Characterization of Microchannels Produced by Friction Stir Channeling: An Experimental Study

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Abstract
Friction Stir Channeling (FSC) is a recent and innovative solid state manufacturing technology that allows, in a single pass, the opening of continuous internal channels in monolithic components and can be used in the mold and heat exchanger industries. However, the development of reliable Non-Destructive Testing (NDT) for the characterization of the channels is a major challenge.
The focus of this work is the non-destructive characterization of micro channels, and the main goal was to experimentally validate which NDT techniques can be used to identify the presence of microchannels, their regularity along the section, and also their location, size, and path.
Five NDT techniques were studied: digital radiology; eddy currents; ultrasounds; thermography; and dye penetrants. These techniques were applied to specimens with linear and curvilinear channels. The specimens were produced using tool pins with 0.5 mm diameter which obtained channels with 0.4 mm width and depths of 0.53 mm.
Digital radiology and ultrasounds were effective in detecting channels regardless of its dimensions. Eddy currents did not allow to confirm the exclusive presence of the channels due to microstructural changes caused by the FSC process. Thermography using cold fluid injection was not successful in the channel's characterization due to the extremely low flow. The dye penetrants confirmed the presence of the channels of all dimensions due to the liquid having traveled along the entire path of the curvilinear channel without reaching the surface.

KEYWORDS: Friction Stir Channeling (FSC), Micro channel, Characterization, digital X-ray, eddy currents, ultrasounds;

1. Introduction

Friction stir channeling (FSC) is a manufacturing technique that uses a rotating non consumable tool to create channels within a material [1,2]. These channels can be used in aerospace and automotive applications. The channels can be used to create lightweight and strong components, such as wing spars or engine parts, by reducing the amount of material required while maintaining strength and stiffness. Recent studies have been

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focusing on the production of micrometric channels with this technology which can have a wide range of applications in various industries, from aerospace and automotive to power generation, oil and gas, biomedical and bioengineering, with the advantage of reducing weight and increase heat transfer efficiency. However, the success of FSC mainly depends on the ability to generate channels with well-controlled geometries. This is where the proper characterization of the channels becomes important. Non-destructive testing (NDT) techniques such as X-ray, ultrasounds, thermography, eddy currents and dye penetrants can be used to characterize the channels, including their size, shape, and distribution within the material. By properly characterizing the channels, researchers and manufacturers can better understand the effects of FSC on the material's performance and optimize the process to create channels with the desired properties. Digital X-ray imaging uses electromagnetic radiation in the X-ray spectrum to generate images of the internal structure of a material [3]. The X-rays penetrate the material and are captured by a detector, creating an image of the internal structure. It may be used to create detailed images of the internal structure of the channels, including their size, shape, and distribution. It may also be used to detect any defects or inconsistencies in the channels, such as porosity or cracks. Additionally, digital X-ray imaging may be used to evaluate the quality of the FSC process, by measuring the width and location of the channels. Ultrasound testing (UT) uses high-frequency sound waves to create images of the internal structure of a material [4,5]. It may be used to measure the size, shape, and distribution of the channels within the material, and may also be used to detect any defects or inconsistencies in the channels. Transient Thermography is a technique that uses infrared cameras to create images of the surface temperature distribution of a material [6]. It may be used to detect and characterize the channels by measuring the material surface temperature with forced heating and/or cooling [7]. This technique may be used to detect defects or inconsistencies in the channels. Eddy current testing (ECT) uses alternating electrical currents to characterize and/or detect defects in electrically conductive materials [8,9]. It is based on the principle that when a conductor is subjected to an alternating magnetic field, eddy currents are generated within the material, which can be used to evaluate the material [10,11]. Eddy current testing may be used to measure the size, shape, and distribution of the channels, and may also be used to detect any defects or inconsistencies in the channels. Dye penetrant testing is a surface-based NDT technique that can be used to detect surface breaking defects such as cracks, porosity, laps and seams. A liquid dye is applied to the surface of the material, and it penetrates any defects that may exist. The excess dye is then removed, and a developer is applied, which causes the dye that has entered the defects to be visible. This technique may be used to detect defects in the surface of the channels.

