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Monitoring of the friction stir welding process: A preliminary study

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Abstract. Friction stir welding (FSW) has received great response in both academia and industry. Extensive research has been carried out to investigate the feasibility of the FSW process for different alloys and configurations. However, the growing demand for sustainable and cost-effective manufacturing, coupled with the pursuit of high-quality products, has led to the need for continuous monitoring of the manufacturing process and machine health. Therefore, the development of robust monitoring methods to assess the condition of the welding during the process becomes crucial for sustaining high production efficiency and ensuring quality standards. In this context, this study aims to provide methods for properly monitoring each phase characterizing the FSW process. Power consumption, vibrations, and temperatures were measured and evaluated in dissimilar friction stir lap welding of aluminum alloys.

Introduction

Friction stir welding (FSW) has met great response in both academia and industry due to its compelling possibilities as a solid-state joining process. Patented in 1991, extensive research has been carried out to explore the feasibility of FSW for different alloys and configurations, experimentally and simulated [1–7]. It is important to highlight that the FSW is considered a more environmentally friendly, energy-efficient, versatile, and economically viable splicing technique in comparison with traditional joining techniques, and it is considered a green technology as it ensures zero gas or radiation emissions to the environment [8]. However, the growing demand for sustainable and cost-effective manufacturing, coupled with the pursuit of high-quality products, has led to the need for continuous monitoring of the manufacturing process and machine health. Monitoring a process involves extracting relevant information from data acquired through sensors. Monitoring begins with the identification of the target parameters or features for analyses, followed by the identification of signals that would be best suited to provide information about specific target parameters or features. Once the signal in question is acquired, a processing technique is chosen to be implemented on the signal to extract the information. These techniques would eventually be used to identify fluctuations occurring within a process and, thus, can help in the control of the above-mentioned fluctuations when required.

For a comprehensive understanding of the FSW process and to ensure high product quality, it is crucial to explore how the various types of sensors are used in other joining processes, such as in fusion welding and, also, in machining processes similar to FSW operation [9]. Traditional fusion welding, like arc welding, involves monitoring welding current, voltage, arc sound, and temperature. In laser welding, on the other hand, monitoring is performed in three stages: the first one is the pre-process, which is dedicated to monitoring the weld bead, then there is the intermediate stage, which is used to monitor the weld pool, weld defects, and spatter, and finally, the post-process stage, for weld geometry and visible defects [10,11].

In a machining process, the various features monitored include gradual tool wear, detection of sudden tool breakage, vibration, or surface roughness. Similarly, monitored features in FSW include defects, positioning of the tool over the joint, temperature in the weld zone, etc.

The challenge then arises regarding the methodology for monitoring these features during the process. Monitoring methods can traditionally be classified into two categories: direct and indirect [12]. The direct method makes use of techniques such as laser, radioactivity, optical system, and camera vision to provide information about a given feature. For example, during the machining operation, tool wear was detected using optical methods, i.e., by analyzing the condition of the tool under a microscope. In addition, particle wear can also be studied through radioactivity and using vision systems [13,14]. Similarly, surface roughness can be determined with optical and vision systems [15]. Machine vision systems have also been used for weld seam tracking and for identifying defects and geometry during welding itself [10]. X-rays are also often used for defect identification [10]. Therefore, direct methods are based on dimensional measurements, providing high accuracy but limited practicality due to various constraints, such as placement in a non-vibration-free environment, their delicate handling, and the need for adequate lighting. Moreover, the wrong use could create an interference with the monitoring system, making the whole system unstable.

To overcome the problems associated with direct monitoring, systems have been developed to detect physical quantities such as current, power, force, torque, and vibration, constituting indirect means of monitoring [12]. These systems are less accurate than direct monitoring methods but are cost-effective, more practical, and suitable for industrial applications. For instance, in the study of Mazlan et al., welding current signals have been monitored to study the quality of welding in Gas-Metal Arc Welding (GMAW) [16]. In another work, Huang et al. reported that acoustic signals have been used during laser welding to monitor weld quality, namely, to differentiate between full-penetration and partial-penetration welds [17].

