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E-design tools for friction stir welding: cost estimation tool

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E-DESIGN TOOLS FOR FRICTION STIR WELDING: COST ESTIMATION TOOL

by

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ABSTRACT

A cost model is an important tool for product design and material selection. An efficient and effective cost estimation tool is necessary for early design evaluation. In this paper, cost estimation models that estimate the production cost for Metal Inert Gas (MIG), Friction Stir (FS), and Friction Stir Spot (FSS) welded joints are presented. These models determine the cost incurred to fabricate each joint along with a detailed explanation of each cost component. Each cost component has been closely analyzed and major cost components have been included in the cost model. We used these cost models to predict the cost of 42 different MIG welded joints, 16 FS and two FSS welded joints. The results predicted by the MIG welding cost model have been compared to those quoted by an expert welder. Initial results show that the cost model and the expert cost estimates follow a similar general trend. Further study is needed to refine and validate the FS and FSS cost models.

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ABSTRACT

A cost model is an important tool for product design and material selection. An efficient and effective cost estimation tool is necessary for early design evaluation. In this paper, cost estimation models that estimate the production cost for Metal Inert Gas (MIG), Friction Stir (FS), and Friction Stir Spot (FSS) welded joints are presented. These models determine the cost incurred to fabricate each joint along with a detailed explanation of each cost component. Each cost component has been closely analyzed and major cost components have been included in the cost model. We used these cost models to predict the cost of 42 different MIG welded joints, 16 FS and two FSS welded joints. The results predicted by the MIG welding cost model have been compared to those quoted by an expert welder. Initial results show that the cost model and the expert cost estimates follow a similar general trend. Further study is needed to refine and validate the FS and FSS cost models.

Keywords

MIG welding, Fiction Stir welding, Friction Stir Spot welding, Cost model.

INTRODUCTION

According to Gallagher [1], "cost estimation is a task of calculating and projecting of costs of men (people), materials, methods and management". Malstrom [2] stated that the accuracy of a project or task estimation depends mainly on two parameters:

(1) extent of information available about a project at the time of estimation

(2) amount of time available for estimation.

A good cost estimation process has to deal with the problems related to cost overestimation and underestimation. As a result, the cost model accuracy is very important as it directly impacts a business unit's performance.

Cost estimation is the prediction of the expected amount of cost to be incurred by producing a product, while cost accounting or costing is the actual value of cost incurred after production [2]. Cost parameters or cost components (CC) involved in these methods are similar, but the main difference lies in the pre-production and post-production calculations. Cost accounting leads to accurate values while cost estimation is a prediction that helps in product design, material selection, decision making, and identifying potential avenues for cost reductions. Studies reveal that cost estimation for a manufacturing function is more complicated and tedious than design and development of products [2]. Cost estimation for a manufacturing function requires basic background knowledge of the production process in order to avoid false assessment [2].

Cost estimating relationships, costing systems, and cost databases aid in determining the cost incurred in manufacturing processes. Cost estimates, in turn, help to target the potential areas for cost reduction and could be used to explore the economic feasibility of alternate manufacturing technologies. At present, many competing metal joining processes exist and the designer is often interested in finding the joint cost using a specific welding method. This paper presents a substantial research effort to develop cost models for MIG, FSW, and FSSW processes. These models are developed to estimate the cost incurred in the above mentioned welding processes and thereby examine the economic feasibility of the friction stir welded joints versus the MIG welded joints.

MIG welding, also known as Gas Metal Arc Welding (GMAW) is a process of joining metals using an electric arc established between a consumable electrode and a workpiece [22]. The consumable bare wire electrode is fed continuously through the welding gun operated either manually or automatically. At present MIG welding is a well established joining process in many manufacturing industries such as the automobile and ship building industries. Many companies use manual and automatic MIG welding for their low and high production applications. Higher deposition rates, relatively shorter cycle times, fewer slag inclusions, and higher weld quality are a few advantages of MIG welding over other joining applications. MIG welding was originally developed for aluminum and other non-ferrous applications, but later found applicability in welding steels [22].

