Transdisciplinary Engineering: A Paradigm Shift
C. Chen et al. (Eds.)

doi:10.3233/978-1-61499-779-5-555

Developing a Cost Model for Aerospace Laser Beam Welding Technology

Estela Balfagon MONSERRATE[a] , Essam SHEHAB[b,1], Shoaib SARFRAZ[b] and Phani CHINCHAPATNAM[a]
[a] *Cost and Value Engineering, Rolls-Royce plc., UK*
[b] *Manufacturing Department, School of Aerospace, Transport and Manufacturing, Cranfield University, UK*

Abstract. A significant proportion of the total unit cost of the product is authorized at the early stage of design phase. Therefore, integrating the capabilities of the manufacturing process into a cost model will lead to optimizing the product design, estimating its cost and attaining a cost reduction from it. Due to the advantages of low cost and greater productivity, Laser Beam Welding (LBW) has been employed as a key process in aerospace industry to manufacture components of gas turbine. This study aims to develop a manufacturing process cost model by collecting and analysing the LBW manufacturing data. The developed model will aid the aerospace industry to estimate the cost of product during early design stage. Detailed statistical analysis of past data was done to develop the LBW cost model which was further validated with several weld inspections to assure the conformity of total unit time and unit cost estimation. LBW cost model will guide the designers to make suitable design at the early design stage which will also be useful in reducing the manufacturing cost of the product and consequently, provide a competitive advantage to aerospace industry.

Keywords. Laser beam welding, aerospace industry, cost model, manufacturing process capability, design parameters

Introduction

Aerospace industry is being recently challenged by the development of advanced manufacturing processes. In order to overcome the intense competition in the changing market of today, most aircraft manufacturing companies struggle to apply innovative methods, technologies and systems to achieve a competitive unit cost from design to manufacturing stages.

Most of the product cost is determined at the design stages during aircraft development. Leading aircraft companies have a necessity to develop methods and tools to integrate and estimate cost in the design phase in order to ensure that advanced manufacturing processes can meet the expected specifications. Hence, modelling cost of manufacturing processes will lead to optimise product design at early stages providing decision support regarding cost and manufacturing process capabilities.

Welding Technology is a key for the manufacturing process of gas turbine components. Aerospace industry is emphasising the development of cost estimation methods as an on-going practice to predict costs aiding complex business decisions at early design stages of product development. Due to its recent application to the aerospace sector and its broad range of manufacturing capabilities involved in the

[1] Corresponding Author, Mail: e.shehab@cranfield.ac.uk.

process, there is a lack of cost modelling in LBW. Therefore, the main motivation for this research is to bridge the existing gap between design and production phase by integrating manufacturing process capabilities required for the application of LBW into a cost model.

As a matter of fact, being able to model the total unit cost of a product welded by LBW will contribute to achieve process optimization and a reduction of the total cost of the aircraft engine. Moreover, a cost model for LBW would be used to guide product development from design to manufacturing stages. Especially considering that in the aircraft industry, 70% of the production cost of a product is determined during the design phase [1]. Therefore, this project aims to develop knowledge about LBW between the design and manufacturing phases of gas turbine components.

1. Background

Laser beam welding (LBW) is a fusion welding technique which is used to join multiple parts by the application of a concentrated beam of light into the material surface. That interaction produces heat which is sufficient to melt or even vaporize the material and join it from the component being melted [2]. LBW provides operation cost savings due to reduced mass of material used for creating the weld, high grade of automation and reduced manufacturing steps such as preheat or post weld heat treatment which may be eliminated [3]. Moreover, there is a corrosion resistance improvement in this technique due to elimination of risk from rivet holes and absence of gaps with this sort of weld [4].

Comparing with other welding techniques, laser beam welding process obtains more advantages from high power density and welding speed. Small Heat Affected Zone (HAZ) and low distortion are both advantages since the volume occupied by the weld is much smaller than for other techniques producing very narrow, deep penetration welds [5]. In that regard, high joint strength and high production rate are achieved with this technique due to the good accessibility and high process flexibility.