Therefore, the development of robust monitoring methods to assess the condition of the welding during the process becomes crucial for sustaining high production efficiency and ensuring quality standards [18]. In FSW, force and torque signals have been used specifically to detect defects and monitor tool position [19–21], but a reliable monitoring methodology and setup still require further investigation. In this context, the aim of this study is to provide strategies for monitoring the FSW process that can be used for the control and detection of anomalies, such as defects in the welds, or for the assessment of the tool conditions. Specifically, power, vibrations, and temperatures were measured to achieve a sound dissimilar lap joint of two aluminum alloys. The proposed method can be useful for the improvement of process from an efficiency and sustainable standpoint.

Materials and methods

In the present work, aluminum sheets served as the workpiece for FSW, with a lap joint configuration. Friction stir welding of aluminum alloys is a robust process that has become increasingly well established in the fabrication of critical components, in particular in the welding of 2xxx and 7xxx alloys for the aerospace industry. Specifically, the materials used are AA 2024-T3 and AA 7075-T6, which are particularly interesting, for example, in the aerospace industry for the fuselage panels of aircraft, which are usually made of AA 2024 skins and strengthened by FSW lap joining of AA 7075 stringers [22–25].

The FSW process was executed utilizing an ADRIA Machine FEL-660HG milling machine equipped with a custom clamping system, shown in Fig. 1. The H13 tool employed was supplied by FPT Industries and characterized by a threaded pin having a truncated cone shape. The dimensions of shoulder and tool diameters are 13 mm and 20 mm, respectively; the major and minor pin diameters are 3.96 mm and 5.40 mm, respectively. As previously mentioned, the joint configuration is a lap joint, with AA 2024 as the upper plate and AA as the lower plate. The chosen parameters for the present experimental campaign are summarized in Table 1.

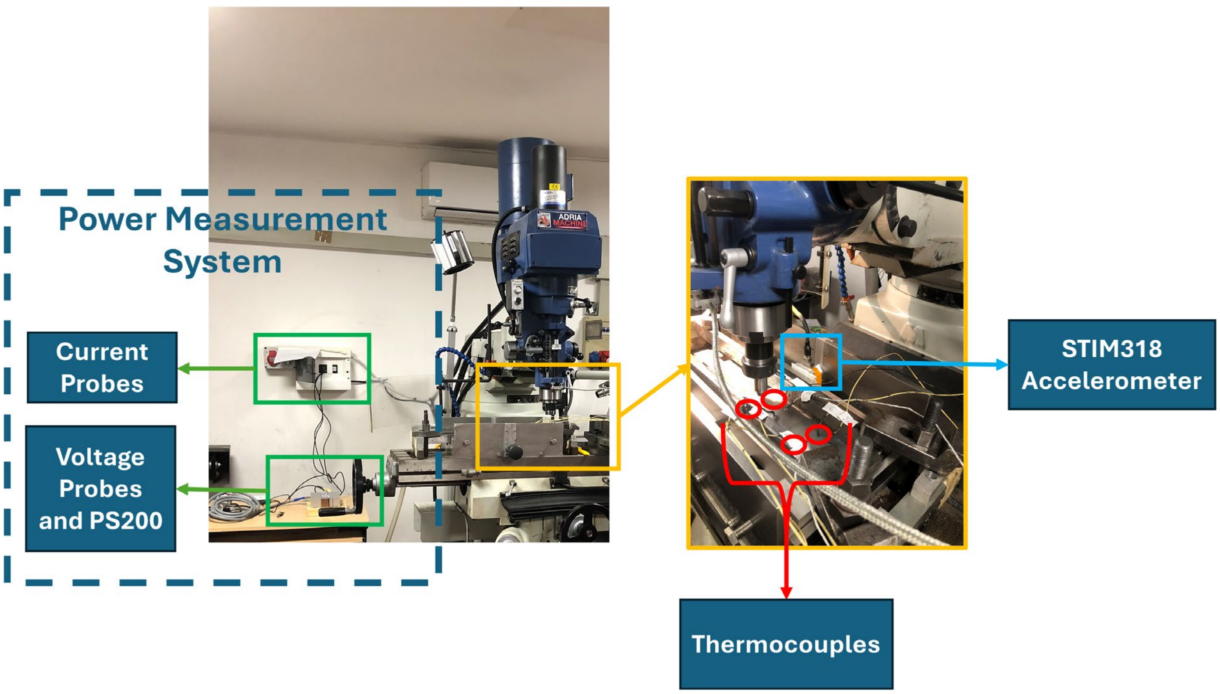

Figure 1. FSW monitoring system setup realized with a power measurement system, an accelerometer, and four thermocouples.

