Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0
M. Peruzzini et al. (Eds.)

doi:10.3233/978-1-61499-898-3-611

Towards Cost Modelling for Laser Drilling Process

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Abstract. Laser drilling is a widely used non-traditional machining process, in power generation and high-value manufacturing industries, to produce components such as nozzle guide vanes, combustion chambers, fuel injection nozzles and turbine blades. The operating cost of the drilling process is one of the critical factors for companies to consider to survive in the competitive global market. This research is intended to develop the cost model for laser drilling process due to its extensive application in the aerospace sector. Cost estimation facilitates the aerospace sector economically through the identification of critical parameters which act as key cost drivers and their relationship with cost. The proposed model will benefit the designers and cost engineers to have a brief overlook of cost distribution before manufacturing the component.

Keywords. Laser drilling, process capability, cost modelling, cost driver

Introduction

In this modern-challenging industrial environment, a cost-effective solution is essential along with the expected performance and quality of the product. Cost plays an important role in countless industrial processes. It also has a significant influence on product outcome due to the advanced technological environment. The recent advancement in manufacturing technology and increased insistence of a market for the quick response, enforce the need for a model for acquiring accurate cost calculation results.

Laser drilling, an unconventional machining process, has widespread use in modern industries including the automotive, aerospace and electronics sectors due to the excellent characteristics of high speed, accuracy and flexibility [1–5]. It is broadly used to produce numerous holes of various sizes (0.25 – 1.0 m) in aeroengine components [6]. These holes provide the function of cooling for the hot section components (such as combustion chamber, turbine blade, afterburner, etc.) and are usually known as cooling holes. Advancements in aeroengine efficiency have promoted the enhancement of exhaust gases and combustion temperature which, on the other hand, needs supplementary cooling of components to sustain such elevated temperature. Consequently, the number of cooling holes have increased enormously and this figure

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is expected to reach 150,000 in the near future [7,8]. It needs to improve the productivity at the same time reducing the cost of manufacturing, which is also the primary concern of industries. Therefore, a comprehensive analysis of laser drilling technology and the associated costs is important. Cost estimation model assists the companies in providing the complete costs information related to the laser drilling process.

1. Literature Review

Laser drilling is one of the prime techniques to drill holes of various shapes and sizes. Due to high level of precision and no direct contact with the material surface, it is used for the machining of high-strength and high-temperature resistant metals and alloys. This technique is much better than the other manufacturing processes especially when drilling of aerospace components is considered [9]. Schematic diagram of laser drilling process is shown in Figure 1. The surface of workpiece is initially melted by using a powerful laser beam; the (melted) particles are then flushed out with the aid of assisted gas poured with high pressure. Melting, vaporisation and melt ejection are the different stages involved in material removal process during laser drilling. When a laser beam is focused on the workpiece surface, the thermal energy transforms the material volume into vapourised or molten state that can be removed easily using the assist gas with high pressure.

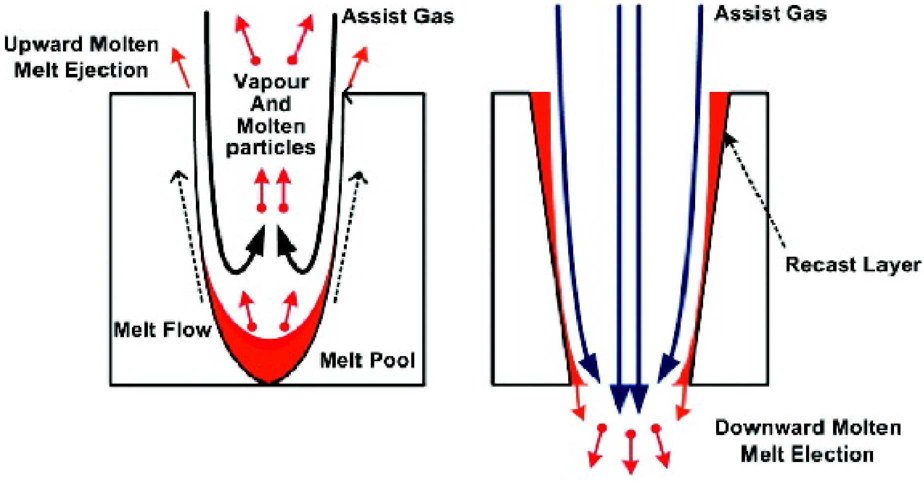

Figure 1. Schematic diagram of laser drilling process [10].