On the other hand, laser beam welding process has barriers and disadvantages when it is implemented in the industry. It has a high capital cost due to the technology used. Hence, there is need to develop a model to evaluate the cost of this process so that necessary measures can be made to control the cost of welded products. Cost modelling systems are cost estimation systems which are capable of optimising the manufacturing cost [6].

Shehab and Abdalla [7] explain cost estimation as a methodology that forecasts the cost related to activities before their physically execution. In the nutshell, cost estimation will be understood as an approach that forecasts and quantifies the manufacturing cost of a product before the production phase. Niazi et al. [8] categorised the cost estimation methods into qualitative and quantitative methods. Qualitative methods are applicable at the early stage of product design and for a rough estimate since a limited amount of data is available in this stage, whereas quantitative methods are suitable for detailed estimation because of the large amount of data available. According to Masmouidi et al. [9], the welding manufacturing process is suited for parametric cost estimation technique. On the other hand, Chayoukhi et al. [10] have considered analytical cost estimation technique such as feature-based approach, the suited technique to estimate the manufacturing cost of the process.

It is observed that little or no effort has been found regarding any cost model or cost estimation technique for this LBW manufacturing process. Hence, a necessity to calculate its cost on a welded product is required in order to achieve competitiveness in today's aerospace market.

2. Research Methodology

Research methodology consists of five phases as shown in Figure 1. The starting point of this project is to understand and define properly the project aim, objectives and scope. Afterwards, the "Literature Review" stage comprehended a deep research in different fields (laser beam welding, cost engineering). The third stage is the identification of the design and manufacturing variables. This could enable the researcher to identify the most relevant variables for the model which potentially was the deliverable of this stage. The fourth and fifth phases will be iterative creating a loop of model building and validation until results are aligned with the intended stakeholders' requirements. "Cost Model Development" phase commenced with the creation of a high level process or model structure map to extract and utilize capability information. Afterwards, the statistical cost model selection will depend on the data analysis of the previous phase of it. Finally the cost model will be implemented into Vanguard Studio. Finally during the fifth phase called "Validation", model output data will be analysed and compared with the expected results.

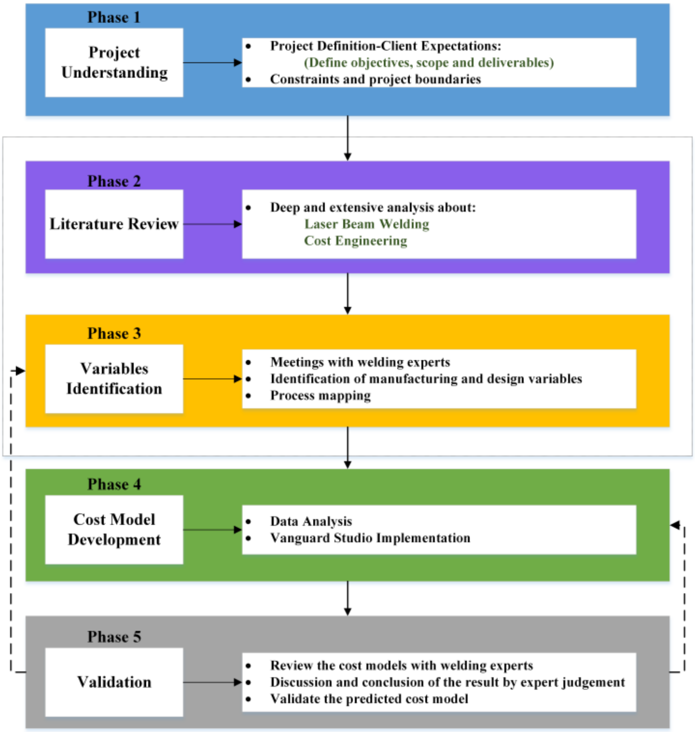

Figure 1. Research methodology.

3. Cost Model Development

LBW cost model has been developed using geometric weld features as inputs and key cost drivers for this manufacturing process. It enables calculation of process operation times and costs for different depth penetrations. Moreover, this model considers two operating modes: Continuous and Pulsed mode. Continuous mode, or also named Continuous wave (CW), stands for continuous wavelength, which means the laser emits a steady beam over a period of time, whilst pulsed mode is when the laser is pumped with short bursts to generate short controlled laser pulses. Generally speaking there are on and off periods to the pulsed laser beam. In that regard, continuous mode is applicable to a broad range of depths of penetration but the pulsed mode is just applicable to depths of penetration smaller than 3 mm.