Table 1. Parameters used in the FSW experimental campaign.

Parameter	Value
Tilt angle	1 [deg]
Tool feed rate	100 [mm/min]
Tool rotation	1800 [rpm]
Tool plunge	4.1 [mm]
Welded length	90 [mm]

Several sensors were employed to monitor the process. Accelerations during the procedure were acquired using a tri-axial MEMS (Micro Electro-Mechanical System) accelerometer, the technical specifications of which are reported in Table 2. The accelerometer is STIM318 from Sensonor™ [26,27], used to monitor the vibrations of plates during the welding process; in particular, the three sensing axes of the accelerometer are oriented one perpendicular to the welding plane (X-axis), one along the welding direction (Y-axis), and one outward from the plane (Z-axis), respectively. Temperature data was gathered with the use of type K thermocouples and a RS 200 Pro data logger. The thermocouples were inserted in 2 mm deep holes drilled on the top surface of the plates. In total, four thermocouples were strategically positioned to map the temperature within the workpiece, with two thermocouples for the upper plate and two thermocouples for the lower plate. Additionally, power consumption was measured by means of a power monitoring device, i.e., the Montronix Power sensor PS200, which is connected in such a way as to measure the spindle motor only. The full system setup is shown in Fig.1, where a Personal Computer acquires the measured power, acceleration, and temperature through Serial Communications that is established by means of a Matlab code in such a way as to acquire synchronized samples from the realized monitoring system.

Table 2. STIM318 accelerometer technical specifications.

STIM318	
Measurement Range	$\pm 10\ [g]$
Bandwidth (-3dB)	$225\ [Hz]$
Bias Instability	0.003 [mg]
Velocity Random Walk	0.015 [m/s/$\sqrt{h}$]
Resolution	$1.9\ [\mu g]$
Sample Rate	2000 [samples/s]

Characterization of the joint surface was carried out with the use of the HIROX RH-2000 Digital Microscope.

Results and discussion

The tests conducted aim to evaluate the power variations, vibrations, and temperature changes in each phase of the FSW process. The monitoring of the process is essential to obtain an efficient process and, therefore, a more sustainable one, and it could be a fundamental element for the preliminary detection of welding defects and tool wear. The first variable was monitored using the power monitoring sensor, i.e., Montronix PS200, connected only to the spindle motor, whereas the vibrations, intended as accelerations in one of the three main axes, were analyzed through an accelerometer, i.e., STIM318, and referred to the vibrations of the aluminum sheets to be joined. Power variations and accelerations are shown in Fig. 2 and relate to the friction stir lap joint welding performed with a welding speed of 100 mm/min and a tool rotational speed of 180 rpm. Both the above-mentioned components are strongly affected by the material flow, and their variation during the process can be strictly related to the processing stage, and as reported in previous authors' studies, the entire procedure can be divided into three regions [28–30]: Phase I, II, and III.

The first phase refers to the initial stage, which includes turning on the machine, the motor, and the tool plunging phase. Therefore, in Phase I, it is possible to observe three peaks, indicated in Fig.2 as A, B, and C, both in the power and acceleration. Specifically, the blue arrows refer to the power peaks, and the orange arrows show the acceleration peaks. The recording started before the machine turned on; therefore, the reported values are at their minimum in the initial seconds but not zero. Then, when the motor turned on, a first peak was recorded, both by the Montronix PS200 and the STIM 318 (points A). Subsequently, power and vibration decrease as the tool goes down until the second peak is reached, corresponding to the first part of the tool plunging (point B). It happens when the rotating pin reaches the AA 2024-T3 top surface, generating a peak, and ends when the sheets are completely penetrated. Finally, a third peak was reported as an outcome of the accelerometer and the power sensor, i.e., points C, when the shoulder comes in contact with the top surface.