Global competition has originated the necessity for organisations to improve product flexibility, novelty, quality and variety while persistently reducing the manufacturing costs of products to survive in the competitive environment. Laser hole drilling has emerging applications in automotive and aerospace sectors, where this process is involved in large volume production of holes on a daily basis. Moreover, the increase in demand for laser drilling process highlights the need for high speed and high-quality process with minimum possible cost. Cost modelling is an effective method to help the designers in selecting suitable means of manufacturing from an economic perspective.

A major portion (70%) of the product cost is committed in the conceptual design phase of a product [11], and it is necessary for the product design and development team to consider this phase critically and put some particular measures to avoid mistakes and unexpected circumstances that could hinder the successful manufacturing of a commodity. The manufacturing cost of a product can be estimated easily during the design phase only if the product designer is provided with the capability of cost estimation. Various researchers have developed cost estimation systems for different manufacturing processes to provide an insight of overall manufacturing cost for that process. Shehab and Abdalla [11] developed an intelligent prototype system which facilitates the inexperienced persons to evaluate the product cost at the beginning of product design stage. One of the key advantages of this system is that it warns users about the features that are expensive and hard to manufacture. However, it was only done for milling and drilling processes. Cost modelling system of machining (EDM, milling, drilling, boring) and injection moulding components was specified by Shehab and Abdalla [12]. Using the proposed (intelligent knowledge-based) system, longer lead time along with redesign cost can be eliminated at the beginning of design stage. Furthermore, a combination of algorithmic, heuristic and fuzzy logic approach was devised [13]. Alternate processes and materials can be explored with the help of developed system which will also permit users to yield precise cost estimates for advanced designs. Cost estimation system, developed by Jung [14], can be utilised by design department (designers) to get appropriate cost information at the prior design stage. However, this system was established only for machined components: whose features were listed into four categories (slab, rotational, prismatic and revolving).

Wasim et al. [15] proposed a cost model for resistance spot welding comprehending three enablers of lean product and process development (Poka Yoke, set-based concurrent engineering and knowledge-based engineering). The developed model enables the users to evaluate the product cost and the values associated simultaneously, simplify decision making whilst eliminating weak alternate solutions, eradicate errors in the design stage and integrate the customer voice into product design and development stage. Different welding processes were also compared by Chayoukhi et al. [16] and Masmoudi et al. [17] to develop the cost estimation system. Urso et al. [18] presented the first cost model to anticipate the manufacturing cost for micromachining (μ-EDM) process while incorporating workpiece, production and tooling information. A cost model, for aerospace (Carbon Fibre Reinforced Plastic) composites, including the cost of quality inspection was developed by Shehab et al. [19] The proposed model assists the designers in estimating the cost of manufacturing at initial development stages seeing that the major portion of manufacturing cost is committed to product design phase.

A comprehensive literature review has been conducted, highlighting the efforts made by researchers in the area of cost modelling for different manufacturing processes. From the ongoing studies, it can be observed that there exists limited or no research on cost modelling for laser drilling process. Therefore, the main objective of this study is to develop a cost model to provide an accurate cost information related to laser drilling process.

2. Development of Cost Estimation Model

One of the primary tasks of cost estimation is to develop a Work Breakdown Structure (WBS). The main objective of WBS is to deliver a uniform structure that incorporates all the elements of the project that will be reported by the cost estimate, where each element depicts the cost to accomplish that project (work). When a WBS involves all the cost information, it may serve directly as a cost breakdown structure [20]. The operating cost breakdown structure of laser drilling is shown in Figure 2.

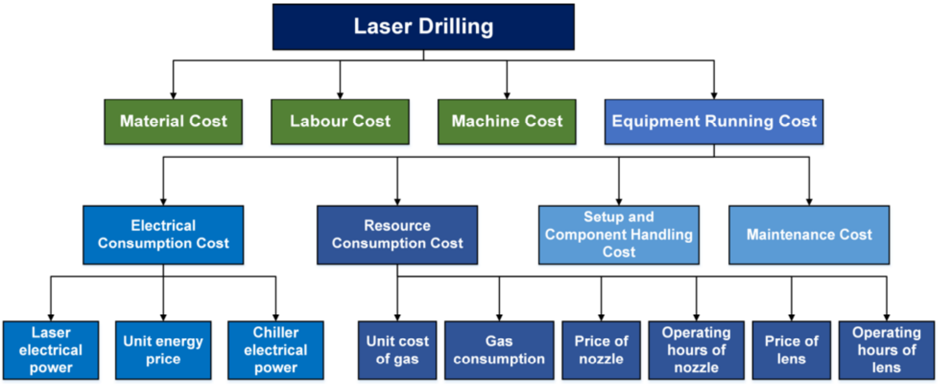

Figure 2. Cost breakdown structure for laser drilling process.

