Development of a novel device and analysis method for characterising electron beams for welding applications

Aman Kaur, Colin Ribton, Wamadeva Balachandran

The quality of electron beam welds depends upon a number of parameters like accelerating voltage, beam current, focus settings, vacuum level, working distance and welding speed. Even if these parameters are tightly controlled, there can be variations in the beam that can affect the quality of the welds, due to changes in cathode and electrode geometry and cathode emission. To ensure the quality of the beam prior to carrying out the welds, a probe device has been developed using the slit-probing method. This paper describes the design of the probe and signal processing of the acquired signals. The novel design of the probe facilitates the alignment of the probe in the vacuum chamber and its verification using the acquired signals. The acquired signals are also processed to characterise the electron beam to indicate the quality of the welds. The sensitivity of the analysis method has been enhanced by the use of wavelet decomposition and features vectors. Trials have been carried out focussed on aero engine manufacture to verify that it is possible to detect changes in the electron beam characteristics before they cause weld defects.

Разработване на ново устройство и метод на анализ за характеризиране електронни снопове за приложения за заваряване (Аман Каур, Колин Рибтон, Вамадева Балачандран). *Качеството на електроннолъчевите заварки зависи от редица параметри като ускоряващото напрежение, тока на снопа, настройките на фокуса, нивото на вакуума, работното разстояние и скоростта на заваряване. Дори ако тези параметри са строго контролирани, може да има вариации в лъча, които могат да повлияят на качеството на заваръчните шевове, поради промени в катодната геометрия и емисията на катода. За да се гарантира качеството на снопа преди извършване на заваръчните шевове, едно е разработено сондово устройство с помощта на метода на сондиране с процеп. Тази работа описва дизайна на сондата и обработката на придобитите сигнали. Новият дизайн на сондата улеснява подравняването на сондата във вакуумна камера и нейната проверка, използвайки получените сигнали. Получените сигнали също се обработват за характеризирането на електронния лъч с оглед индикация на качеството на заваръчните шевове. Чувствителността на метода на анализ е подобрена чрез използването на вълнова декомпозиция и вектори на характеристиките. Изпитанията са проведени с фокус върху производството на аеро-двигател, за да се потвърди, че е възможно да се открият промени в характеристиките на електронния сноп, преди те да причинят заваръчни дефекти.*

Introduction

High power electron beams are used for welding purposes where the kinetic energy of fast moving stream of electrons focused on the work-piece is converted into heat. Due to its capability to create narrow and deep welds with minimal distortion and high reproducibility, it is a favored choice for welding critical components in aerospace, nuclear and medical industry. The process is carried out in vacuum chambers which provide the opportunity to weld reactive metals that might suffer from contamination if not adequately shielded in inert gas [1]. The technology of electron beam welding (EBW) was initially evaluated in 1960's by Rolls-Royce and has been in use for welding critical aero-engine components such as compressor drums. An aero-engine compressor assembly along with zoomed electron beam weld and a turbine rotor assembled from a number of disks are shown in fig. 1 (a) and (b) respectively [2]. Due to the complex nature of components, high quality requirements and high associated costs of manufacturing in the aerospace industry, processes are tightly controlled. To ensure the quality of the electron beam welds, the quality of the beam needs to be consistent throughout the series of production.

Fig. 1a. Compressor assembly with zoomed electron beam weld [2].

Fig. 1b. Turbine rotor constituted from several disks [3].

The quality of the beam depends on the gun operating parameters, condition of the cathode producing the electrons and alignment of the gun components. Due to changes in these over time, the quality of the beam can vary resulting in welds outside the tolerance limits of quality parameters which makes it essential to monitor the beams before carrying out the welds. Various devices and systems exist to check the beam quality [4]. In the present paper, development of a novel device and signal processing to characterise an electron beam is discussed.

Inverted two-slit probe

Although there are many ways of characterising the beam, but in general measurements are derived from the beam current. The beam current can be measured either in full or in part. The Faraday cup is the basic device used to collect the electrons constituting the beam current. As the electron beams are focused on the work piece and have very high energy density of the order of 10^8 W/cm^2, if exposed, the measuring device can be damaged in a very short time. Therefore, the beam is usually deflected at high speed over the device and positioned in a parking position when not in use.