Motor power and accelerations do not show significant variations between points A and B, unlike what happens between points B and C, and this is in agreement with the physical process, considering that in the time range delimited by points A and B, there is only the descent of the tool, but still no interaction between the sheets to be welded and the tool itself. While between points B and C, it is possible to notice an increasing trend in both power and accelerations, again in agreement with the welding process, since the rotating pin is progressively entering the material, involving greater power consumption and increasing the acting forces, which in turn involve an increase in vibrations.

Phase II is related to the dwell time, characterized by a power-decreasing trend due to the softening of the material caused by the heat generated by the rotating tool. The same happens to the accelerations after an initial increment.

Phase III starts with the other two recorded peaks. Specifically, this phase is related to the welding process, and point D indicates the movement of the rotating pin. Therefore, there is a steady state, followed by a decrease in power and acceleration due to the end of the welding.

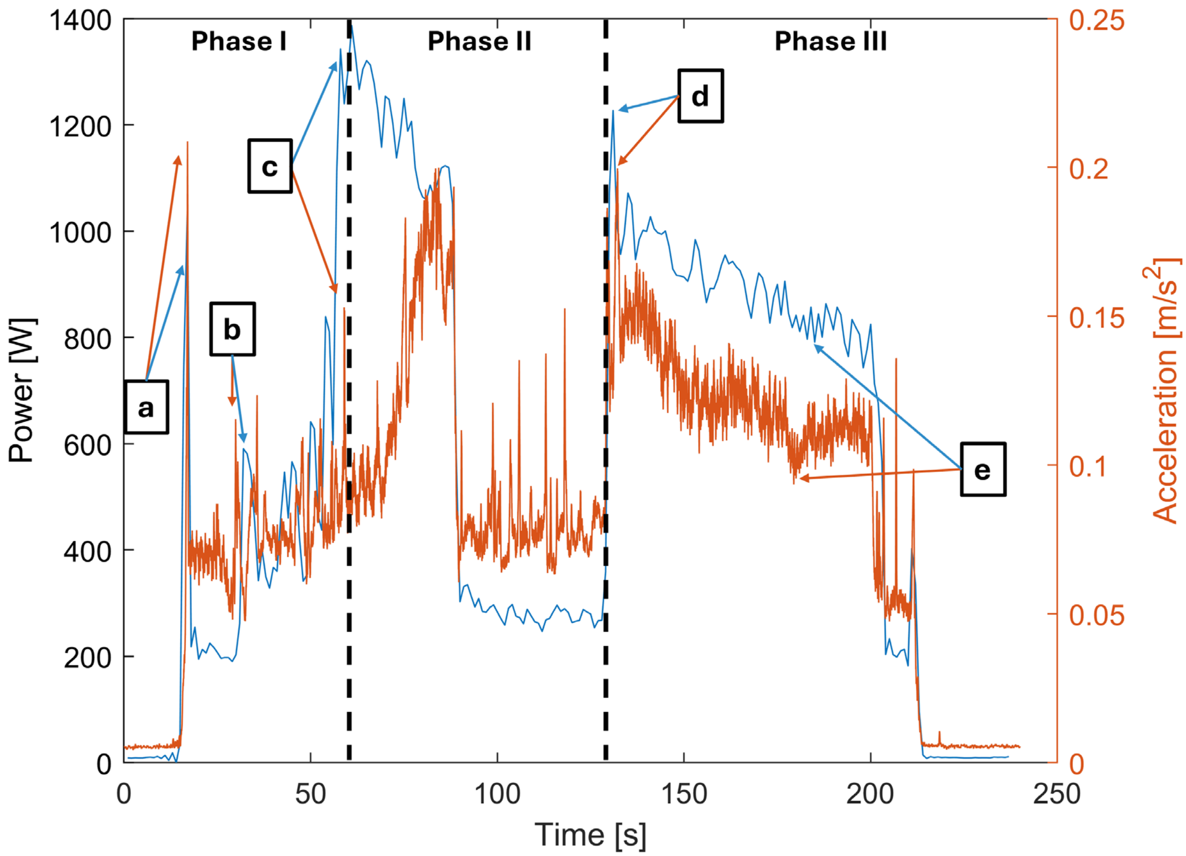

Figure 2. Power and acceleration vs time during the FSW process.

