necessary to increase travel speed and reduce rotation speed.

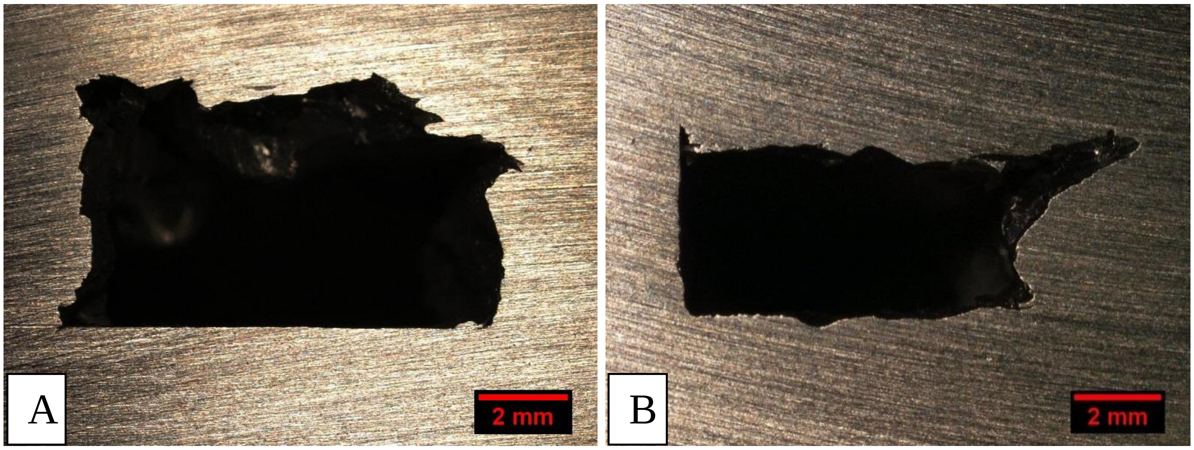


Figure 20 - Transects cross-section macrographs of FS channels produced at: A) 800 rpm, 120 mm/min and B) 1000 rpm, 90 mm/min.

Table 17 - Obtained channels area with various geometrical and technical conditions

Channel	**A**	**B**
Shoulder	1 scroll pitch 2	1 scroll pitch 2
Probe	N7	N7
Rotation speed	800 rpm	1000 rpm
Travel Speed	120 mm/min	90 mm/min
Channel area	30.66 mm²	14.05 mm²

5.5.1.2 Comparison of Channel Roof Roughness

The inside surface roughness of channels is a critical parameter in fluid flow applications such as heat exchangers and cooling systems. The main affection of roughness in these applications is pressure drop inside the rough paths. In this work, the roughness of channel walls and inside surface are investigated. The longitudinal cross-section of channel is needed for inside roughness of channel investigation. The inside surface roughness of the channel occurs when an amount of material is displaced with each rotation. Figure 21 illustrates roughness of channels with rotation speed 800 rpm, travel speed 120 mm/min and 1000 rpm, 90 mm/min. In case of Figure 21.a, the running pitch was 0.15 mm/rot and in case of Figure 21.b, it was 0.09 mm/rot and the distance between peaks in both samples is 1 mm in average.

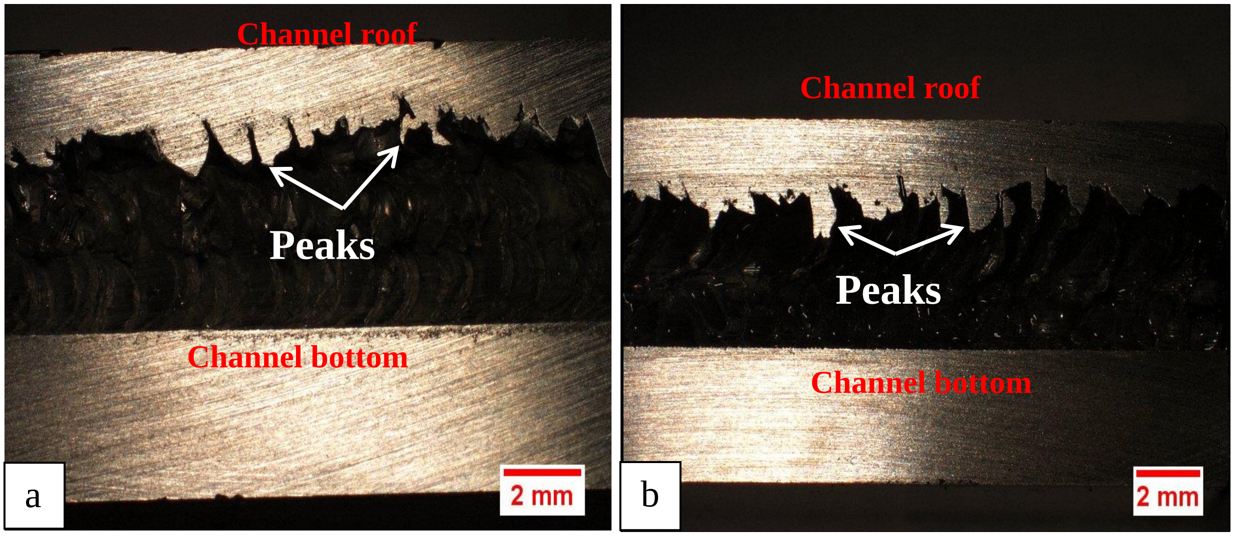


Figure 21 - Longitudinal cross-section of the channel shows the roughness on the roof of channels. (a) Channel A (b) Channel B.

5.5.2 Comparison of Curved Channels Production Technical Parameters

Two curved path channels were produced during this work. The base material was aluminum alloy AA5083-H111. First channel was produced by forced control and the second channel produced by position control.

For the first curved channel (channel 1), Table 18 shows the tool specifications and technical parameters used to produce the channel by force control. As Figure 22 shows, the final surface of the channel does not have high quality and by the force control the material cannot come out completely. However, roof of the channel is closed completely without any holes and leaks. To obtain a high quality surface of the channel, it is possible to remove the material from the surface by milling. Figure 23 reveals the channel 1 after surface milling.

Table 18 - Tool specification and technical parameters used to produce curved path channel 1.

