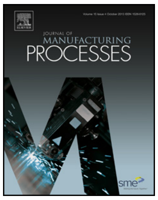
Journal of Manufacturing Processes 24 (2016) 217–224

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro



Development of a novel approach for characterising electron beams and quality assurance of welds

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ARTICLE INFO

Article history:
Received 15 May 2016
Received in revised form 30 August 2016
Accepted 3 September 2016
Available online 6 October 2016

Keywords:
Electron beam welding
Wavelet transform
Quality assurance

ABSTRACT

This paper presents a novel approach to characterise electron beams for quality assurance of electron beam welded joints for the aerospace industry. The weld quality depends on beam characteristics that can be affected by variations in the gun controls and power supplies, physical changes in the electron gun or the conditions in the vacuum chamber. In the present research, a device using a slit based measuring technique has been used to capture a small portion of the electron beam and to characterise it. The acquired signals are processed to generate a set of features using wavelet transforms. The focus of the paper is to demonstrate the significance of these features generated from different decomposition levels in differentiating electron beams with different characteristics and hence their role in providing quality assurance of welds.

1. Introduction

For the aerospace industry, designing aircraft with capabilities of flying higher and faster has been a consistent aim. This demands highly complex, performance-optimised and weight-minimised systems that typically employ exotic materials and advanced technologies. Manufacturing in the aerospace industry is characterised by very complex and costly technologies used to produce high quality components. The design requirements are stringent due to operating environments, high performance optimisation and extremely lightweight systems. This is compounded by the severity of any associated catastrophic failures [31]. Highly specialised materials, manufacturing processes, tooling and facilities are necessary to produce aerospace components and assemblies. These requirements for high quality have been the driving forces for development in the field of manufacturing for aerospace applications. For instance, in the mid twentieth century riveting was used as the joining technology for airframe components and welding for aero-engine components. However, in late twentieth and early twenty first century the paradigm has shifted to use welding even for airframe components [6].

As with any other manufacturing process in this industry, welding is characterised by low unit production, high unit cost, extreme reliability, and severe operating conditions [28]. Over a period, a number of techniques have been developed and used. Friction welding, arc welding, resistance welding, plasma welding, laser welding and electron beam welding have all been deployed. These can be ranked based on the intensity of heat used [20]. For example, electron beam welding is a high heat intensity process whereas friction welding is a low heat intensity process. The choice of the welding method is governed by the type of weld and the materials to be joined. For example, titanium is one of the materials extensively used for aerospace applications in manufacturing of critical components because of its high strength to weight ratio and excellent heat and corrosion resistance over the competing materials like steels, aluminium or super-alloys. To achieve lighter weights and higher speeds, strength to weight ratio has been the prime driver for choosing a material for both engines and the aircraft. In addition to this, the operating capabilities at very high and sub-zero levels of temperatures, fatigue, crack development resistance, toughness and working in stringent environments also play a significant role in selecting a suitable material. In this respect, titanium and titanium alloys are a typical choice in the manufacturing of critical components in aerospace applications due to their high strength to weight ratio, excellent heat and corrosion resistance over the competing materials like steels, aluminium or super-alloys. Ti–6Al–4V, one of the α-β titanium alloys is currently the 'work horse' which accounts for almost 60% of the total titanium production. They have more strength than its α-alloys and better welding capabilities than β-alloys. It also maintains good mechanical properties at high

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http://dx.doi.org/10.1016/j.jmapro.2016.09.005

temperatures up to 400 °C. The combination of these two gives a good balance of strength, ductility, fracture toughness, weldability, creep characteristics and is used for manufacturing various components in airframe and aero-engines where high reliability is required [13,2]. However, titanium is a highly reactive metal. At higher temperatures from 600 °C to 800 °C it reacts with the atmosphere and burns [18]. If there is insufficient protection while carrying out welding, due to the high temperatures generated, titanium can pick up oxygen and nitrogen from the atmosphere due to preferential affinity of the metal for these elements and this can cause contamination in the welded joint. Electron Beam Welding (EBW) is a preferred method for welding titanium as it is carried out in vacuum and can avoid the interaction of the metal with the atmosphere during the process [35]. EBW process also facilitates defect free very narrow and deep penetrations.