The frequency domain analysis of the acceleration along the three axes (Fig. 3) highlights three different vibration effects, which were evaluated separately by means of the Fast Fourier Transform (FFT); in particular, the acquired signal was divided and analyzed into three parts in such a way to identify the different contributions: *(i)* the motor vibration that is equal to 31Hz, according to the tool rotation (Table 1), this effect can be observed on all axes but is most evident on the Y-axis where the acceleration amplitude is equal to 0.3 m/s^2; *(ii)* the Dwell time where the frequency of about 100Hz and acceleration amplitude of 0.05 m/s^2 on the Z-axis have been measured, and *(iii)* in the welding process, the frequency evaluated is about equal to 160Hz, and the acceleration amplitude is equal to 0.01 m/s^2. For the sake of clarity, the motor vibration is also present in the Dwell time, and during the welding process, the motor vibration and a residual contribution of the Dwell time correspond to the complete insight of the sheets.

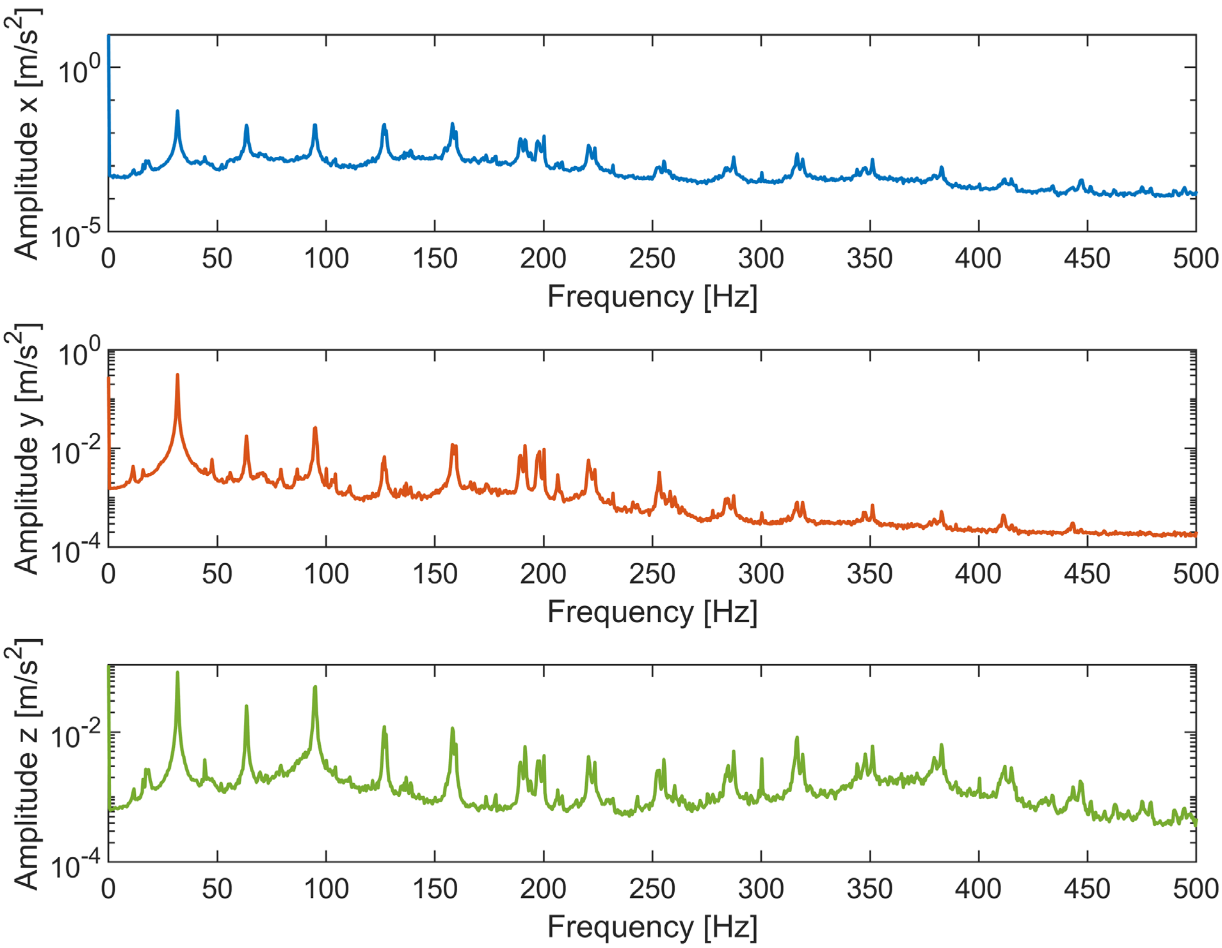

Figure 3. One-side spectrum of the measured acceleration along the three axes during the FSW process.