Channel	1
Probe	N7
Shoulder	1 scroll pitch 2
Probe Plunge length	7 mm
Force	5.5 kN
Rotation speed	450 rpm
Travel speed	70 mm/min

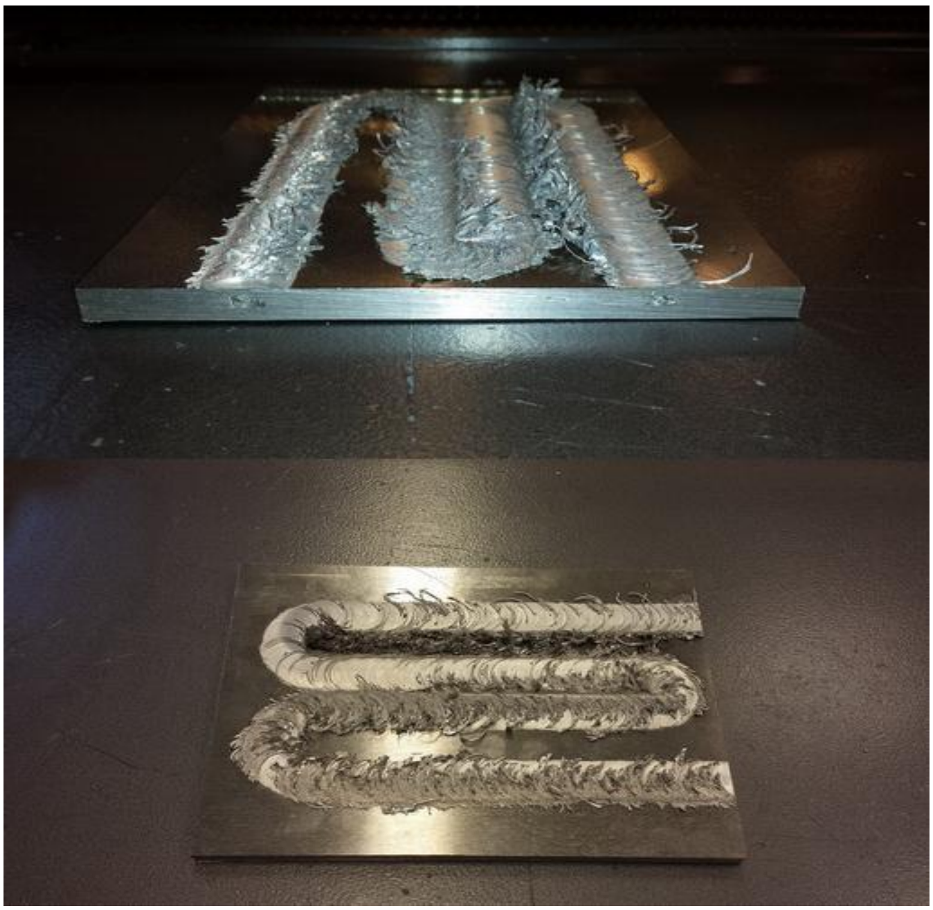


Figure 22 - Curved channel 1 produced by force control.

Figure 23 - Curved channel 1 after surface milling.

The second curved path channel (channel 2) was produced by position control inside aluminum alloy AA5083-H111. Table 19 illustrates tool specification and technical parameters used for producing channel 2. As Figure 24 shows, channel 2 has final surface with high quality and therefore it is not necessary to remove material by milling to make a smooth surface. However, it is difficult to produce channels without any holes and leaks using position control, and it requires more tries and samples in order to achieve the desired surface of channel.

Table 19 - Tool specification and technical parameters used to produce curved path channel 2.

Channel	2
Probe	N7
Shoulder	1 scroll pitch 2
Probe Plunge length	7 mm
Penetration	6.2 mm
Rotation speed	450 rpm
Travel speed	70 mm/min

Figure 24 - Curved channel 2 produced by position control.

6 Potential of FSC for Industrial Applications

This chapter discusses potential of using FSC in industrial applications. It focuses on cooling system of industrial Lithium-ion batteries. Producing conformal cooling moulds and heat exchangers are high potential industrial applications of FSC. In addition, in order to evaluate effectiveness of obtained channels, this chapter analyzes behavior of flow and heat transmitting of fluid inside channels produced by our FSC method.

6.1 FSC for Heat Exchanger Production

Heat exchangers are used in a wide range of industries which makes it a high potential application for FSC. Heat exchangers are devices that are used to transfer thermal energy between two or more fluids or between fluid and solid surface at different temperatures. Heat exchangers are used in a wide range of applications such as power plants, process and chemical engineering, food production, electronics, environmental engineering, manufacturing industries and space applications. Heat exchangers are divided into contact and surface types. Moreover, heat exchangers can be classified according to transfer processes, number of fluids, construction features, flow arrangements, heat transfer mechanisms and surface compactness [27], [28].

Main objectives of compact heat exchangers are maximizing the efficiency of a heat exchanger and reducing the size of heat exchanger. Compact heat exchangers are especially used in gas-to-gas or liquid-to gas heat exchangers and generally are used in gas flow applications.

Compact heat exchangers are characterized by a large heat transfer surface area per unit volume of the exchanger. This results in reduced space, weight, support structure and footprint, energy requirements and cost, as well as improved process design and plant layout and processing conditions, and a low fluid inventory. A gas-to-fluid exchanger is considered a compact heat exchanger if it has a heat transfer surface with a surface area density greater than about 700 m^2/m^3 or a hydraulic diameter of $D_h \leq 6$ mm for operating in a gas stream, and 400 m^2/m^3 or higher for operating in a liquid or phase-change stream. A laminar flow heat exchanger (also referred to as a meso heat exchanger) has a surface area density greater than about 3000 m^2/m^3 or hydraulic diameter of 100 µm $\leq D_h \leq$ 1 mm. The term micro heat exchanger is used if the surface area density is greater than about 15,000 m^2/m^3 or 1µm $\leq D_h \leq$ 100 µm [28].

In 2004, Satish G. Kandlikar and Granda presented a different classification of minimum channel dimension (D_h) for compact heat exchangers [29]. Table 20 presents this channel classification.

Table 20 - Channel classification of heat exchangers by Kandlikar and Granda, 2004 [29].

Channel	Hydraulic Diameter
Conventional channels	$D_h > 3mm$
Mini channels	$3mm \geq D_h > 200\mu m$
Micro channels	$200\mu m \geq D_h > 10\mu m$
Transitional channels	$10\mu m \geq D_h > 0.1\mu m$
Transitional micro channels	$10\mu m \geq D_h > 1\mu m$
Transitional nano-channels	$1\mu m \geq D_h > 0.1\mu m$
Molecular nano-channels	$0.1\mu m > D_h$

For manufacturing heat exchangers, FSC offers the benefit of a single step channel fabrication process. FSC technology has the capability to design and produce integral channels of different size, and single piece heat exchangers in monolithic plates [30]. Figure 25 shows the internal FS channels in a monolithic plate and an integral channel.

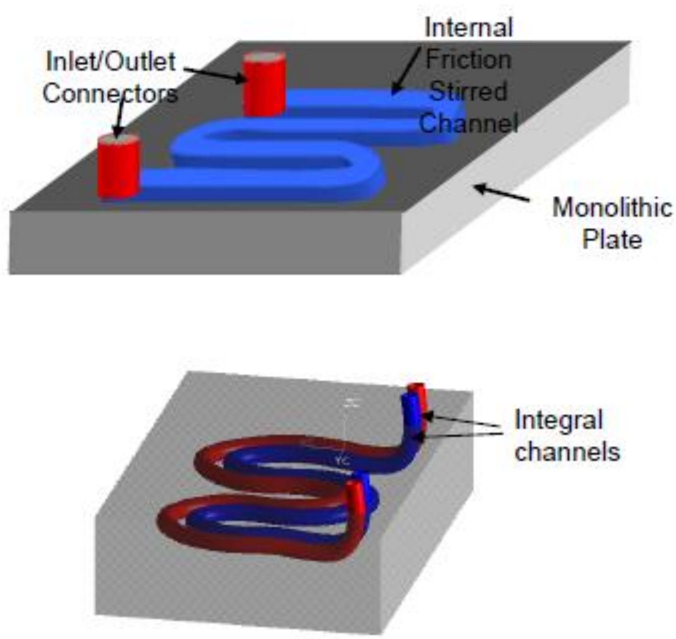


Figure 25 - Integral channel heat exchangers [30].