Overall, these are all NDT techniques that may be used to characterize the channels created by FSC. Each technique may provide different information about the channels, such as their size, shape, and distribution, as well as any defects or inconsistencies that may exist. By using a combination of these techniques, one may gain a comprehensive understanding of the channels and optimize the FSC process to achieve the desired properties in the material.

2. Materials and Methods

2.1 Materials

FSC technology is frequently used in the production of heat exchanger devices. As such, it requires a material with high thermal diffusivity and the ability to attain the desired mechanical properties for proper functioning. Additionally, if the material has excessively high mechanical resistance, it may undermine the processing, resulting in tool wear or breakage. With this in mind, the chosen material for the samples production was the AW1050 aluminum alloy. This alloy has characteristics such as low mechanical resistance, high corrosion resistance, high thermal and electrical conductivity. Plates measuring 200 × 100 × 5 mm were used. This material demonstrated the desired characteristics, particularly in terms of ease of processing, allowing for the successful production of samples.

2.2 Samples

The FSC was performed using a Haas Super Mini Mill 2 CNC machining centre. The tool used is depicted in Figure 1a. It is composed by a tool pin and a shoulder. The tool pin has a diameter and height of 0.5 mm, and the thread is one entry right-handed with a sawtooth profile in a clockwise direction and with a pitch of 0.13 mm. The shoulder used has a diameter of 3.5 mm. The tool rotation and feed speed were 4000 rev/min and 145 mm/min, respectively, leading to a Ω/V ratio of 28 rev/mm. Two types of tests were performed, linear and curvilinear, also known as serpentines (Figure 1d).