Finally, temperatures were also evaluated to assess the main parameters useful for monitoring the FSW process, as shown in Fig.4. The thermal trend is measured by means of four thermocouples, two placed on the upper aluminum sheet and two placed on the lower one. The temperature variations highlight in such a way the different phases above described for the power and acceleration. In particular, the recording starts at room temperature, about 35 °C, followed by an increasing trend corresponding to phases I and II, that is, the penetration of the tool into the sheets and the dwell time, and related to the heat generated by the rotating tool. During the final phase III, i.e., the welding phase, a second peak is registered, it was caused by the passage of the tool in correspondence with the position of the four thermocouples.

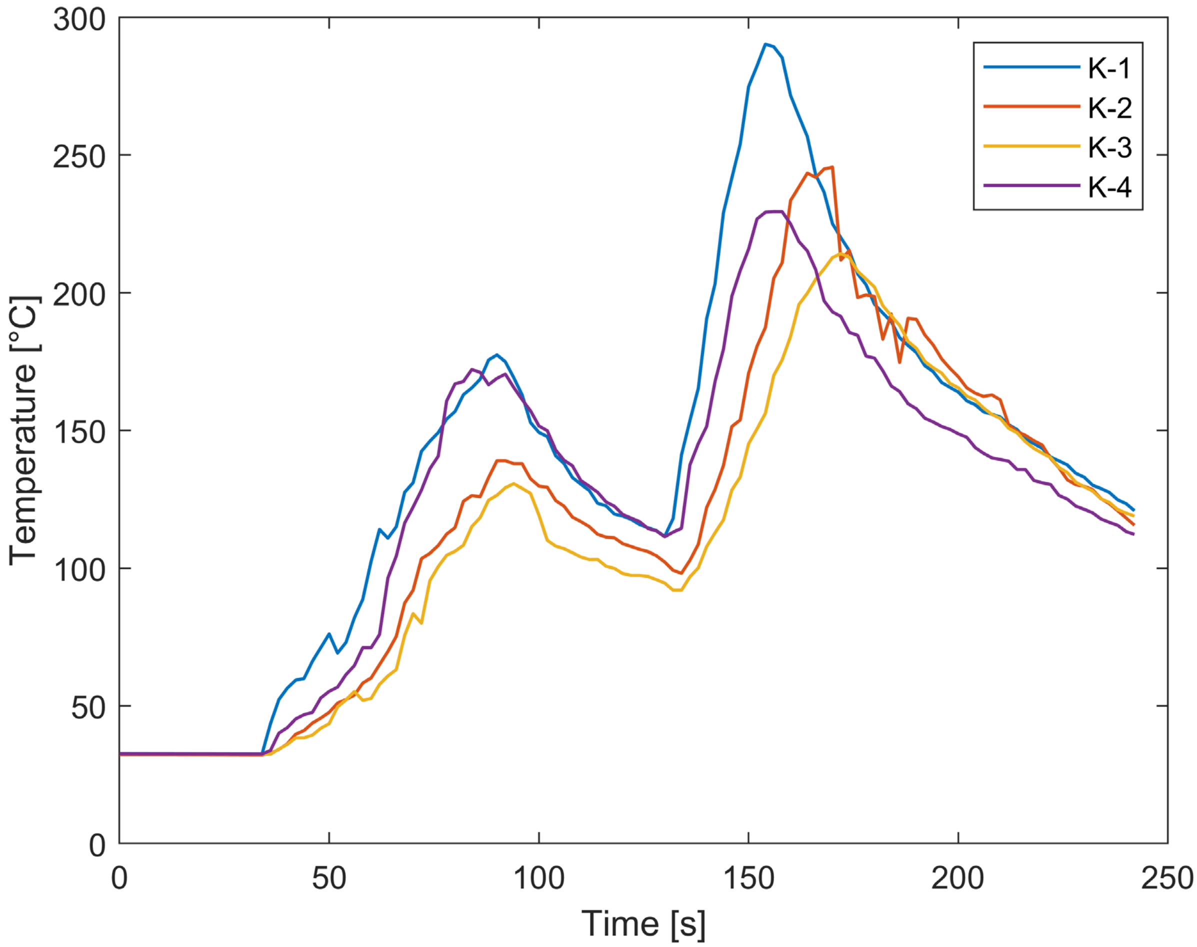

Figure 4. Thermal trend measured by the four thermocouples in the FSW process.

