Friction Stir Welding Tool Condition Prediction Using Vibrational Analysis Through Machine Learning – A Review

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Abstract. Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be the most significant development in metal joining in a decade. Recently, friction stir processing (FSP) was developed for micro structural modification of metallic materials. In this review article, the current state of understanding and development of the FSW and FSP tool process parameters are addressed. To identify the tool parameters, it is necessary to monitor the tool condition. Diagnosis the recognition of the nature and cause of a certain phenomenon. It is generally used to determine cause and effect of a problem. Machine fault diagnosis, a field of finding faults arising in machines. To identify the most probable faults leading to failure, many methods are used for data collection, including vibration monitoring, Thermal imaging, Oil particle analysis etc. Then these data’s are processed using methods like spectral analysis, wavelet analysis, wavelet transform, Short term fourier transform, high resolution spectral analysis, waveform analysis etc. The results of this analysis are used in a root cause failure analysis in order to determine the original cause of the fault. This paper presents a brief review about one such application known as machine learning for the friction stir welding tool monitoring

Keywords: Vibration analysis, machine learning, feature extraction, feature selection, feature classification, Friction stir welding Tool condition monitoring, Process Parameters.

1. Introduction

The Welding Institute (TWI) in the United Kingdom developed friction stir welding (FSW) in 1991 as a solid-state joining technique for aluminium alloys[1-3]. The basic concept of FSW is deceptively simple. Between the abutting edges of the sheets or plates to be joined, a non-consumable rotating tool with a specially designed pin and shoulder is mounted and rotated along the joint axis. (Figure 1).
The FSW tool has two main functions: (a) heating the work piece and (b) material movement to form the joint. Friction between the tool and the work piece heats it up, as does deformation of the work piece due to plastic deformation. Owing to localised heating, the material around the pin softens, and the combination of tool rotation and translation allows material to move from the front to the back of the pin. As a result of this process, a 'solid state' joint is formed. Due to the tool's various geometrical features, material movement around the pin can be very complicated. [4]. During the FSW phase, the material is subjected to intense plastic deformation at high temperatures, resulting in the formation of fine and equiaxed recrystallized grains. Friction stir welds (FSW) are regarded as the most important advancement in metal joining in a decade and are a "green" technology due to their fine microstructure and energy efficiency, environmental friendliness, and versatility. [5]. When compared to traditional welding methods, FSW uses significantly less energy. The process is environmentally friendly since no flux is used. Since no filler metal is used in the joining, Any aluminium alloy can be joined without regard for composition compatibility, which is a disadvantage of fusion welding. [6]. When needed, dissimilar aluminium alloys and composites can be joined with equal ease. Friction stir welding, unlike traditional friction welding, can be used on a number of joints, including T butt joints, lap joints, fillt joints, and butt joints. [7].

In Friction stir welding process a rotating tool is plunged into the work piece material along the joint line. After plunging it is kept for some time in that condition. This time period is called the dwell time. Then the tool being plunged into the work piece is followed along the axis of the joint. After the welding is complete the tool is retracted back [8].

The friction between the shoulder and the work piece is the primary source of heat in FSW. This heat is assisted by adiabatic heating caused by extreme plastic deformation of the material caused by the tool's stirring action. [9]. As the tool rotates and moves inside the work piece the material in front of it gets heated which can be easily plasticized by the tool. The flow of material in FSW is difficult to understand as the physics of the problem is still not clear. Many researchers have studied material flow behavior in FSW which can be found in the literature [10].

2. Process Parameters in FSW:

Process parameters involved in FSW process are tool rotational speed, welding speed, tool tilt angle, plunging depth, tool pin diameter, length and profile. Among these parameters tool rotational speed, welding speed and plunging depth are most important [11].
Tool Design - This is a vital aspect since it will increase both the efficiency of the weld and the overall welding speed possible[12]. At the welding temperature, a tool material that is sufficiently solid, durable, and hard wearing is needed[13].