FSW is a relatively new solid state joining process developed in 1991 by The Welding Institute (TWI). Welding aluminum is made easier by using the FSW process. This process is mainly used for applications which require the least possible amount of change in original metal characteristics. In this process, a rotating cylindrical-shouldered tool with a threaded or unthreaded pin is introduced into the adjoining edges of a workpiece and is then traversed on the joint line. This act allows the displacement of material in contact with the tool due to the friction existing between the tool and the workpiece to create a weld [3]. The weld produced is caused by the three primary actions carried out by the tool, namely, heating of the workpiece, material displacement, and containment of the hot material by the tool. The friction existing between the tool and the workpiece results in heat generation that softens the workpiece. The tool rotation and translation governs the material displacement while the thrust force exerted by the shoulder on the workpiece aids in workpiece material containment [3]. Figure 1 illustrates FSW along with tool and workpiece designations.

FSW has led to the development of Friction Stir Processing (FSP), in which the rotating tool is traversed over a single solid workpiece. The idea in this case is to increase the strength of the material by allowing micro-structural changes through FSP. FSSW is another variant process of the friction stir family in which spot welds are achieved using similar friction stir principles.

There is a need to develop cost models for other joining processes such as laser beam welding, mechanical fastening, etc., so that a cost comparison between competing joining processes can be established. Establishing economic comparisons between various joining processes will help the designer(s) to select economically viable processes for a given project.

The idea is to prepare a cost model for MIG welding process and simultaneously perform an economic analysis of the FSW metal joining process, starting with the identification of parameters and determination of cost of each parameter based on the experimental work conducted at the Center for Friction Stir Processing (CFSP) laboratory of the University of Missouri-Rolla (UMR)[1]. A general study of various cost estimation

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[1]Effective Jan. 1, 2008, UMR becomes Missouri University of Science and Technology (Missouri S&T).

techniques has been conducted and a suitable cost estimation technique has been identified.

This paper includes cost models generated for MIG, FS, and FSS welding processes, along with the development of an E-design tool generated in collaboration with the E-Design Smart Laboratory, Virginia Polytechnic Institute and State University. This tool is equipped with industry case examples of various types of industrial automobile joints. Figure 2 shows a snapshot of the e-cost estimation tool developed using the ontology. This is a collaborative effort between CFSP and E-Design Smart Laboratory.

BACKGROUND AND RELATED WORK

A literature survey was conducted to identify a suitable cost estimation technique for the development of a cost model for MIG welding. Thereafter, this model was also applied to FSW and FSSW processes to carry out an economic comparison between MIG and FSW joining processes. This comparison will aid in the selection of economically viable techniques for a given task. Several textbooks [4-7] described the categorization of different cost estimation techniques. Niazi *et al*. [8] classified qualitative and quantitative product cost estimation techniques to cover a wide variety of issues. This classification is based on groups of cost estimation techniques with similar features. Qualitative techniques are further divided into intuitive and analogical cost estimation techniques. Intuitive cost estimation technique, according to Niazi *et al*. [8], is based on the domain expert's past experience. These experiences are captured in the database in the form of decision trees and other judgment analyses used for estimating the cost incurred in producing different parts. Case-Based methodologies and Decision Support Systems

(DSS) are grouped as intuitive cost estimation techniques. Analogical cost estimation techniques include Regression Analysis and Back-Propagation Neural Network (BPNN) Models [8]. According to [8], Regression analysis models create linear relationships between parameters and cost based on the past data and these linear relationships are used to address future queries. On the other hand, BPNN models train a neural network to reply to queries experienced never before. Quantitative techniques are subdivided into parametric and analytical cost estimation techniques [8]. Operation-based approach, breakdown approach, tolerance-based cost model, feature-based cost estimation and activity-based costing (ABC) systems are grouped as analytical cost estimation techniques. These approaches decompose production into various activities that comprise the production process of the product being analyzed. Resources involved in realizing these decomposed activities are expressed in terms of cost by summarizing the components. Niazi *et al*. [8] also presented the key advantages and limitations of each technique.

Niazi *et al.* [8] presented a hierarchical classification of different product cost estimation techniques which are extensively discussed by a few researchers [9-10]. Cavalieri *et al.* [9] identified analogy-based, parametric, and engineering approaches as the three basic approaches for cost estimation. Zhang *et al.* [10] categorized cost estimation techniques into activity-based, break-down, regression-based, and group technology-based techniques. Lorenzo *et al.* [11] provided a cost model for friction stir welding (FSW) using the break-down cost estimation technique. An economic analysis of a FSW production run was made taking into account all the production related costs in order to estimate the total cost. Each production related cost or cost component (CC) is considered individually and later summarized to determine the total cost of production. The cost model is analyzed using basic joints such as butt, tee, and double tee joints for variations in the length and number of joints. It also accounts for variations in sheet thickness.