2.1. Cost Drivers

To develop a cost model, it is necessary to identify the cost drivers (those factors which affect the cost most significantly). The main cost drivers associated with the laser drilling process have been identified through literature review and some experts' opinion (see Table 1). Equipment running cost, material cost, labour cost and machine cost are the important cost drivers in laser drilling cost estimation. After a detailed study, it was found that equipment running cost further consists of electrical (power) consumption, component handling and resource consumption (gas, coolant, lens, nozzle, etc.) costs. Once all the cost drivers are finalised, the cost is assigned to each driver.

Table 1. Cost drivers for laser drilling process.

Cost drivers	**(Ion, 2005)**	**(Williams, 2004)**	**(Dahotre and Harimkumar, 2008)**	**(Williams, Wescot and Price, 2017)**
Equipment running cost	Electrical consumption cost	Electricity cost	Equipment cost	Equipment cost (beam delivery and motion system)
	Gas consumption cost	Water usage cost		
	Cavity mirrors (lense) cost	Replicable components (nozzle, lense)		
		Component handling		

Cost drivers	(Ion, 2005)	(Williams, 2004)	(Dahotre and Harimkumar, 2008)	(Williams, Wescot and Price, 2017)
		Robot movement		
Material	Material cost		Material cost	
Labour	Labour (laser operators and engineers) cost	Labour (operator) cost	Labour cost	

2.1.1. Material Cost

The cost of material (Cmat) for laser drilling can be estimated as follows [9]:

$$C_{mat} = W_m \times C_w \tag{1}$$

$$W_m = V_{comp} \times \rho \tag{2}$$

Where:
W_m = weight of material (kg)
C_w = unit price (£/kg)
V_{comp} = volume of component (mm^3), and
ρ = density of material used (kg/mm^3)

2.1.2. Labour Cost

The labour cost is a function of unit labour cost multiplied by the time needed to accomplish the process. The following equation can be used to calculate the labour cost [18].

$$C_{lab} = L_c \times \sum_{i=1}^{n} Lb_i \times T_i \tag{3}$$

Where:
C_{lab} = total cost of labour (£)
L_c = labour charges per hour (£/hr)
Lb_i = number of labours for ith operation, and
T_i = process time for ith operation (sec)

2.1.3. Machine Cost

This component depends on the capital cost of equipment, machine overhead and depreciation rate. The depreciation rate of machine can be determined based on amortisation duration, working hours per day and production days per year. Machine overhead comprises of the cost of factory floor space used and the cost of lighting/HVAC. Its value is to be estimated about 30% of the depreciation rate. The machine cost (C_{mac}) is given as:

$$C_{mac} = 1.3\left(\frac{C_{eq}}{P_{am} \times P_h \times P_d}\right) \times T_{drill} \tag{4}$$

Where:
C_{eq} = cost of equipment (£)
P_{am} = period of amortisation (years)
P_h = production hours per day (hr)
P_d = production days per year (days)
T_{drill} = drilling time (sec)

2.1.4. Electrical Consumption Cost

During a machining process, electricity (energy) is consumed to machine the components. The electricity consumption depends upon machining time, machine power and efficiency of a machine [21]. Eq. 4 can be used to estimate the electricity cost of laser drilling machine.

$$C_e = C_{power} \times \frac{P_m}{\eta_m \times 3600} \times T_{drill} \tag{5}$$

Where:
C_e = electricity consumption cost (£)
C_{power} = unit energy price (£/KWh)
P_m = machine power (KW), and
η_m = efficiency of the machine

2.1.5. Resource Consumption Cost

Different resources are consumed while the equipment is running. Some resources are consumed instantly, and their cost can be calculated by simply multiplying unit cost with the consumption rate (e.g. gas, coolant); while some of the resources have a useful life and it is necessary to determine the expected operating time to proceed with cost estimation (e.g. lens, nozzle). The resource consumption cost of laser drilling machine can be found by using the following equation.