Tool Rotational Speed - Friction stir welding is a solid state joining process that involves creating friction between the tool pin profile and the plate. The amount of friction produced is determined by the rotational speed. Weld consistency is likely to improve or decrease as the tool's rotational speed is increased or decreased. [14].

Welding Feed Speed - The temperature at the local location drops as the welding speed is increased. However, when the feed speed is slow, the temperature rises. [15].

Axial Force - As the thickness of the material is raised, the axial force increases [16].

3. Welding Methods
Welding is the technique of combining two or more parts of the same or different materials together in order to obtain full solidification. This is the only way to build homogeneous structures, and it's usually done with the help of heat and pressure[17]

3.1 Fusion Welding
The base material in fusion welding is heated until it melts. Here, no filler metal is used. The category of fusion welding is much more significant.

3.1.1. Oxy-fuel gas welding (OFW): The term OFW used to describe the process of cutting and separating metal plates and other pieces. To melt the base material, a flame is created using a mixture of oxygen, acetylene, and filler metal. It's a cost-effective, flexible method that's ideal for low-volume development and repairs.[18]

3.1.2. Arc welding (AW): Here the metals are heated using an electric arc. Filler metal is added during most arc welding processes to increase the volume and strength of the weld joint. The molten weld pool solidifies in the wake of the electrode as it moves around the joint. [19].

3.1.3. Resistance Welding (RW): To achieve coalescence, it uses a combination of heat and pressure. Electrical resistance to current flow at the interface of two parts to be welded generates the heat needed. [20].

3.1.4. Solid-state welding
Joining occurs without fusion at the interface when two surfaces are brought together without any liquid or molten phase present. Solid-state welding is the most widely used welding technique, which can be divided into the following general categories. [21].

3.1.5. Diffusion welding: Diffusion welding process that uses pressure and high temperatures to achieve coalescence of the faying surfaces. Since the temperatures are far below the melting points of the metals, surface plastic deformation is minimal. It's a popular method for joining dissimilar metals that's mostly used in aircraft and aerospace.[22].

3.1.6. Friction welding: It is a process that causes materials to coalesce as a result of heat generated by mechanically-induced sliding motion between rubbing surfaces. Under strain, the work parts are kept together. This procedure normally entails rotating one part against another in order to produce
frictional heat at the joint. The pieces are then pushed together with enough force to form a metallurgical bond. [23]

3.1.7. Ultrasonic welding: It's a method of inducing coalescence by applying high-frequency vibratory energy locally while holding the work parts pressed together. Welding takes place when an energy coupling device, like an ultrasonic tip or electrode, is clamped against the work parts and allowed to oscillate in a plane parallel to the weld interface. There are several ductile metals that can be welded together, as well as various combinations of dissimilar metals. [24].

4. Weld defects in conventional welding processes
The majority of welding defects are caused by incorrect welding procedures. Below are the major defects or discontinuities that affect weld consistency.

4.1. Porosity:
Gas pores in a solidified weld bead are referred to as porosity. Pores are strewn about in an erratic fashion. However, only the weld core has porosity. Pores may form underneath or on the surface of the welded joint. The most common cause of porosity is contamination of the atmosphere. [25].

4.2. Slag Inclusion:
Slag is usually visible as elongated lines running the length of the weld, either continuous or discontinuous. Slag inclusions are often linked to flux processes. Welding conditions are important, and molten slag will float to the surface of the molten weld metal rather than being entrapped if the right methods are used.

4.3. Incomplete Penetration:
Welding current has the greatest impact on penetration. Low welding current is the most common cause of incomplete penetration, which can be corrected by simply increasing the amperage. Another cause may be the use of a torch with a low travel speed and an incorrect torch angle. Weld metal will roll in front of the arc in both cases, preventing penetration. [26].