3.1. Variables Identification

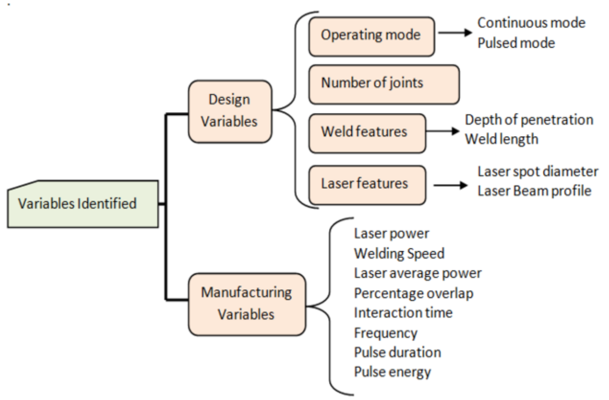

Figure 2. Variables Selected.

The variables involved in LBW process cost model can be divided into two main categories, manufacturing variables, also known as key process variables, and geometry variables or design variables (see Figure 2). The former are related to all the manufacturing parameters such as welding speed, laser power, interaction time, wavelength among other machining parameters. The latter are weld design variables such as depth of penetration, weld quality, type of joint among others, but also the type of operating mode used and number of laser welds on the product. Thus, these geometry variables are closely related with the design stage of the product, in this study High Pressure Intermediate case.

It is understood through literature review that a stable LBW process depends on defining and controlling the process parameters which have a relevant influence on process stability to reliably produce high quality welds at high welding speeds [11]. Hence, the LBW manufacturing parameters and their effects on quality welds have been widely studied during the last years. The suitable parameters were selected by doing a deep research about LBW parameters and relationships among them as well as interviewing welding experts from the industry.

3.2. LBW Process Map

After identifying the main variables, which have an impact on time and cost in the LBW process, an understanding about the essential stages for the LBW process is

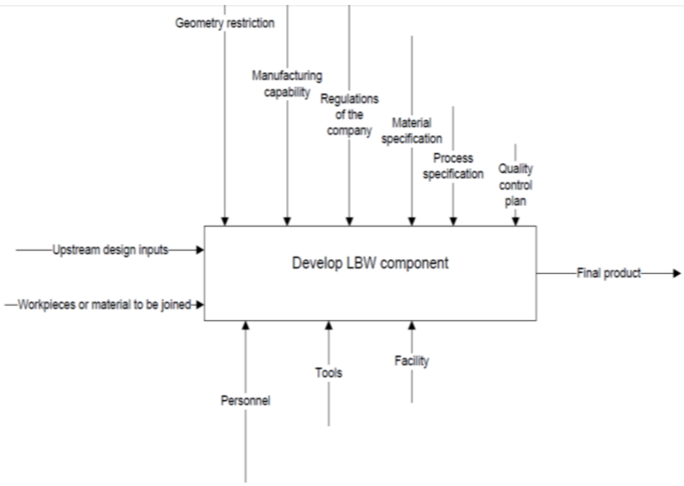

Figure 3. Process map of LBW procedure.

required to take into account every activity in the process and to ease the accuracy estimating the operation process time.

The process map of LBW procedure is shown in Figure 3. According to the process map, a clearer understanding of the LBW procedure was obtained as inputs, outputs, mechanics and controls have been illustrated in the process map. This process map gathers all the information and activities from the design phase to the manufacturing stage.

The main inputs of LBW process include upstream design variables, which have been define previously, and the type of material to be joined but in this case, it will be always titanium since High Pressure Intercases are made of it. The final output will be the welded product.

This procedure is controlled by several restrictions about the manufacturability of the combination of weld design variables in the current production capability and regulation which the aircraft industry follows as well as quality controls. On the other hand, the main mechanisms used are personnel including structure designers, process engineers and welding operators, tools such as computer or design software and facility such as LBW equipment.