The construction of the inverted two-slit probe is shown in fig. 2. It consists of two fingers with two slits on each and a pickup plate. There are Faraday cups under each slit for collection of the electrons. The device is capable of measuring part of the beam current through the slits and the full beam current measurement through a pickup plate.

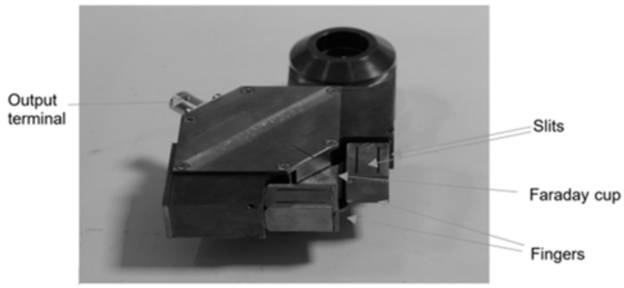

Fig. 2. Construction of the probe. (Reproduced by permission of TWI Ltd.)

To measure the beam, the electron beam is deflected over the device in a circular pattern as shown in fig. 3.

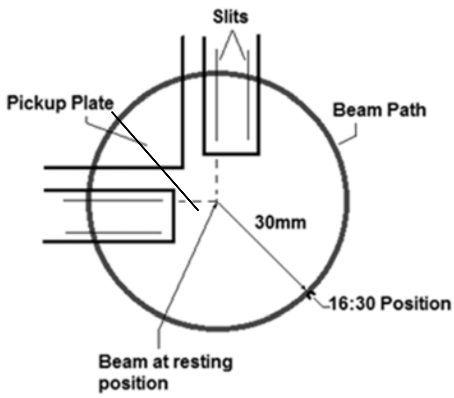

Fig. 3. Beam scanning over the probe. (Reproduced by permission of TWI Ltd.).

A circle of 30 mm diameter is generated by deflecting the beam. Usually, the free fall position of the beam should be at the intersection point of the inner slits of the fingers. During the beam current measuring operation, when the beam is not deflected, it is positioned in the parking location at 16:30 position indicated in fig. 3.

The earlier version of the probe was with two fingers with one slit on each and the fingers pointing outwards with Faraday cup [5]. This version required a triangular scanning pattern to cover the two fingers and the faraday cup. This was installed in an industrial environment and has been in production operation for several years. However, the initial alignment of the fingers with the beam and installing in the chamber required effort and specialized skills. This problem has been simplified in the inverted two-slit probe by providing additional signals to assure the alignment of the probe.

A typical output signal of the probe is shown in figure 4. Peaks 'a', 'b', 'd' and 'e' are from the slits of the fingers that capture the part of the beam whereas the broader peak 'c' is from the pickup plate representing the full beam current. The time difference between signals 'a' and 'b' or between 'd' and 'e' are used for speed measurement and signals 'b' 'd' are used to characterize the beam in two perpendicular directions depending on the position of the probe with respect to the welding direction.

As can be seen in fig. 4, the two signals from the inner slits i.e. 'b' and 'd' should be 90° apart if the probe is aligned with the free fall position of the beam falling at the intersection of two inner slits axis. This position can be measured by the time difference between the signals from these slits. For instance, for a 5 kHz scanning frequency, it should be 50 µs. Each time the probe is moved or reinstalled, the time difference can ensure the installation in the same position.

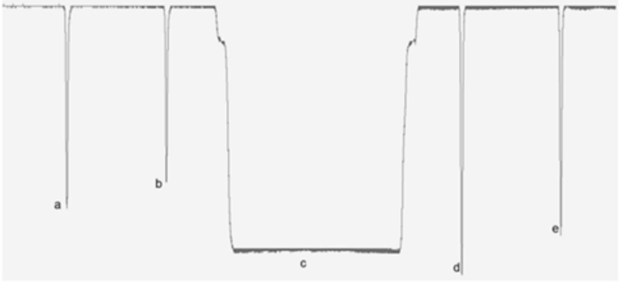

Fig. 4. A typical output of the probe. (Reproduced by permission of TWI Ltd.)