$$C_{res} = ((C_{gas} \times Cons_{gas}) + \left(\frac{C_{nozz}}{T_{op-nozz}}\right) + \left(\frac{C_{lens}}{T_{op-lens}}\right)) \times T_{drill} \tag{6}$$

Where:
C_{res} = cost of resources used (£)
C_{gas} = unit cost of gas (£/litre)
$Cons_{gas}$ = gas consumption (litre/hr)
C_{nozz} = price of nozzle (£)
$T_{op\text{-}nozz}$ = (expected) operating hours of nozzle (hr)
C_{lens} = price of lens (£), and
$T_{op\text{-}lens}$ = (expected) operating hours of lense (hr)
n = number of laser drilled holes

2.1.6. Setup and Component Handling Cost

Setup and component handling costs and times are important when mass production is considered. It involves the times needed to setup the CNC programming and adjusting the tooling. Equation (3) can be used to calculate the setup and component handling cost. A schematic diagram of complete Nd:YAG laser drilling system is provided in Figure 3 to have a brief overlook of the components involved in laser drilling setup.

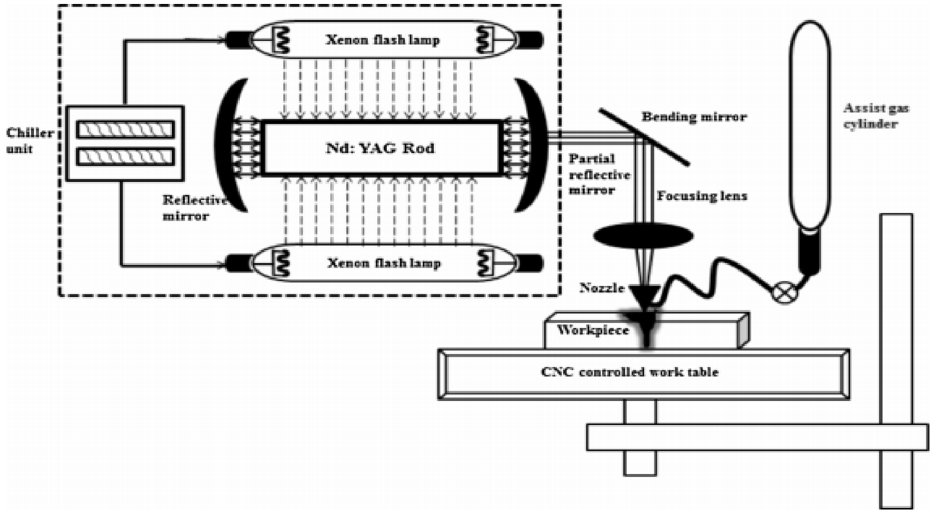

Figure 3. Schematic diagram of Nd:YAG laser drilling system [5].

2.1.7. Maintenance Cost

This component consists of routine maintenance cost which depends on the equipment maintenance time and the expected available operating time of machine before breakdown. The following expression represents the equipment maintenance cost (C_{main}).

$$C_{main} = C_{lab-main} \times \frac{T_{main}}{T_{mac-work}} \quad (7)$$

Where:
$C_{lab-main}$ = cost of labour for maintenance (£/hr)
T_{main} = maintenance time (hr)
$T_{mac-work}$ = (expected) available working time of machine before breakdown (hr)

3. Conclusion and Future Work

High-value manufacturing industries are continually adapting to produce high-quality products but the action is still needed to reduce the capital and operating costs to overcome the competition. This research work is an attempt towards the development of a cost model for laser drilling process. All the key process cost drivers have been identified through literature review and experts' opinion. This work will be integrated, in future, into a comprehensive cost model for laser drilling production of holes which will assist the companies in proving the complete cost information related to laser drilling process. Further work will be carried out to conduct case studies for different materials and processing conditions, and finally to develop the mentioned cost model. Additional efforts should be made to validate the findings.

Acknowledgement

The authors would like to thank The Punjab Educational Endowment Fund (PEEF, Pakistan) and Cranfield University (United Kingdom) for funding this research project.