4.4. Weld Profile or Unacceptable weld Profile:
In multi-layer welds, the weld profile is crucial because it can reveal incomplete fusion or slag inclusions. Here are some examples of inappropriate profiles: Excessive weld fill can be described as irregular weld profile, excessive concavity or convexity, or excessive surface roughness. [27].

4.5. Cracks:
Longitudinal, transverse, crater, toe cracks, Fusion line, root, and under bead cracks are the most common. This can happen as a result of thermal shrinkage or as a result of a combination of strain and phase shift. High residual stresses and cracking can occur in due to a combination of bad design and inappropriate procedure, welded stiff frames. [28].

4.6. Surface Damage:
During welding, any metal will spatter and deposit as small droplets on adjacent surfaces. The electrode may come into contact with the parts being welded in areas other than the weld zone in arc welding, for example. Surface discontinuities may occur at the weld part. To avoid surface damage, it is important to use proper welding techniques and procedures. [29].
5. Friction Stir Welding

Fusion welding process generate fumes, gases, or smoke, which can be hazardous to workers. Porosity and slag inclusions are more likely in the fusion welding process. It uses a lot of resources and has a low process efficiency. It's difficult to weld dissimilar alloys and complex shapes together. The most common problem in fusion welding is work piece distortion and spatter. Friction stir welding, a modern solid state welding technique that uses a non-consumable method to connect two facing work parts without melting the work piece material, can effectively resolve these flaws and disadvantages of traditional welding methods. [30]

Heat is produced by friction between the rotating tool and the work piece material, resulting in a softened area near the FSW tool. The method mechanically intermixes the two pieces of metal and uses mechanical pressure to forge the hot and softened metal as it passes along the joint axis.[31]. It is often used on wrought or extruded aluminium, and it is especially good for structures that need a lot of weld power. Aluminium alloys, copper alloys, titanium alloys, mild steel, stainless steel, and magnesium alloys can all be joined with FSW. It has recently been used to successfully weld polymers.[32]. FSW has also recently accomplished the joining of dissimilar metals such as aluminium to magnesium alloys[33].

5.1. Process Parameters in FSW:

Process parameters involved in FSW process are tool rotational speed, welding speed, tool tilt angle, plunging depth, tool pin diameter, length and profile. Among these parameters tool rotational speed, welding speed and plunging depth is most influencing [34]. Tool design is critical because it influences both the efficiency of the weld and the maximum welding speed that can be achieved. At the welding temperature, it is essential to use a tool material that is sufficiently solid, tough, and long-lasting.

Tool Rotational Speed - Friction stir welding is a solid state joining process that produces friction between the tool pin profile and the plate. Rotational speed affects friction generation. Weld consistency is likely to improve or decline as the tool's rotational speed is increased or decreased. Welding Feed Speed - As welding speed increases, the temperature at the local location decreases. The temperature will rise if the feed speed is slow. Axial Force- As the thickness of the material is increased, the axial force increases as well.

The quality of the weldment, highly depends on the above parameters. If either these parameters are not properly maintained, or I there is any distortion in the tool, the weld quality will be affected. The tool quality is also one of the key criteria in the FSW process. Any faults in the tool or in the process parameters, the weld quality is worsely affected. These can be analysed using the vibration signatures.

6. Faults in Friction Stir Welding

FSW offers a number of benefits. Since FSW is solid-state, it avoids the problems of porosity and hot cracking that plague fusion welds [35]. FSW, on the other hand, has a few glitches and flaws. This section contains a brief overview of these vulnerabilities, as well as a review of the related literature. In the literature, faults in friction stir welding are discussed in terms of their types, causes, and consequences. [36].