Signal processing

The acquired signals 'b' and 'd' are processed and features are extracted to characterise the beam. Due to the distinct advantage of wavelet transforms of analyzing the signals in time and frequency domains over other methods, it has been used to process the probe signals. A wide range of applications have used wavelet transforms for feature extraction and pattern recognition including fault classification in power systems, rotating machinery, speech recognition and many more [6, 7, 8].

Wavelet transform expands the signal using basis functions called 'waves' as Fourier transform does using sine and cosine functions [9]. Wavelet analysis uses the multi-resolution analysis technique to analyse a signal by decomposing it into different frequency bands. The discrete wavelet transform (DWT) uses a complimentary pair of low pass and high pass filter banks. The output of high pass filters is called 'details' and the low pass as 'approximations'. The low pass filter output is further fed to a pair of filters to decompose the signal into next level of low and high frequency components. At each level, the numbers of samples are half of that at its previous level. This process can be expanded depending on the required resolution [10]. Fig. 5 shows the decomposition of a signal x(k) to 3 levels.

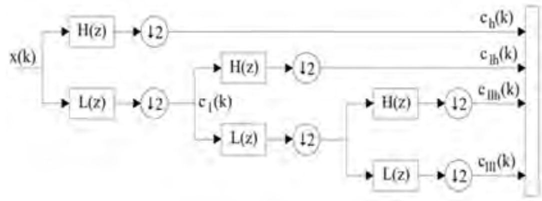

Fig. 5. Decomposition of signal to 3 levels. [9]

A set of signals for different machine settings by varying the beam current and focus settings were analysed by using wavelet transform. By using the co-efficients of each level of decomposition an enormous number of features can be derived to represent the signal. It has been seen that the energy distribution among decomposition levels was able to represent the beams with different characteristics [11]. The study was extended to correlate these features with the weld quality.

Experimental work

To correlate the weld quality parameters with the features extracted from the wavelet analysis, melt runs were conducted on 8mm thick titanium plates for 5mm partial penetration welds for five beam current and five focus settings. The range of beam currents used was from 7 mA to 9 mA at an interval of 0.5 mA which was determined by earlier experimentation. Focus settings were chosen one at sharp focus, two over-focused and two under-focused at an interval of 10% of the sharp focus setting. For each setting, before carrying out the melt run, the probe was moved to the free fall position of the beam to capture its characteristics. Also, each time the position of the probe with respect to the beam was verified by measuring the time difference between signals 'b' and 'd' as described earlier.

The probe signals were acquired at a sampling rate of 1GHz. From the complete probe signal, 'b' and 'd' signals were extracted and processed using wavelet analysis. Using 'dB3' basis function, the signal was decomposed into 11 decomposition levels representing the frequency bands given in table 1. A11 represents the last approximation level.

Table 1

Frequency ranges for decomposition levels.

Decomposition level	*Frequency band (in MHz)*
d1	250 – 500
d2	125 – 250
d3	62.5 – 125
d4	31.25 – 62.5
d5	15.62 – 31.25
d6	7.81 – 15.62
d7	3.9 – 7.81
d8	1.95 – 3.9
d9	0.977 – 1.95
d10	0.488 – 0.977
d11	0.244 – 0.488
A11	0 - 0.244

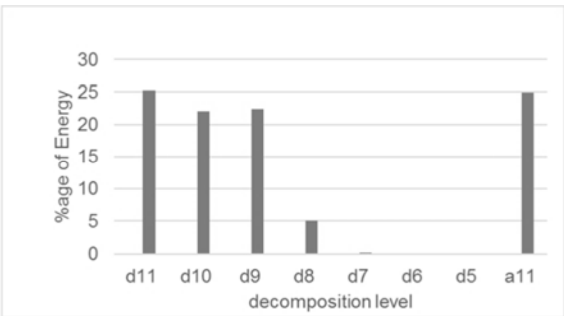

Fig. 6. Distribution of energy among decomposition levels. (Reproduced by permission of TWI Ltd.)

On decomposition, it was observed that the major component of energy was distributed among detailed levels d8-d11 and a11 whereas the levels d1- d7 were having negligible portion of the energy. For a typical signal the distribution of energy among different decomposition levels is shown in figure 6. Hence, only the levels d8 to d11 and a11 were used in as features for characterizing the beam.