3.3. LBW Cost Model

In order to develop the cost estimating tool, Vanguard Studio software was utilised. This software is a numerical modelling tool that uses equations in a similar manner to Microsoft Excel. Hence, Vanguard Studio is a comprehensive business solution to improve reliability on the cost model activities throughout the entire aerospace organisation. This software presents equations as linked boxes called nodes rather than rows and columns of data and it eorks with a hierarchial tree interface. Vanguard studio automatically constructs a visual diagram which is aligned with the logical formulae introduced. Therefore, it is beneficial to tackle complex manufacturing processes as LBW process and that is main reason why this software has been used.

The developed cost model is built up by two main branches, as shown in Figure 4. According to which operating mode is chosen, continuous or pulsed mode, one of those branches will calculate the outputs for the selected operating mode. Both branches follows the same structure to obtain the outputs in terms of cost and time but the inputs which need to be filled in are different because of the dissimilar manufacturing parameters utilised in each operating mode.

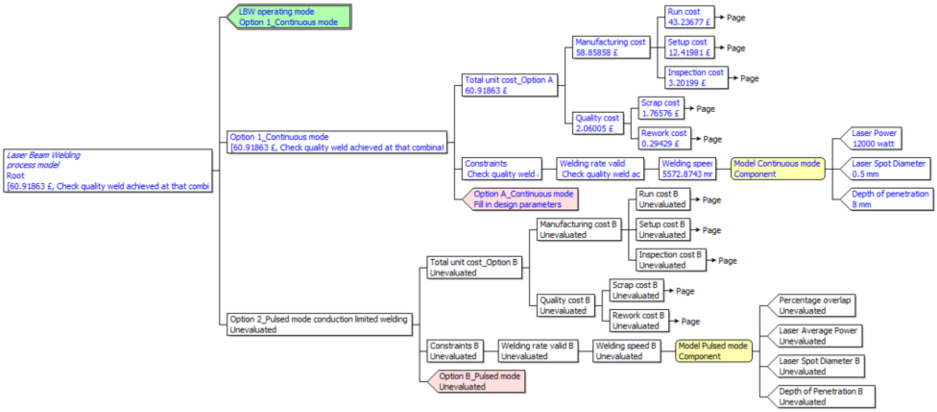

Figure 4. LBW cost model in vanguard studio.

3.3.1. LBW Continuous Cost Model

This model uses data of weld trials as a basis to calculate the welding speed. These weld trials were carried out in order to achieve different depth of penetrations. Due to the data confidentiality, penetration depth have been omitted. This data is illustrated in Table 1.

Table 1. Gathered data of weld trials.

Depth of penetration A		**Depth of penetration B**		**Depth of penetration C**	
Interaction time (ms)	**Power Factor (MW/m)**	**Interaction time(ms)**	**Power Factor (MW/m)**	**Interaction time(ms)**	**Power Factor (MW/m)**
10	5.946129	10	12.89326	10	23.1593
15	4.974555	15	10.78655	15	19.37516
20	4.383098	20	9.504072	20	17.07152
30	3.666916	30	7.951143	30	14.2821
40	3.230933	40	7.00578	40	12.58401
50	2.928785	50	6.35062	50	11.40719
60	2.703011	60	5.861062	60	10.52783
70	2.525755	70	5.47671	70	9.837443
80	2.381633	80	5.164203	80	9.276108
90	2.261349	90	4.903387	90	8.807622
100	2.158909	100	4.681262	100	8.408632
110	2.070244	110	4.489005	110	8.063296
120	1.992483	120	4.320392	120	7.760427

In order to obtain an estimation of the welding speed required for performing the weld with the design features introduced by the user, a graphical representation of both parameters for these three depth of penetrations is depicted in Figure 5 in order to show the relations between interaction time and power factor.