6.2 FSC for Conformal Cooling production

Conformal cooling is a new concept for production of moulds in which the cooling channels are produced in a way that conform to the surface of the mould cavity. There are advantages in using conformal cooling channels that follow the shape of the cavity and core, reach hot spots, and promote temperature uniformity in the plastic materials being molded. The results are significant: shortened cycle times, improved plastic part quality and more importantly cost reduction.

Nevertheless, many manufacturers with long experience in the industry still consider conformal cooling as a difficult and expensive process. One possible solution is to reduce the time spent on cooling the part which would significantly increase the production rate and reduce the costs. Therefore, it is important to optimize the heat transfer process within a typical moulding process. The rate of the heat exchange between the injected plastic and the mould influences the economic performance of an injection mould [31], [32]. Figure 26 shows the cooling circuit which is produced by drilling and innovative conformal cooling.

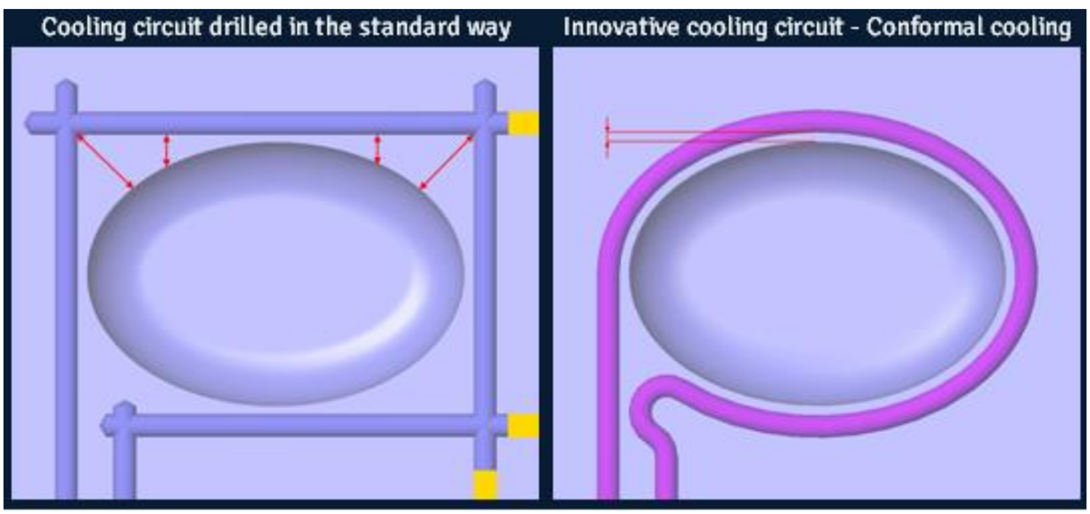


Figure 26 - Cooling circuit by drilling and conformal cooling [32].

FSC is a new method to produce conformal cooling channels for above-mentioned industries. Due to unique capability of producing conformal cooling channels with desired passage, high productivity and low cost of production, FSC is a suitable way for this purpose.

6.3 FSC for Cooling System of Lithium Batteries

There has been a constant increase in production of Lithium-ion (Li-ion) batteries during the last decades because of their excellent performance and efficiency, energy density and long life. Li-ion batteries are used for consumer electronics (such as mobile phones and laptops), automotive and industrial applications including energy storage [33].

A main challenge in application of Li-ion batteries is that they are efficient only in a limited range of temperature. In general, life time of these batteries decreases above 40˚C and working characteristics and efficiency rapidly decreases below 10˚C. In this regard, heat generation during operation is one of the important issues with Li-ion battery. Therefore, heat management of these batteries during operation can increase the life time and sufficiency of batteries [34]. Figure 27 shows an industrial lithium battery and cells inside it, and Figure 28 illustrates the arrangement of cells within the battery case.

Figure 27 Industrial lithium battery and battery cells.

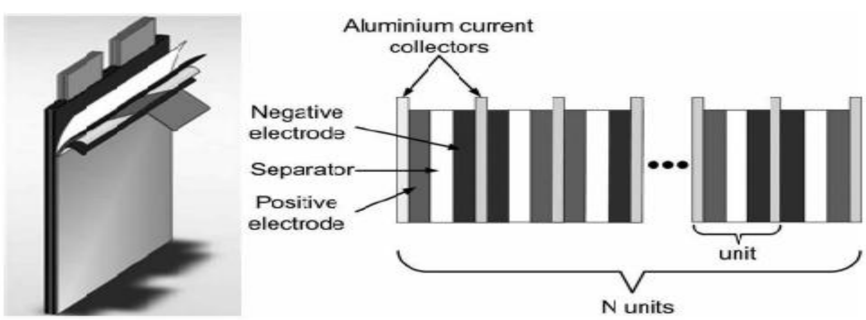


Figure 28 - Structure of lithium battery pouch cell [35].

Figure 29 illustrates temperature distribution on the surface of the lithium battery cells. The highest temperature can be observed at the top of the cell near the terminals and the lowest temperature at the bottom of the cell during charging and discharging cycle of the battery [35].

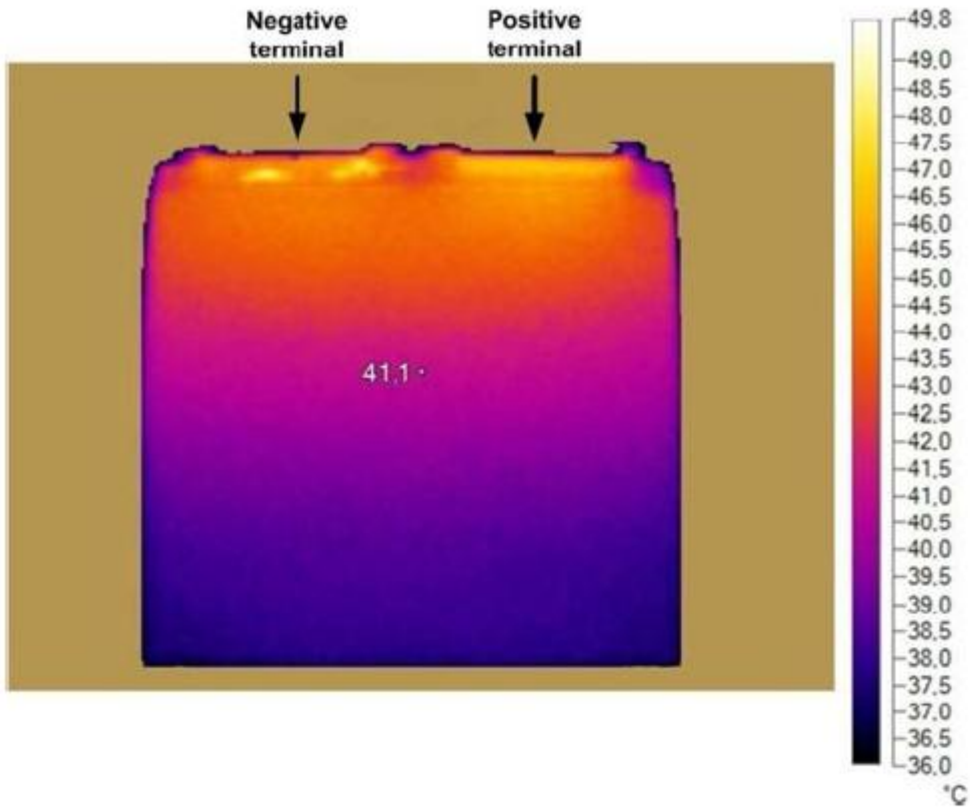


Figure 29- Infrared photo of temperature distribution on the surface on the lithium battery cell [35].