The paper "Flaws in Friction Stir Welds," describes flaws in friction stir welding in detail. FSW has the advantage of avoiding common fusion welding flaws including porosity and heat-affected liquidation cracking. [37], as mentioned in the report The paper then goes on to explain and analyse the flaws that do pose a problem for FSW, as well as the reasons for them. Voids, root faults, and joint line residues were the defects examined in this report. The authors attempted to establish these flaws by putting gaps between the weld samples, using inadequate plunge pressure, wrongly setting weld parameters (welding speed in this case), and finally anodizing the samples to make the oxide layers larger. [38].
| Flaw type            | Location                                                   | Causes                                                                 |
|---------------------|------------------------------------------------------------|------------------------------------------------------------------------|
| Void type           | Advancing side at edge of weld nugget.                      | 1. Forging pressure is reduced.                                           |
|                     | Beneath top surface of weld.                               | 2. Welding speed too high.                                               |
|                     |                                                             | 3. Plates not clamped together tightly enough. Joint gap is excessively high. |
|                     |                                                             | 4. Welding speed too fast.                                               |
| Joint Line Remnant  | Weld nugget, extending from the root of the weld at the point where the original plates butted together. | 1. Inadequate oxide removal from plate edges.                           |
|                     |                                                             | 2. Inadequate tool disruption and dispersal of oxide.                     |
|                     |                                                             | 3. Welding speed increased.                                              |
|                     |                                                             | 4. Increase in tool shoulder diameter.                                   |
| Root flow type      | Weld nugget extend from the root of the weld at the point where the original plate butted together. | 1. Tool pin very short                                                   |
|                     |                                                             | 2. Incorrect tool plunge depth                                            |
|                     |                                                             | 3. Poor joint to tool alignment.                                          |

Table 1. Flaws Types in Friction Stir Welding

So far the faults identified in Friction stir welding are not addressed much using machine learning and condition monitoring. Hence in this research the FSW tool conditions with various faults will be addressed.

7. Vibration analysis

One of the most common methods of fault diagnosis is vibration analysis. This section[39-40] is devoted to a study of works in the field of vibration analysis for FSW tool condition monitoring. Below is a summary of the literature review conducted under the subheadings of traditional approaches, frequency domain analysis, time domain analysis, and pattern recognition.

Condition monitoring (CM) is a form of preventative maintenance that keeps track of how well machines are working. This can be accomplished using instrumentation methods such as vibration analysis. Vibration analysis is the most common method for diagnosing rotating devices. The frequency of the vibrations can also be mapped in order to detect failures since certain frequencies are only present when conditions indicate an imminent defect. The information needed to decide when maintenance is required is given when the vibration spectra of a defective condition signal and a good condition signal are compared. [41].

7.1 Fault diagnosis through vibration analysis

Since there is a lack of published literature in the field of FSW process monitoring by signal processing, the current study focuses on monitoring the friction stir welding process using signals obtained during the welding process. During the welding process, four signals were recorded: the main
spindle motor’s current and voltage signals, the motor’s current signal, and the tool rotational speed signal. At a sampling rate of 10 kHz, all of the signals were acquired using a high-speed data acquisition system (NI-USB-6259). The signals are acquired using MATLAB. Root mean squared (RMS) are obtained which is along with the process parameters used for developing regression models. The regression models are developed for correlating the signal information and the process parameters with ultimate tensile strength (UTS) and yield strength [42]

As the physics of FSW process is not clear and it involves many process parameters and the effect of which cannot be studied separately so only relying on process parameters for monitoring the process is not sufficient. Apart from the process parameters signals acquired during the process can also play an effective role in monitoring of the FSW process. Force signals, current and voltage used force signals[43] for monitoring FSW process using dynamometers. The force associated with FSW process are the vertical force (z-direction), Horizontal force (y-direction) and side force (x-direction). Most of the researchers commented that among the three forces, z-direction force and y-direction force are more important than the x-direction force. Apart from the force signals, acoustic signals were also acquired by many researchers during FSW process. The use of acoustic emission signal for studying the effect of tool wear in FSW process. It also acquired acoustic emission signals during FSW process. They used wavelet analysis for signal processing. From the signals they commented that the material flow is different in advancing side and retreating side of the weld as the patterns of the acquired signals were different. The developed a criterion to find out onset of defect formation based on force signals data acquired during FSW process[44]