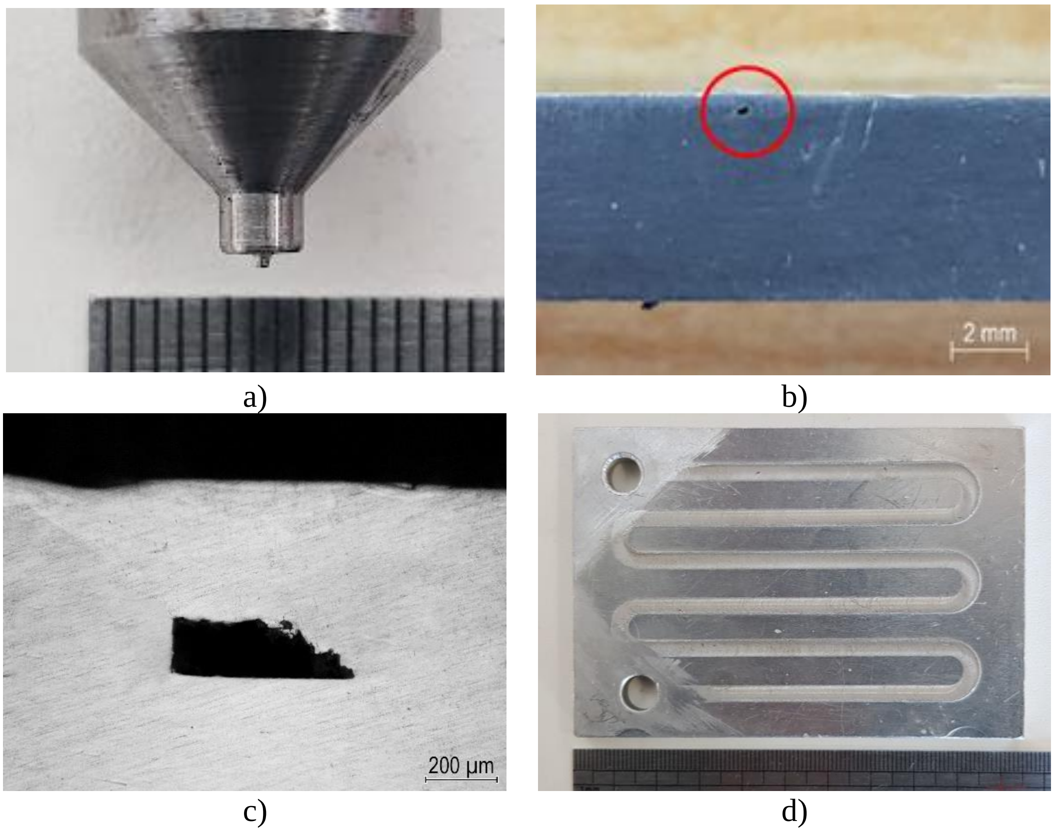


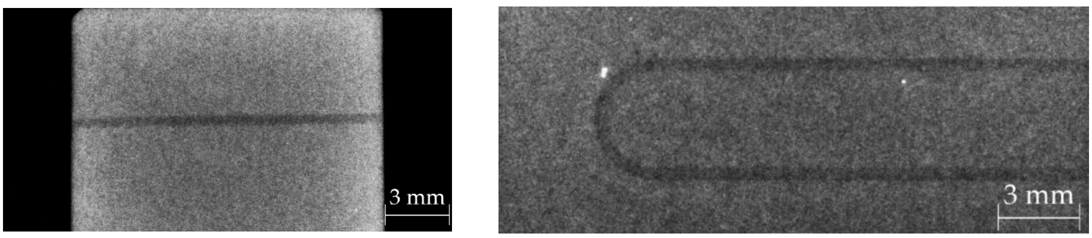
Figure 1. a) tool; b) profile picture of the produced channel; c) channel micrography; d) surface finish of a produced serpentine channel.

2.3 NDT methods

The use of digital radiography was implemented using a KODAK RVG 5100 system and a KODAK 2100 RX unit. This unit is capable of producing high frequency X-ray images with a voltage of 60 kV and a collimator. The active sensor area is 22 × 30 mm and the maximum integration time is 620 ms. To ensure accuracy, it is important to make sure that the surface of the samples being inspected is smooth.
Eddy Current technique was carried out using the Nortec 600D equipment from Olympus and a straight shaft surface absolute bridge probe U8623177. A customized XY scanning device was used to automate the samples characterization process.
Ultrasonic technique was performed using the Krautkramer USM 36 equipment. This equipment allows for the reading of the time or space traveled by sound waves based on user-adjusted gain. To identify the channels, a 3.18 mm diameter V129-RM probe from Olympus was used operating at 10 MHz. This technique was applied in two ways, contact inspection and immersion inspection. The goal of contact inspection was to locate the channel in the sample thickness and quantify its thickness. To perform the test, the surface and base of the sample must not have roughness. Immersion inspection aimed to detect the presence of the channel and its disposition, water was used as couplant. The thermography tests were performed heating the plate to 200 °C and injecting a -20 °C fluid while measuring the temperature of black painted surface of the plate with a Fluke Ti400 infrared camera.
Die penetration tests were performed using KD-check liquids from Karl Deutsch. These tests were not performed in the traditional format. The application of the penetrant was done using a syringe. It was necessary to ensure a smooth sample surface and that the entrance and exit regions of the samples were open to allow for the injection of the liquid penetrant. Afterwards, the developer was applied to the plate surface.

3. Experimental Results

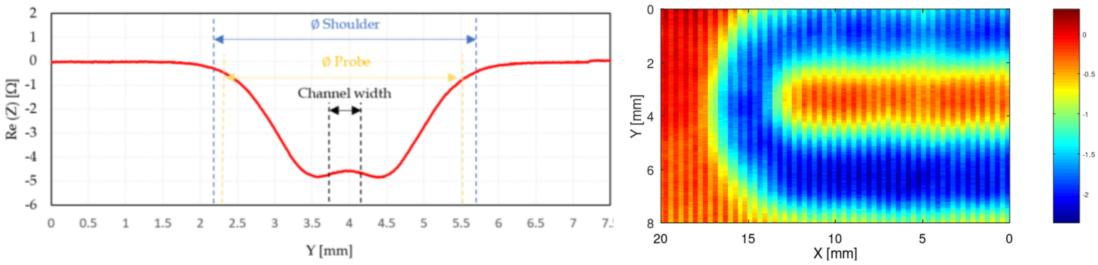
Digital radiography tests were able to detect the channels with the optimal exposure time being 240 ms. This technique was able to determine the presence of channels, their regularity, and different trajectories in the case of serpentines as seen in Figure 2. These tests also allowed for the identification of non-conforming channels. It also allowed for the determination of the width of the produced channels, which was 0.4 mm.



a) b)

Figure 2. Radiography test results with a 240 ms exposure time; a) linear channel sample; b) serpentine channel sample.