Normally industries use water cooling system to decrease operating temperature of batteries. For this purpose, curved copper pipe within the side walls of battery case is implemented. Figure 30 shows such cooling system for a Lithium battery which is used in vehicle engineering laboratory in Aalto University.

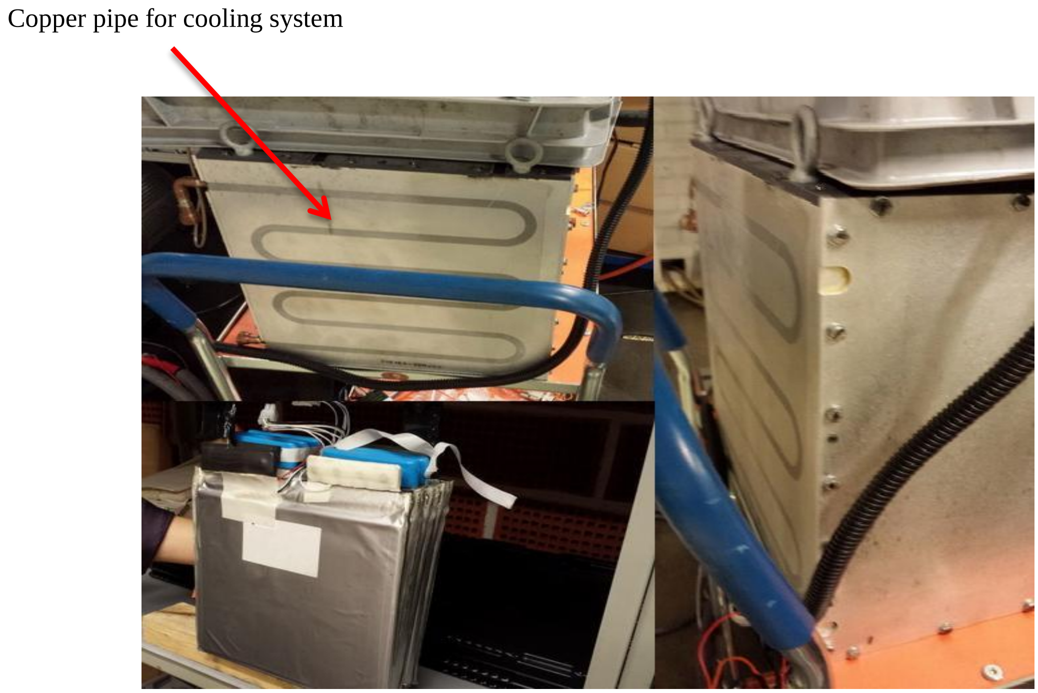


Figure 30 - Cooling system of industrial lithium battery.

As mentioned before, it is important for battery manufacturers to decrease operating temperature in order to increase lifetime of lithium batteries. In this regard, FSC technology has a high capability to produce curved path channels for cooling system of batteries. Using this method, it is possible to eliminate the copper pipes and thus reduce the heat transfer resistance between fluid and the battery case plate. In addition, to decrease operating temperature of these batteries even more, this thesis proposes using FS channels not only for battery case side walls, but also to make small diameter channel within a thin plate workpiece, which then can be installed between battery cells.

6.3.1 Computational Development

In this work, for computational modeling of curved channel for battery cooling system, an aluminum alloy plate with dimension 200 x 120 x 10 mm is selected. Figure 31 shows the 6 mm diameter channel modeled by SolidWorks for flow and thermal analysis.

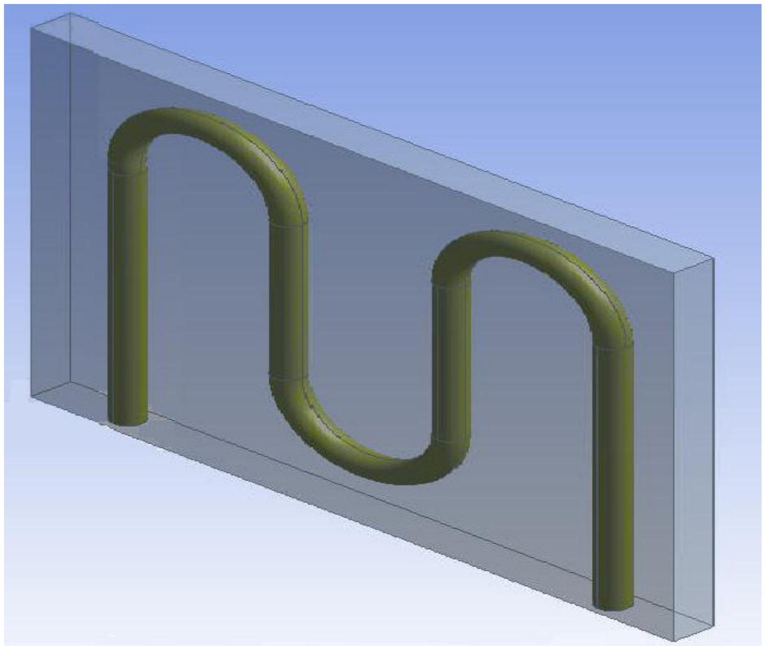


Figure 31- Curved channel modeled by SolidWorks.

6.3.2 Flow Analysis

Velocity and pressure behaviors of fluid are analyzed for two modeled channels with the same path but with different roughness of 0µm and 500µm. Second channel represents a path created by FSC method and its roughness value is assumed to be 500 µm. The fluid was water with 20˚C inlet temperature and flow inlet velocity was 2m/s. Flow analysis are done by SolidWorks.

Figure 32 and Figure 33 illustrate the velocity analysis of the fluid in both channels. As these figures show, the velocity of the fluid tends to increase in the middle of straight part of path and reach its maximum value in the full developed region (Figure 34) and decrease when hit the curve part of path.

The outlet velocity in smooth channel in the middle of outlet area (Figure 32) is 2.21 m/s and the velocity in rough channel produced by FSC (Figure 33) is 2.74 m/s. By comparing the velocity values of fluid, it is concluded that the velocity increases significantly in the channel with high roughness.