![Figure 2](image)

**Figure 2.** Friction Stir Welding Process and Stages

### 8. Machine Learning

The aim of fault diagnosis in early 1975 is to protect the vibration spectrum and provide graphical resources so that the analyst could easily access the data and assess the machine's problem[45]. The collection, storage, and processing of vast amounts of data has become possible thanks to advances in computer technology. The majority of data collection systems will accurately log real-time data in digital form. The cost and size requirements for storing large amounts of data have been reduced as a result of technological advancements in memory devices. [46]. Memory systems today are much more reliable to advances in technology. Engineers can solve complex problems with high-speed processors. Many machine learning approaches are iterative in nature, necessitating the use of high-speed processors. The aforementioned advances hasten the implementation of machine learning approaches for real-time problem solving. Machine learning approaches are commonly used in fault diagnosis[47].
8.1. Feature Extraction

Extraction of features is the first step of experimental data analysis. Vibration signal [48] analysis is the crucial part for number of condition monitoring techniques. Frequency-centered spectra are widely used to locate defects in rotating components. Because of its simplicity in measurements, vibration-based diagnosis is the most common monitoring method. When a segment's vibration elements originate at a specific point, the health state of the segment must be defined by interconnecting the patterns with those relating to its normal and faulty conditions. The feature extraction technique is one of these approaches that is often considered for a health condition monitoring strategy. The vibration signal can be used to extract a variety of features. They are namely i) statistical feature[49] ii) wavelet feature[50] iii) histogram feature[51].

8.2. Feature Selection

The process of choosing or highlighting the best features from a wide number of choices is known as feature selection. Feature selection's main objective is to define a collection of input variables using features that provide little or no information. Feature selection improves the comprehensibility of emerging classifier models and also leads to a model that generalises better to hidden points. The features may be used to quantify the signal, but their importance will be determined by how well they aid in the classification process. Countless techniques were encompassing for feature selection. Some of them are decision tree (DT)[52], genetic algorithm (GA)[53], principle component analysis (PCA). Among them, principal component analysis (PCA), decision tree (DT) and select attribute evaluator was using especially[54].

8.3. Feature Classification

The final step in machine learning is classification. The classification procedure can be carried out by training and checking the data that is available. To train the data, a model or system is used. The model is validated with untrained data according to the preparation. In machine learning, this is the method used. An algorithmic approach is needed to train the model. Three such algorithmic models Best First Tree [55] and Random Forest [56] and Support Vector Machine have been discussed in the following subsections.

9. Future scope

There are some machine learning approaches which have not been even tried for the fault diagnosis study in FSW tool condition monitoring. Referring to the literature study, the machine learning approach has been proposed for monitoring of Friction Stir Welding Process through signals (Current and Voltage signal) acquired during the welding (Bipul Das et al.) 2014. Hence, this review suggested that the same machine learning approach can be implemented on the real-time model considering all possible faulty conditions. An onboard diagnostic model consists hardware and software for extracting features from the acquired vibration signals. The feature selection and feature classification, displaying the condition of the FSW tool are the ongoing research attempts which have been carried out in this fault diagnosis study.

10. Conclusions

Machine learning techniques have been successfully tested for tracking machine components such as gears, tool condition, bearing faults, pump impeller faults, wind turbine blade faults, brake
faults, and so on. According to the above review, machine learning approaches in the field of fault diagnosis have a lot of potential. The results of the study showed that properly collected statistical and histogram data can be used to diagnose Friction Stir welding tool faults. On the basis of this knowledge, a decision about the action to be taken can be made. This will result in a fault diagnostic model that accurately describes the state of the FSW method. The application of machine learning can be extended for monitoring the FSW Tool condition on are al-time system which is an ongoing attempt.

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10

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