In EBW process, electrons moving at high speeds are focused on the work piece. When the electrons interact with the material, the kinetic energy is transformed into thermal energy. This results in the formation of a keyhole consisting of the melted and evaporated material [27]. The creation of this fusion zone is characterised by the beam width, height and penetration. Ideally, the shape of a partially penetrating fusion zone can be considered as Gaussian but can vary depending on beam characteristics, which in turn depend upon the process parameters such as accelerating voltage, beam current, focus current, welding distance, welding speed and vacuum levels in the working chamber. Liebig et al. [17] have also mentioned about the spot size and the divergence angle as influencing factors. To maintain the quality of the welds thus generated, the processes are highly controlled. However, even minor variations in the electron gun itself can result in variations in the beam characteristics with significant effect upon the quality of the welds. Hence, it is very important to check the beam characteristics prior to carrying out the welds. The work presented in this paper is focused on the development of a methodology for characterising the electron beam to differentiate between the beams that can result in acceptable or unacceptable weld quality.

2. Related work

Various techniques and devices to characterise electron beams for welding have been developed over time and are discussed in Kaur et al. [15]. These devices measure the distribution of current over the beam cross section. For welding applications, high power electron beams are used which are focused on very narrow beam diameters resulting in high power densities of the order of 10^{10} W/m^2 [10]. If these dwell on the measuring device, the device will be damaged. To overcome this problem, the beam is deflected over the measuring device at high speeds to capture full or part of the beam. Rotating wire, slit-probing and pin-hole are the major techniques used for capturing the beam currents [23]. The captured signals from the device are processed further to extract the information about the beam characteristics.

Beam measurement devices available commercially have a range of capabilities and limitations. Some of these devices provide a detailed map of power density distribution of the beam and the beam diameters but are limited in the beam powers they can work with, and not all provide an effective means of using the detailed information in correlating with weld quality. Some of the devices provide limited information about the beam characteristics but are capable of operation at high powers.

Published work reports the use of these devices in characterising electron beam machines [24], transferring parameters from one EB machine to another [26] and correlating weld shapes with beam diameter and power density distribution [7]. These studies were mainly carried out using stainless steel at low power beams. One of the studies focussed on aerospace industry [25], was concerned with finding out the differences between the variations in operator's set focuses and the ones readjusted by using the measuring device. However, these studies were limited in their evaluation of the effect of focus changes and their operation at low powers. A device with high power capability was used in the aerospace industry to capture the beam characteristics before each weld for more than 4 years. It was used for capturing the beam parameters in terms of beam diameter at the FWHM (Full Width Half Maximum) and the peak current intensity. During production, whenever there were maintenance events, the variations in the captured data were observed [5]. The device had also been used to study the variations in weldment dimensions against the focus sweep in controlled industrial environment with an aim to establish the ability of the probe to relate probe measurements with physical weld profiles [5,14,15]. The device was also used by Huang [11] for estimating the beam diameters at focus to validate keyhole models for EB welding. Though these devices and systems have great potential for use in quality assurance, still their use in the industry is uncommon. This indicates the need to develop a system that can be easily incorporated in the quality assurance process. As suggested by Dave et al. [6], the development and use of in-process quality assurance is today's need and emerging as a new paradigm in the aerospace industry for efficient manufacture, compared to post process inspection.

The present research is focused on development of a novel method which can enhance the capability of characterising the electron beams by exploring the parameters that can better describe the beam characteristics with an aim to facilitate the inspection and to flag the variations before they lead to defects in the welds. A data-driven approach has been used consisting of experiments to conduct melt runs for various beam settings; acquiring the measuring device output, processing using wavelet transform and classifying by linear discriminant analysis. Firstly, the acquired signal is decomposed into different frequency bands using discrete wavelet transform (DWT), next, the features vector is generated by the parameters to characterise electron beam and then using the linear discriminant analysis, the welds are classified based on the quality requirements.

3. Experiments and data collection

To achieve the above aim, understanding the correlations between weld parameters and features of the beam was essential. Because of the complex nature of the process, to do it by mathematical modelling was difficult. Therefore, an experimental approach was taken for the present work. The above problem can be represented as a typical pattern recognition problem for decision making consisting of feature extraction, dimensions reduction and classification to indicate a particular class depending on the features profiles selected. Experimental work was carried out towards the above aim with the following objectives:

- Use a measuring device capable of working at high powers to acquire the beam signals.
- Apply a signal processing technique on the acquired signals from the measuring device corresponding to the welds with different profiles and quality parameters which could give a features vector to accurately characterise the electron beam.
- Train the classifier by categorising the features profiles characterising the electron beam based on the weld quality parameter tolerance limits and indicate when the features profiles was drifting, which could result in weld defects.