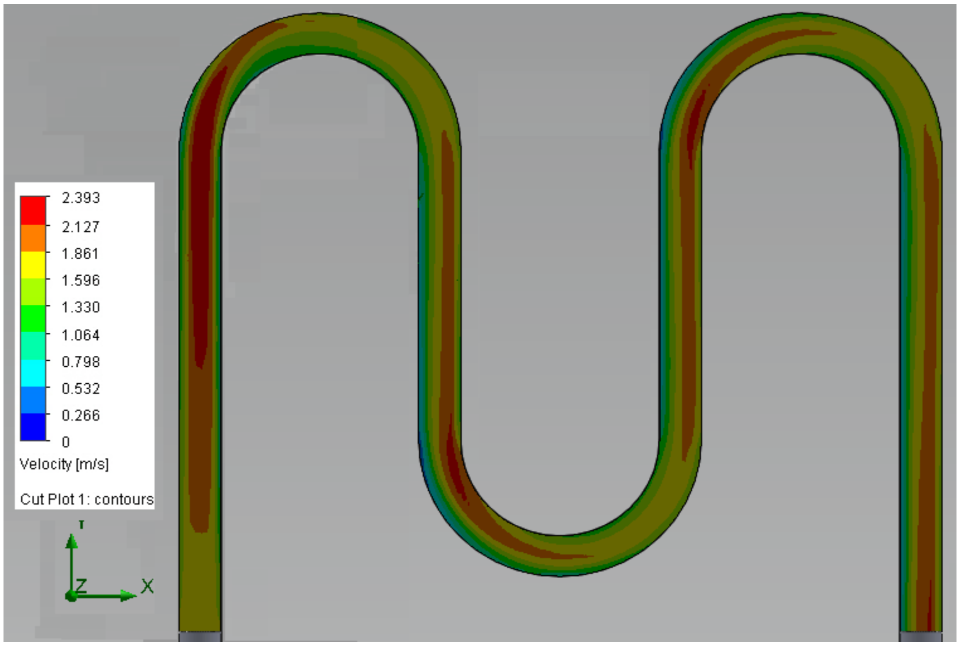


Figure 32 - Fluid velocity in non-FS channel with roughness = 0µm.

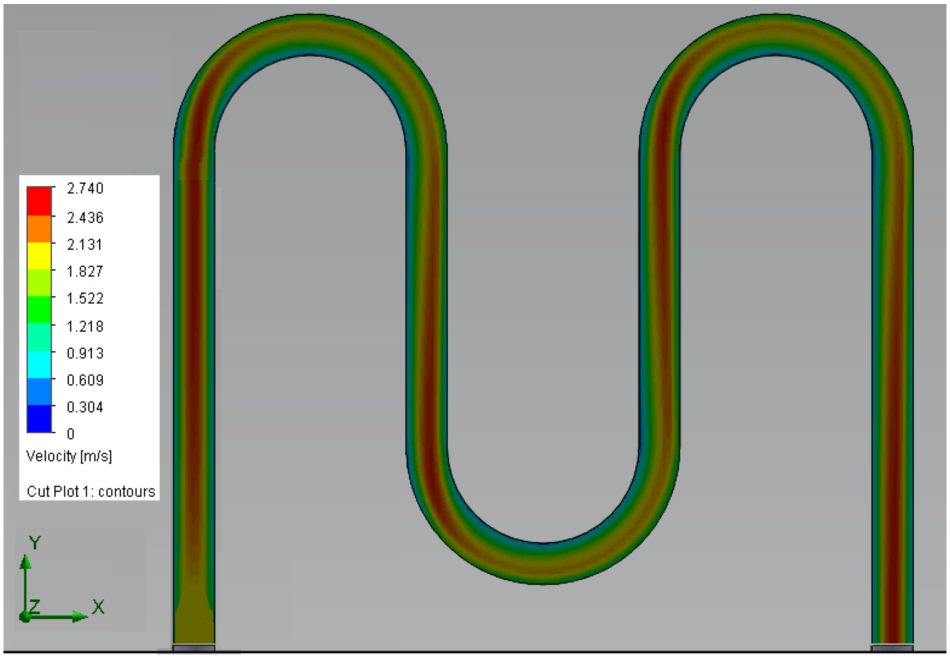


Figure 33- Fluid velocity in FS channel with roughness = 500µm.

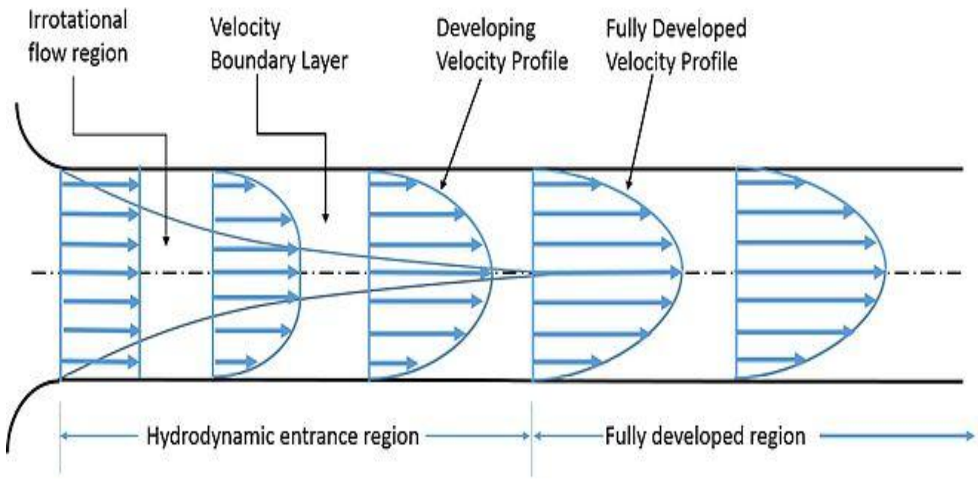


Figure 34 - Fluid velocity profile within a pipe [36].

Pressure behavior of fluid is analyzed in this work as well. Figure 35 and Figure 36 present the measured pressure in the smooth and rough channel. It is concluded from comparing these two figures that the fluid pressure drops significantly in the rough channel. Outlet pressure is 101.325 kPa while inlet pressure is 105.368 kPa in the smooth channel (Figure 35) and in the channel with 500 µm roughness (Figure 36), outlet pressure is 101.323 kPa while the inlet pressure is 111.452 kPa.

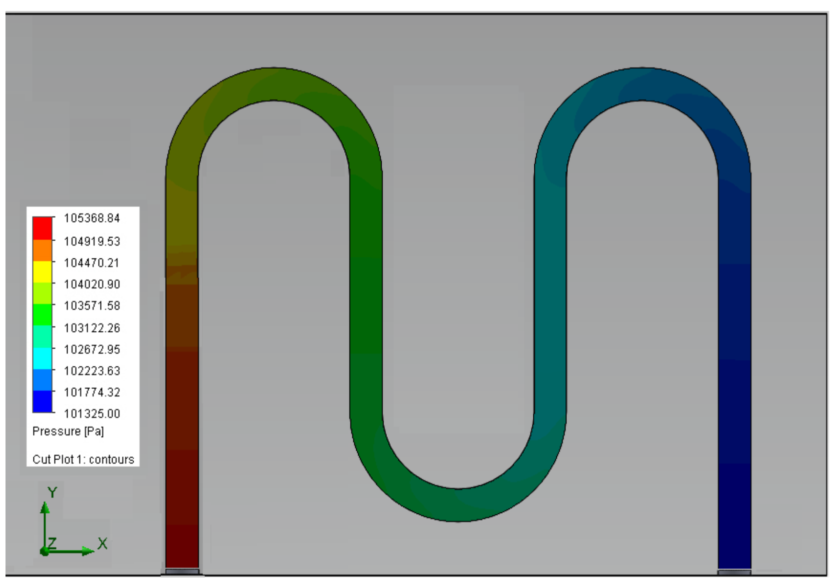


Figure 35 - Fluid pressure in non-FS channel with roughness = 0µm.