In summary, the monitoring methodology presented herein provides a means to properly identify the phases of the welding process in case of overlap welding by taking advantage of multiple sensors. Moreover, it enables the detection of anomalies during the welding operations, as evidenced by deviations such as further peaks, valleys, or oscillations in power, vibrations and temperature data acquisition, distinct from those previously observed and described. An illustration of this is depicted in Fig. 2, where minimal variations, denoted by point D, are indicative of the presence of defects. Specifically, it is possible to observe a valley in the acceleration, indicated by the orange arrow, and oscillation in power consumption, indicated by the blue arrow. The presence of the defect is also detected in Fig. 4, wherein the highest temperature is recorded by the thermocouple K-1, and so by the thermocouple positioned on the upper plate. The anomalies correlated to these variations are illustrated in Fig. 5, where it is possible to note excessive flash and waves of softened material associated with elevated temperatures, reflecting issues in the material flows. Notably, temperature emerges as the most influential characterizing parameter for these surface defects. Moreover, this method could help to check for variations with prolonged use of the tool, investigating the influence of the tool wear on the aforementioned outputs. In conclusion, it is possible to use the proposed method to identify optimal process parameters and enhance overall welding efficiency. While traditionally, the selection of process parameters has been primarily guided by the desired characteristics of the end product, contemporary practice dictates prioritizing combinations that minimize energy consumption, integrating process sustainability into decision-making processes. On these bases, early anomaly detection plays a crucial role, not only in ensuring a robust welding process but also in preventing the production of faulty components, thereby minimizing waste materials and conserving energy resources.

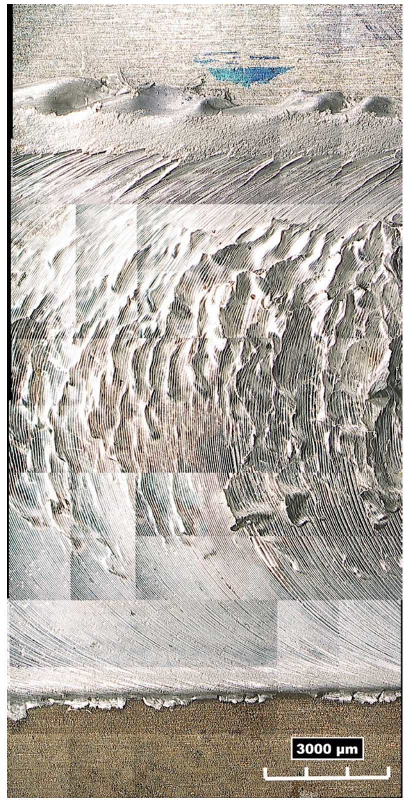

Figure 5. Flash and surface defects.

Conclusions

The findings of the present work provide reliable strategies for monitoring the welding process. In particular, a suitable monitoring system has been proposed to measure the main quantity of interest during the FSW process, i.e., the power consumption, the plate vibrations, and the welding temperature. To this aim, a power measurement system was connected directly to the tool motor while a tri-axial MEMS accelerometer was mounted on the welding plate, and four thermocouples were on the aluminum sheets. The research carried out highlights that by taking into account these parameters, the different characteristic FSW stages can be identified and divided into three main phases with the aim to help in the early detection of defects, tool conditions, power consumption, and tool failure also during the welding. Specifically, the occurrence of flash and surface defects during the welding resulted in peaks in the recorded temperature and alterations in both accelerations and power consumption. The obtained outcomes can be useful for assessing the state of health of the machine and the tool and, concurrently, for improving the process from a sustainable point of view. Early anomaly detection assumes great importance, ensuring a robust welding process and avoiding the production of defective components, thus minimizing waste materials and preserving energy resources.

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