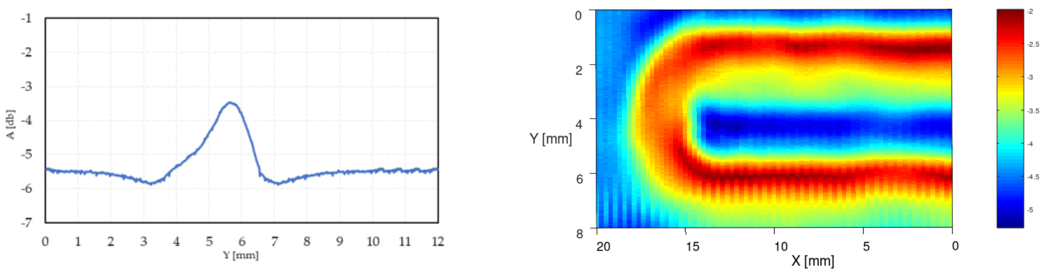
Eddy currents allowed for significant impedance variations to be detected (Figure 3), with the frequency that produced the best results being 20 kHz. Despite the impedance changes, the presence of the channel cannot be exclusively confirmed because the refined microstructure resulting from the process also has an influence on the test. In the case of serpentines, it was possible to verify a region with impedance changes indicating the channel trajectory.



a) b)

Figure 3. Eddy currents output signal operating at 20 kHz; a) linear test performed perpendicular to the channel; b) C-scan of serpentine channel sample.

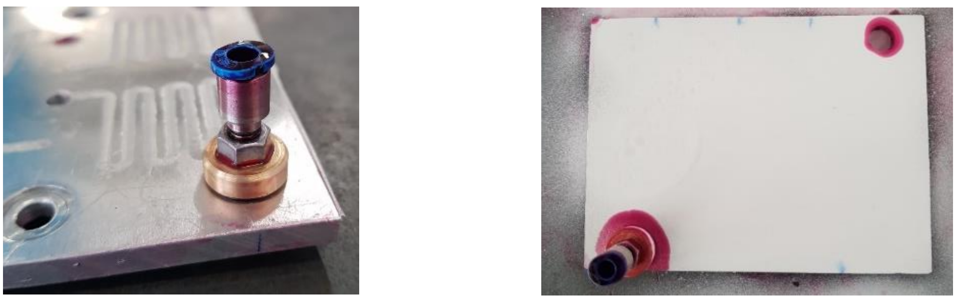
The ultrasonic immersion experiments were carried out with the help of the XY scanning device. C-scans were performed to monitor the variation of the sound amplitude.
As seen in Figure 4, it was possible to determine the presence of channels and in the case of serpentines, the channel, its dimension, and trajectory were also determined.



a) b)

Figure 4. Immersion ultrasonic results operating at 10 MHz; a) linear test performed perpendicular to the channel; b) C-scan of serpentine channel sample.

Thermography tests did not produce good results, and it was not possible to clearly identify the channel and its trajectory through thermal contrast since the flow with cold liquid was extremely low.
Tests carried out with die penetrants confirmed the presence and continuity of the channel due to the liquid covering the entire length of the serpentine (Figure 5), but it did not detect defects on the channels, guaranteeing it was defect free.



a) b)

Figure 5. Die penetrant testing; a) liquid injection accessory; b) Test output after applying the developer.

3. Conclusions

In order to simplify and compare the different results obtained from all the NDT techniques applied, Table 1 is presented. It is imperative to understand that the characterization of channels requires the use of multiple techniques in order to obtain a comprehensive and accurate representation. By combining the strengths of different techniques, one can ensure that all aspects of the channel are thoroughly evaluated, and no important information is missed. This way, a more reliable characterization can be obtained, and conclusions can be drawn with greater confidence.

Table 1. NDT techniques applicability to the channel's characterization.

		NDT techniques				
		RX	EC	US	Thermography	DP
Channel characteristics	Presence	✓		✓		✓
	Regularity	✓		✓		
	Electrical conductivity		✓			
	Trajectory	✓	✓	✓		
	Dimension	✓				
	Surface opening defects					✓

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