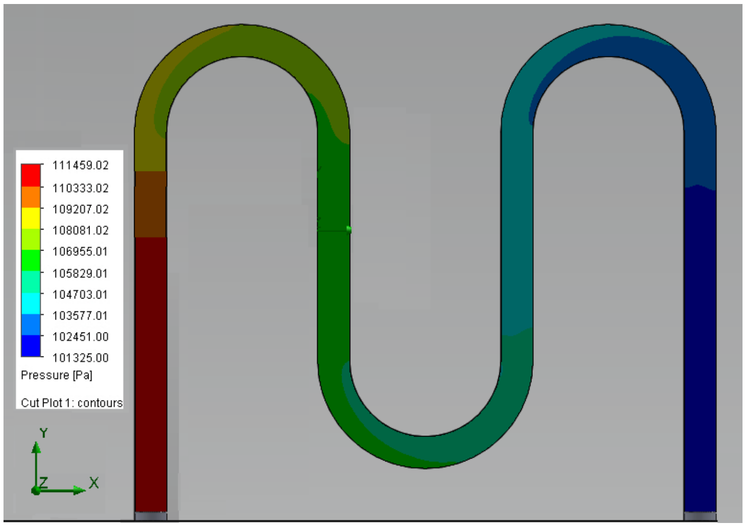


Figure 36 - Fluid pressure in FS channel with roughness = 500µm.

6.3.3 Thermal Analysis

For thermal analysis, one side of plate was selected with temperature of 328.15˚K (55˚C) representing the inside wall of battery case and the other sides were in environment temperature. Inlet velocity of fluid and inlet water temperature values was set to 2 m/s and 20˚C. Thermal analysis was done at time = 60 seconds by SolidWorks.

As Figure 37 shows, temperature of the fluid (water) increased from 293.15˚K inlet temperature up to 300.98˚K in smooth channel when temperature of inside wall of battery case was 328.15˚K and in the FS channel with 500µm roughness (Figure 38) fluid temperature increased significantly up to 304.84˚K. It is concluded that rate of heat transfer in the FS channel is more than smooth channel.

By analyzing temperature distribution of plate surface (Figure 39) it is concluded that temperature decreased more in FS channel (Figure 39, B) by comparing with non-FS channel (Figure 39, A) . By using FSC, it is possible to produce long curved channel with small diameter of curvature part of path to decrease temperature more.

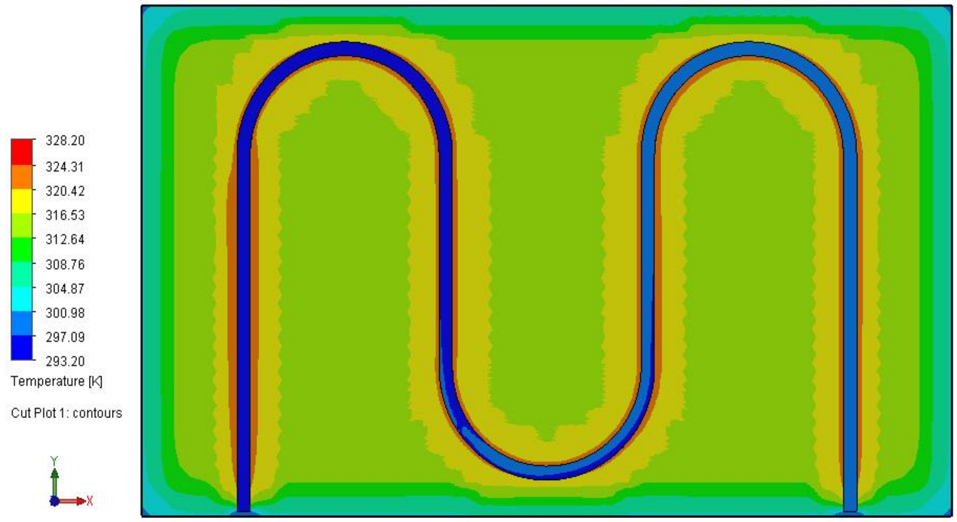


Figure 37 – Temperature of cooling fluid in non-FS channel at time = 60 seconds, Channel roughness = 0 µm

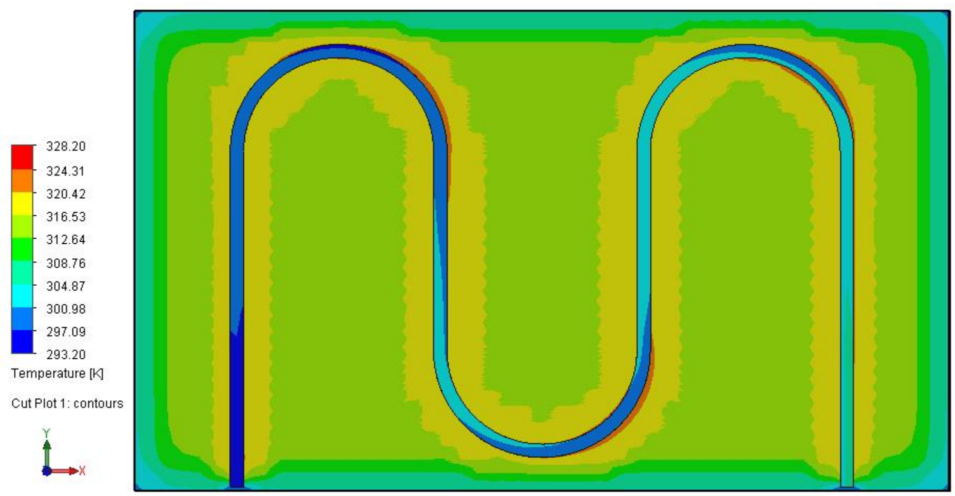


Figure 38 – Temperature of cooling fluid in FS channel at time = 60 seconds, Channel roughness = 500 µm