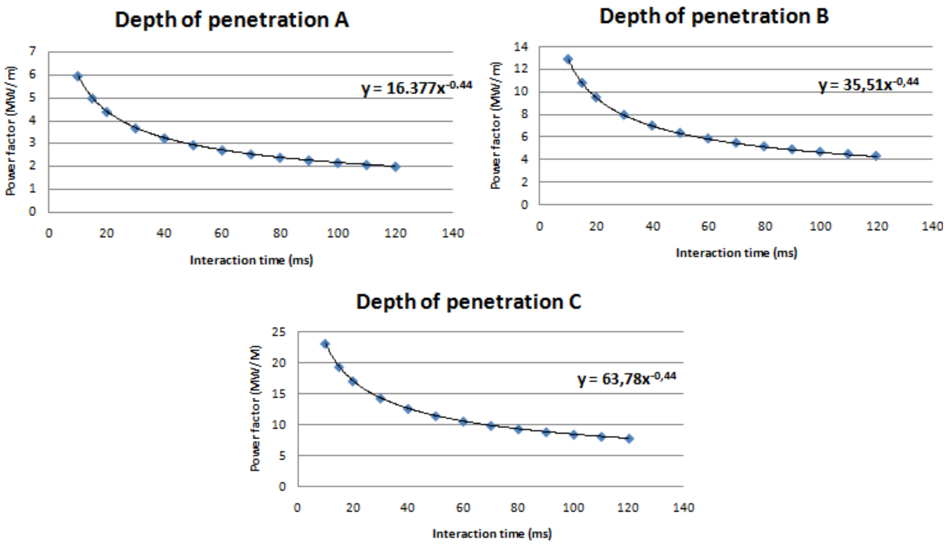

Figure 5. Graphical representation of power factor vs interaction time.

In order to obtain the welding speed for the continuous welding mode, the power factor for the combination of parameters introduced by the user is going to be calculated using Equation 1. Once the power factor (MW/m) is ascertained mathematically, the interaction time for these three depths of penetrations can be obtained using Equation 2.

$$PowerFactor = PowerDensity \times LaserBeamDiameter = \frac{LaserPower}{LaserBeamDiameter} \quad (1)$$

$$InterationTime = \frac{LaserBeamDiameter}{WeldingSpeed} \quad (2)$$

However, the way to proceed will be different since the power factor is the known data and the interaction time is the data the continuous mode model needs to estimate the welding speed. To do so, these equations will be used but interaction time will be the dependent variable also called "y" and the power factor will be the independent also named "x". Hence, the equations used for each depth of penetration have the next expression:

$$y = \frac{x}{\frac{A}{B}^{\frac{-1}{C}}} \quad (3)$$

These equations will provide the interaction time for these three different penetration depths and as welding speed is defined as laser spot diameter divided by interaction time, three values of welding speed will be obtained and a new relationship between welding speed and depth of penetration can be displayed. This relationship will provide an equation which independent variable will be the welding speed and the depth of penetration as dependent variable. Any depth of penetration can be used as an input and an estimation of welding speed will be calculated applying potential regression to that equation.

3.3.2. LBW Pulsed Mode Cost Model

This model uses four inputs from the LBW cost model which are Laser average power, Laser spot diameter, Depth of penetration and Percentage of overlap in order to obtain the appropriate manufacturing parameters such as the welding speed for that combination of parameters. The outputs displayed will be Welding speed in pulsed mode, Frequency which can be defined as the pulse repetition rate, Pulse energy which is the energy produced in each pulse and Pulse duration which is the time duration of each pulse.

In order to obtain the Pulse energy, the model uses a rule of thumb which is considered as relevant and accurate estimation when the depth of penetration is small. It consists in each millimetre of penetration depth requires a joule of energy. The Frequency is estimated by dividing the Laser average power by the Pulse energy obtained previously by using the rule of thumb stated. Additionally, the pulse duration is the inverse of the Frequency. Finally, the Welding speed for the pulsed mode is ascertained mathematically by the following equation:

$$WeldingSpeed = LaserSpotDiamter \times (1 - PercentageofOverlap) \times Frequency \quad (4)$$

4. Validation

The validation of this LBW Cost Model was done mainly by expert judgement. After every result was completed, a validation was carried out in order to meet collaborator company requirements and fit the cost model for purpose. The process followed is illustrated in Figure 6.