References

[1] A.K. Dubey and V. Yadava, Laser beam machining-A review, *International Journal of Machine Tools and Manufacture,* Vol. 48, 2008, pp. 609-628.
[2] J. Meijer, Laser beam machining (LBM), state of the art and new opportunities, *Journal of Materials Processing Technology,* Vol. 149, 2004, pp. 2-17.
[3] W. Schulz, U. Eppelt and R. Poprawe, Review on laser drilling I. Fundamentals, modeling, and simulation, *Journal of Laser Applications,* Vol. 25, 2013, pp. 012006.
[4] C.Y. Yeo, S.C. Tam, S. Jana and M.W. Lau, A technical review of the laser drilling of aerospace materials, *Journal of Materials Processing Technology,* Vol. 42, 1994, pp. 15-49.
[5] G.D. Gautam and A.K. Pandey, Pulsed Nd:YAG laser beam drilling: A review, *Optics and Laser Technology,* Vol. 100, 2018, pp. 183-215.
[6] C.A. McNally, J. Folkes and I.R. Pashby, Laser drilling of cooling holes in aeroengines: state of the art and future challenges, *Material science and technology,* Vol. 20, 2004, pp. 805-813.
[7] M. Antar, D. Chantzis, S. Marimuthu and P. Hayward, High speed EDM and laser drilling of aerospace alloys, In: *18th CIRP Conference on Electro Physical and Chemical Machining,* Tokyo, 2016, pp. 526-531.
[8] S. Sarfraz, E. Shehab and K. Salonitis, A review of technical challenges of laser drilling process, In J. Gao et al (Eds.) : *Advances in Manufacturing Technology,* Vol. 6, 2017, pp. 51-56.
[9] T. J. Rockstroh, D. Scheidt and C. Ash, Advances in laser drilling of turbine airfoils, *Industrial Laser Solutions for Manufacturing*, Vol. 17, 2002, pp. 15–21.
[10] Z. Y. Li, X. T. Wei, Y. B. Guo and M. P. Sealy, State-of-art, challenges, and outlook on manufacturing of cooling Holes for turbine blades, *Machining Science and Technology*, Vol. 19, 2015, pp. 361–399.
[11] E.M. Shehab and H.S. Abdalla, Manufacturing cost modelling for concurrent product development, *Robotics and Computer-Integrated Manufacturing,* Vol. 17, 2001, pp. 341-353.
[12] E. Shehab and H. Abdalla, An intelligent knowledge-based system for product cost modelling, *The International Journal of Advanced Manufacturing Technology,* Vol. 19, 2002, pp. 49-65.
[13] E.M. Shehab and H.S. Abdalla, A design to cost system for innovative product development, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* Vol. 216, 2002, pp. 999-1019.
[14] J.Y. Jung, Manufacturing cost estimation for machined parts based on manufacturing features, *Journal of Intelligent Manufacturing,* Vol. 13, 2002, pp. 227-238.
[15] A. Wasim, E. Shehab, H. Abdalla, A.Al.-Ashaab, R. Sulowski and R. Alam, An innovative cost modelling system to support lean product and process development, *The International Journal of Advanced Manufacturing Technology,* Vol. 65, 2013, pp. 165-181.
[16] S. Chayoukhi, Z. Bouaziz and A. Zghal, Costweld: a cost estimation system of welding based on the feature model, *Advances in Production Engineering and Management,* Vol. 4, 2009, pp. 263-274.
[17] F. Masmoudi, Z. Bouaziz and W. Hachicha, Computer-aided cost estimation of weld operations, *The International Journal of Advanced Manufacturing Technology,* Vol. 33, 2007, pp. 298-307.
[18] G.D.-Urso, M. Quarto and C. Ravasio, A model to predict manufacturing cost for micro-EDM drilling, *The International Journal of Advanced Manufacturing Technology,* Vol. 91, 2017, pp. 2843-2853.
[19] E. Shehab, W. Ma and A. Wasim, Manufacturing cost modelling for aerospace composite applications, In J. Stjepandic et al. (eds.): *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment*, Springer, London, 2013, pp. 425-433.
[20] NASA, *Cost Estimating Handbook*, NASA, Washington, DC, 2008.
[21] I. Masood, M. Jahanzaib and A. Haider, Tool wear and cost evaluation of face milling grade 5 titanium alloy for sustainable machining, *Advances in Production Engineering and Management,* Vol. 11, 2016, pp. 239-250.

2018-12-31

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Sarfraz S, Shehab E, Salonitis K, et al., (2018) Towards cost modelling for laser drilling process. In:Proceedings of the 25th ISPE Inc. International Conference on Transdisciplinary Engineering, 3-6 July 2018, Modena, Italy. Advances in Transdisciplinary Engineering: Volume 7: Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0

https:doi.org/ 10.3233/978-1-61499-898-3-611