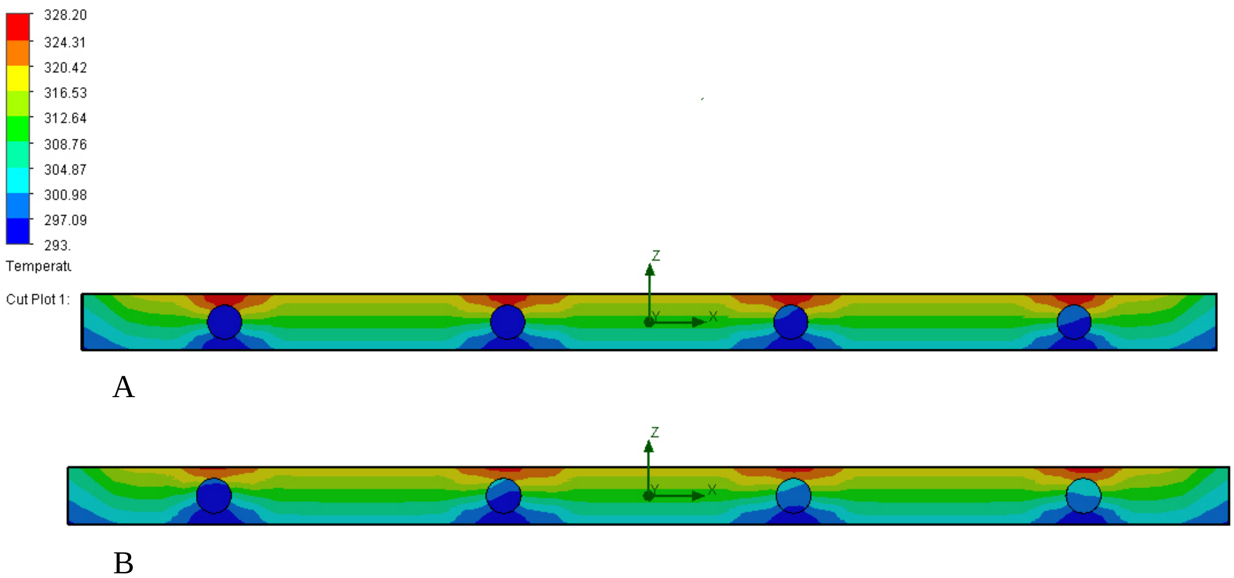


Figure 39 – Temperature distribution in the plate at time = 60 seconds. A) non-FS channel roughness=0, B) FS Channel roughness 500 µm

6.3.4 Pressure and Leak-Testing

Pressure testing is a non-destructive test to evaluate integrity of the pressure shell of pressure equipment. There are several methods for pressure and leak testing [37] in the field, such as:

- Hydrostatic testing using water or oil as pressure medium
- Pneumatic testing using air or another gas as pressure medium
- Combination of pneumatic and hydrostatic testing, where low pressure air is first used to detect leaks
- Vacuum testing, which uses negative pressure to check for the existence of a leak
- Static head testing, normally performed for drain piping with water left in a standpipe for a set period of time
- Halogen and helium leak detection

In this work, three samples of straight channel were selected for hydraulic and pneumatic test. Figure 40 shows these selected channels for leakage test. Table 21 shows the technical parameters for producing these samples.

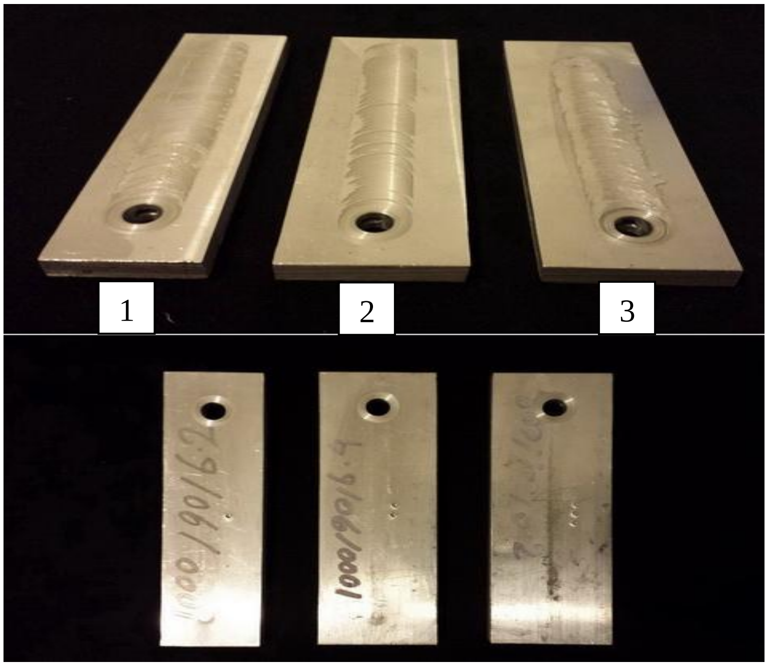


Figure 40 - Three straight samples of channel selected for leakage test.

Table 21 - Technical parameters of producing leakage test samples

Channel No.	1	2	3
Material	AA6082-T6	AA6082-T6	AA6082-T6
Rotation speed	1000 rpm	1000 rpm	800 rpm
Travel speed	90 mm/min	90 mm/min	100 mm/min
Probe penetration	6.2 mm	6.4 mm	6.2 mm

Hydraulic and pneumatic test for leakage test of samples above was done in fluid power laboratory in Aalto University. The connection fitting was made by laboratory and hydraulic pressure prepared by an ENERPAC. As Figure 41 illustrates, the samples were put under 100 bar hydraulic pressure for two minutes.

Figure 41 - Equipment for hydraulic test.

For pneumatic test, pressured air was used and samples were put in water to observe the bubbles in case there were some holes in samples. Figure 42 shows the process of pneumatic test. Our samples endured 100 bar pressure without any problems and no holes were detected during this pressure and leak test.