As the study was focused on welding of aero-engine components, the welds were examined against the specifications suggested by a typical aerospace standard BS EN 13919-1:1997 [12]. According to the standard, the allowed variation in weld penetration is 15% of the weld depth or 0.5 mm whichever is smaller. To assess the weld profiles, these were micro-sectioned. To correlate the weld data with the beam characteristics derived from wavelet analysis, a data driven approach was used where the experimental data was used for pattern recognition and classification.

Based on the penetration depths, the welds were classified into three categories; class1 (welds within tolerance limits), class0 (welds with lesser penetration than the lower limit) and class2 (welds with penetration depth more than the upper limit). These categories along with their associated features vectors were used as training data for a classifier based on linear discriminant analysis which was able to distinguish between different weld qualities based on the features vector as input.

The performance of the method was assessed by the classification rate of the classifier. By using the total energy of the signal and the energy levels in different decomposition levels, a classification rate of 89.8% was achieved. A comparison study was also carried out to evaluate the significance of the wavelet analysis where the similar analysis was carried out by using the peak intensity and full width half maximum pulse width parameters of the signal as used in the earlier work [4]. With these two parameters, the classifier resulted in 78% of classification rate. It clearly showed that wavelet analysis was able to enhance the accuracy in characterising the beam and correlating with the weld quality.

Conclusions

The present paper has discussed the design of an inverted two-slit probe and its use in characterising the electron beams. Through the experimental work, the capability of the device for better alignment of the probe in the chamber is demonstrated. The signals acquired from the probe were processed to decompose into different frequency bands by using the wavelet transform and energy distribution among these frequency bands was used to characterise and differentiate between different beams. The correlation of the characterising parameters with the weld quality was carried out by the classification method. The results achieved has proven the significance of the wavelet analysis in enhancing the accuracies in characterising the beams and correlating with the weld quality. For the present work, weld penetration depth has been used as one of the parameters defining the weld quality which can be extended for analysis of other parameters.

Acknowledgements

This work has been supported by The Welding Institute (TWI), UK and Brunel University London, UK as part of a PhD programme.

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Aman Kaur *graduated from TIET, Patiala, India with a Master's degree in Instrumentation & Control Engineering. She is currently pursuing PhD at Brunel University London and TWI, Cambridge, UK. Her research interests include application of signal processing techniques for characterization and diagnosis of electron beams for various applications, design and development of data acquisition systems, embedded hardware and software for real-time control applications.*

Tel.: +44 (1223) 899000;

e-mail: Aman.Kaur@brunel.ac.uk.

Colin Ribton *- CPhys, CEng, MInstP, MWeldI graduated from The University of Nottingham with a joint honours degree in Pure and Applied Physics.*

His roles at TWI have involved him in the computer modelling of electron optics and high voltage components, the design of high voltage power supplies, the design and optimisation of radiation shielding, real-time control system architecture, and the design of digital and analogue electronics. In particular, he has been involved in the development of equipment and processes to manufacture major components in power generation, nuclear, aerospace and medical applications. He is presently a Technology Consultant in the EB group where he is active in promoting EB technology for new applications

Tel.: +44 (0) 1223 899000;

e-mail: colin.ribton@twi.co.uk

Prof. Wamadeva Balachandran *- He is Professor of Electronic Systems and served as Head of Department of Systems Engineering at Brunel University London, UK, from 1999 to 2004. Before joining Brunel University London in 1995, he was a Reader in the Department of Electronics & Electrical Engineering at the University of Surrey, UK. He received his MSc and PhD degrees in Control Engineering and Measurement & Instrumentation from University of Bradford, UK, in 1975 and 1979 respectively. His research interest spans several different disciplines: Electrostatics & Charge Particle Dynamics, Electrohydrodynamics, Micro/Nano particles and fibre generation, Transport of DNA using DEP force, Lab-on-a-chip, Electromagnetic Field Sensing, EM Interaction with Human Body, Dynamic Measurement Systems, Global Positioning Satellite System for Navigation and Medical Electronics. He has actively pursued research in these fields for more than 20 years and published over 200 papers to date and filed 10 patent applications.*

Tel.: +44 (0)1895 265774;

e-mail: wamadeva.balachandran@brunel.ac.uk