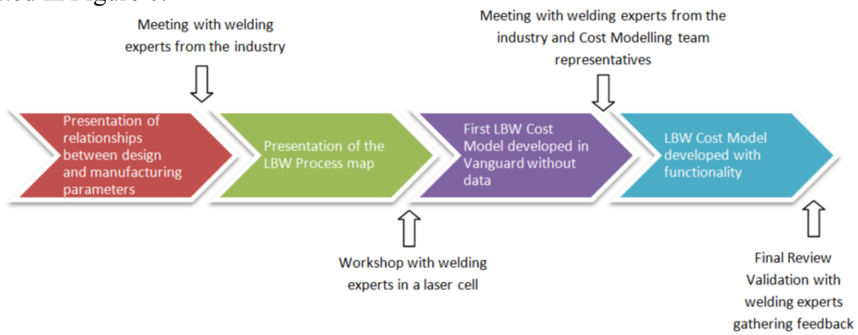

Figure 6. Validation Process.

From the feedback obtained through the different stages in the validation process, these are the main points which should be highlighted as the main strengths of the results achieved:

1. This study will guide designers to understand the feasibility of their combinations of parameters for developing the weld on the product and it will help to achieve a better performance between design and production stages.
2. The process mapping of this process can be used and follow in the aircraft industry since it can be stated as a common practice. It gathers the most

common activities required to manufacture a weld on any product in the aerospace sector.

3. The developed cost model provide an accurate result from early design stage according to the data provided by the collaborator company to build it.

5. Conclusions

In conclusion, this research promotes LBW application in the aerospace industry which is starting to expand its utilisation. Therefore, its application will bring an accurate and high speed process as well as cost reduction to manufacture aircraft engine components. Developed cost model will potentially improve the performance and the interaction between manufacturing and design departments allowing to the designers of the weld features on the product know the weld quality and feasibility of each combination of parameters specified. Hence, this cost model can be used as a basis to help the designing team of the aerospace company to determine the weld features.

The proposed cost model is limited to titanium as material to be joined and some process variables such as beam profile, incident angle and the shielding gas used were assumed and considered constant during the development of the proposed cost model. In future, cost model can be developed for different materials by integrating aforementioned process variables.

Acknowledgements

The authors would like to thank Rolls-Royce for funding this research project. We would also like to express our appreciation to to thank Mr. Steve Beech and Mr. Clive Grafton-Reed for their time, guidelines and data provided to successfully complete this project.

References

[1] E. Shehab, and H. Abdalla, Manufacturing cost modelling for concurrent product development, *Robotics and Computer-Integrated Manufacturing*, 17 (2001), pp. 341-353.

[2] O. Aharon, High power beam analysis, In: *SPIE LASE*, San Francisco, 2014.

[3] D. Farson, and R. Duhamel, Taking advantage of laser welding, *The Fabricator,* 28 (2001), http://www.thefabricator.com/article/automationrobotics/taking-advantage-of-laser-welding.

[4] K. Schneider, and J. Schumacher, Laser technology–a key competitive aspect of modern structural engineering in the civil aviation industry, *Laser Beam Joints, Steel Engineering,* 19 (2002), pp. 5-9.

[5] C. Dawes, *Laser welding: a practical guide*, Woodhead Publishing, Cambridge, 1992.

[6] A. Wasim, et al., An innovative cost modelling system to support lean product and process development, *The International Journal of Advanced Manufacturing Technology,* 65 (2013), pp. 165-181.

[7] E. Shehab and H. Abdalla, An intelligent knowledge-based system for product cost modelling, *The international journal of advanced manufacturing technology,* 19 (2002), pp. 49-65.

[8] A. Niazi et al., Product cost estimation: Technique classification and methodology review, *Journal of manufacturing science and engineering*, 128 (2006), pp. 563-575.

[9] F. Masmoudi, Z. Bouaziz and W. Hachicha, Computer-aided cost estimation of weld operations, *The International Journal of Advanced Manufacturing Technology*, 33 (2007), pp. 298-307.

[10] S. Chayoukhi, Z. Bouaziz and A. Zghal, COSTWELD: a cost estimation system of welding based on the feature model, *Advances in Production Engineering & Management,* 4 (2009), pp. 263-274.

[11] X. Cao, et al., A review of laser welding techniques for magnesium alloys, *Journal of Materials Processing Technology*, 171 (2006), pp. 188-204.