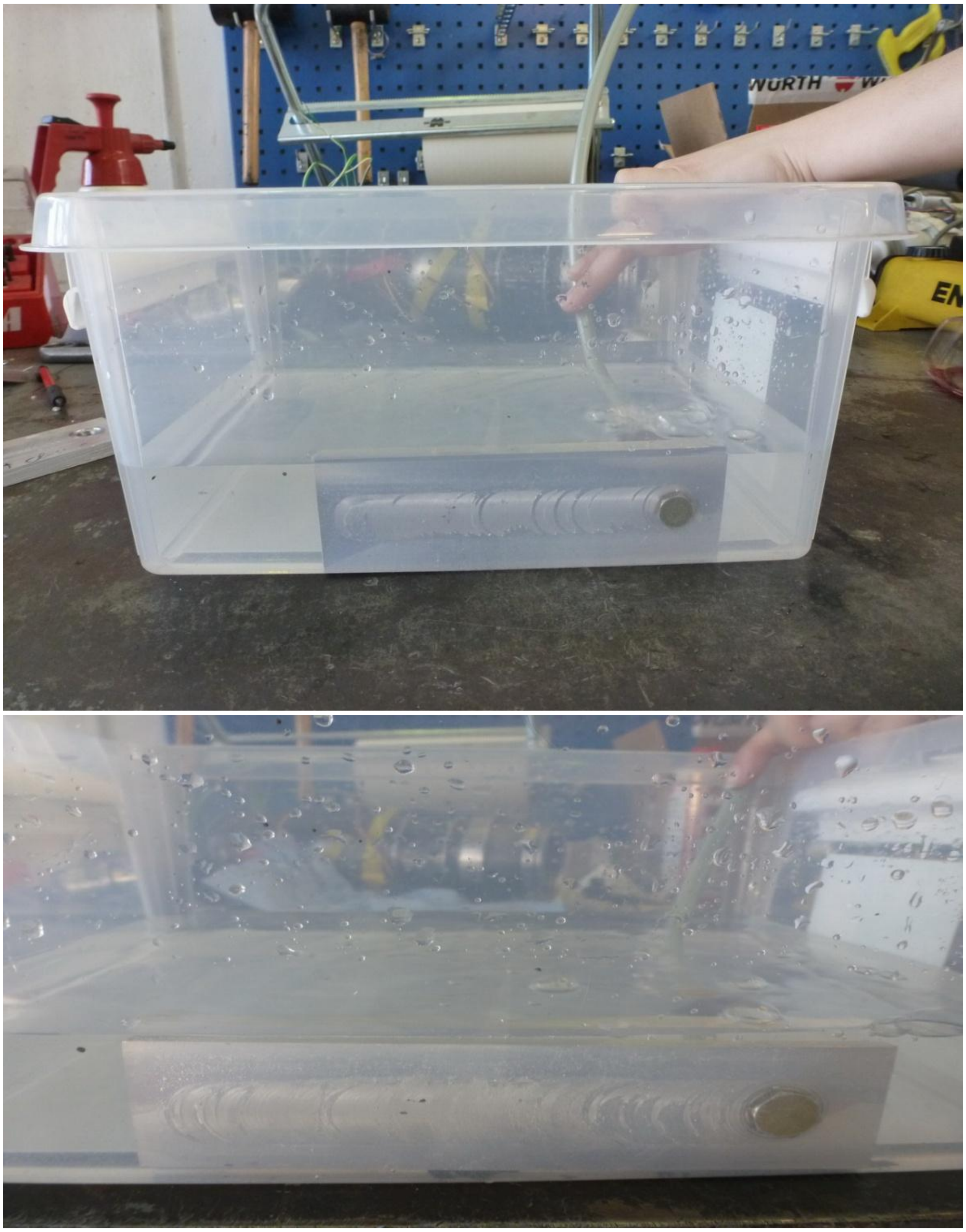


Figure 42 - The process of pneumatic test of samples.

7 Comparison with alternative technologies

This section presents a SWOT (strengths, weaknesses, opportunities and threats) analysis comparing FSC with each of the three alternative technologies in order to determine in more details advantages or disadvantages of FSC in relation to each of these technologies. Each table below explains strengths, weaknesses, opportunities and threats of FSC as opposed to alternative technologies (Drilling, EDM and Milling).

7.1 FSC vs Drilling

Strengths:	**Weaknesses:**
• Produces continuous internal curved channel only in a single step in a monolithic plate. • Channel can have different dimensions along the same path. • High roughness of internal sides of channels is an advantage for heat exchangers and conformal cooling as it increases heat transfer. • Possibility to determine various paths of channel according to device requirements. • Faster production time • Tool does not need external cooling	• Produces open hole at the end of the path. • Narrow range of used material • Roughness of internal and external surface finish • Lack of available standardization • Unknown for industries
Opportunities: • High potential to target new markets • High productivity • High usability in heating/cooling systems	**Threats:** • Needs more research budget in order to develop enough to reach the market

7.2 FSC vs Milling

Strengths:	**Weaknesses:**
• Produces continuous internal closed ceiling curved channel only in a single step in a monolithic plate. • High roughness of internal sides of channels is an advantage for heat exchangers and conformal cooling as it increases heat transfer. • Tool does not need external cooling • Faster production time • High productivity • Lower cost	• Narrow range of used material • Roughness of internal and external surface finish • Lack of available standardization • Unknown for industries
Opportunities:	**Threats:**
• High potential to target new markets • High productivity • High usability in heating/cooling systems	• Needs more research budget in order to develop enough to reach the market

7.3 FSC vs EDM

Strengths: • Produces continuous internal curved channel only in a single step in a monolithic plate. • High roughness of internal sides of channels is an advantage for heat exchangers and conformal cooling as it increases heat transfer. • Faster production time • Lower cost	**Weaknesses:** • Narrow range of used material • Roughness of internal and external surface finish • Lack of available standardization • Unknown for industries
Opportunities: • High potential to target new markets • High productivity • High usability in heating/cooling systems	**Threats:** • Needs more research budget in order to develop enough to reach the market

7.4 Summary

This analysis provides indications on how the FSC technology should be developed and enhanced further to be a successful internal channel producer in various industries. The three SWOT comparisons elaborated in this section can be applied to any industry in which FSC improves the state of the art technology. According to above SWOT tables, it is concluded that FSC has a high potential to offer solutions that alternative technologies cannot provide.

8 Conclusion

Friction Stir Channeling (FSC) is an innovative technology to produce continuous internal channels in monolithic plates in a single step. FSC process is capable of producing both straight and curved channels in metal components with control of the technical parameters similar to that of Friction Stir Welding (FSW). Unlike FSC, conventional technologies Electrical Discharge Machining (EDM), Drilling and Milling, each have their own shortcomings in creating continuous straight or continuous curved internal channel. However, FSC is in initial phases and still more research needs to be done in order to improve FSC tools for producing channels in more diverse metals.

In this work, new tools for FSC with improved geometrical parameters were designed and built. By means of these new tools, experiments were performed in order to investigate technical condition of FSC and its capability in various industries. This thesis produced various Friction Stir (FS) channel prototypes in Aluminum Alloy plate AA6082-T6.

The following conclusions are arrived at:

- The improved tools designed in this thesis enabled creating of improved continuous internal channels with desired size and with low roughness on the outer roof of the channel as seen on the workpiece surface.

- The experimental results of this work showed that by means of improved FSC tools and by selecting the right technical process parameters, high quality of channel surface finish with low roughness can be obtained.

- Moreover, experimental results showed that various sizes of FS channel can be achieved by changing rotation and travel speed. Channel size increases by increasing travel speed and decreasing rotation speed.

- Comparison of two curved channel prototypes demonstrated that to obtain high quality of surface finish, using position control (as opposed to forced control) can give a high quality surface with low roughness.

- Result of investigation in this thesis showed that FSC has high potential in heat exchanger industries because it has the capability to design and produce internal channels of different size, and single piece heat exchangers in monolithic plates.

- Moreover, result of our investigation showed that FSC is a new method to produce conformal cooling channels for mould industries due to its unique capability of producing conformal cooling channels with desired passage, high productivity and low cost of production.

- For Lithium-ion battery manufacturers, it is important to decrease operating temperature in order to increase lifetime of lithium batteries. Therefore, this thesis analyzed using FSC-produced channels for cooling system of batteries. This method makes it possible to eliminate the copper pipes and as a result reduce the heat transfer resistance between fluid and the battery case plate. To decrease the operating temperature even more, it was proposed to use FS channels not only in battery case, but also to make small diameter curved path channel within a thin plate workpiece to be installed between battery cells..

- The flow analysis performed in this work concluded that the velocity decreases significantly in the FS channel (high roughness) compared to a non-FS smooth channel and also the fluid pressure drops significantly in the FS channel.

- By comparing modeled FS channel with the modeled non-FS channel in terms of temperature of cooling fluid and temperature distribution, it was concluded that temperature decreased more in FS channel compared to the non-FS channel and it is possible to decrease temperature more by producing a longer channel with small diameter of curvature part of path.

- The results of leakage and pressure tests clearly showed that the FS channels produced in this work can endure 100 bar pressure without any problems.

- The SWOT analysis in this work showed that FSC has a high potential to offer solutions that alternative technologies cannot provide.

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