Creese *et al.* [12] listed various cost models for different machining and manufacturing processes. They asserted that the development of a generalized model makes optimization easier for specific machining processes. Minimum cost and maximum production conditions are applied to the models developed for any specific cutting speed or tool life. Creese *et al.* [12] developed models based on the break-down approach. Models are developed separately for each process involved in the production and the summation later yields the total cost. Firkins [13] listed the events or tasks effecting the production and cost of welding. Firkins [13] focused especially on the labor cost (the major contributor towards the total welding cost) and the ratio of material to labor cost. Firkins [13] described the advantages associated with break-down cost modeling, such that this kind of modeling aids in identifying various sections of improvement, whether it may be the welding position (horizontal, vertical, or over-head) or deposition rate, or others.

Many researchers [11, 14, 15] developed cost models in the field of MIG and FS welding. Substantial contributions were made in developing cost models for MIG welding process where as FS welding still suffers from superficial cost modeling. Lorenzo *et al.* [11] provided a basic framework for FS welding cost modeling. A framework along with a cost model is proposed in this paper based on the case study of the automobile industry. The cost models developed are based on the actual physics of the process due to the novelty of friction stir technology. Even though there are several sophisticated models existing for MIG, a modified version of the cost model proposed by Creese *et al.* [12] is used in this paper to allow for peer level comparison with friction stir technology. An effort has been made to develop an e-tool for estimating the cost of a joint for MIG, FS, and FSS welding processes. The tool is designed to support various case examples, thereby, creating a library of joints for the above mentioned metal joining processes. This e-tool has been developed using an ontology platform [16] to map the complex relationships among the machine-interpretable definitions. Park *et al.* [16] reported on the ontological approach to cost management in product family design using activity-based cost ontology to establish a product cost knowledge base for developing cost management systems. This paper similarly focuses on developing a product cost knowledge base system for MIG, FS, and FSS welding processes.

Laan *et al.* [14] developed a cost model for FSW that was implemented in multidisciplinary knowledge based engineering tools to automate the cost estimation process. This design tool supports access not only to manufacturing, but also structural and aerodynamic issues. This tool allows designers to quickly access the FSW potential for their design. Several other researchers, including Koonce *et al.* [17], Hoffmann [18] and Ramirez *et al.* [19], have implemented cost models of knowledge based tools to expedite the process of estimation and to use the historical data. The tools are designed to facilitate the cost estimation based on frameworks developed using expert comments and experimental data. However, the cost estimation model in this paper involves frameworks for different metal joining processes to facilitate the user's decision making ability, apart from typical cost estimation. The e-design tool also has the ability to store parameters related to queries, thereby, creating a database of various joints.

The framework described in this paper is based on the break-down cost method. Laan *et al.* [14] discussed the pros and cons associated with parametric, analogous, and bottom-up cost estimation techniques. Based on a detailed study of cost estimation techniques and reviews from Niazi *et al*. [8], Lorenzo *et al.* [11], and Laan *et al.* [14], the break-down cost model has been identified as the most suitable cost estimation technique for our study. The break-down cost estimation technique has the advantages of being easy to handle and able to accommodate future refinements while considering various technical parameters.

The break-down cost method requires detailed information about the production process to derive the relevant cost components. Labor, overhead, tooling, maintenance and repair, etc., are commonly used cost components for developing cost models for any manufacturing process.

The application of a neural network to cost engineering is thoroughly discussed in [20 - 21]. Neural network application requires historical data to train the network prior to operation. But the generation of historical data for FSW process is difficult since it is a relatively new manufacturing process. This paper discusses mathematical cost models which involve uncertainties due to the assumptions made. However, models generated using neural network can be used to tackle these of problems. The uncertainties in the mathematical models can be addressed using a probabilistic design approach.

METAL INERT GAS (MANUAL) WELDING COST MODEL

Apart from functionality, the choice of a particular joining process is usually based on cost issues. Therefore, it is necessary to develop a model for cost estimation. Various cost components are available for cost estimation. The commonly occurring components are discussed below. Other cost components critical for special products and processes must be included during cost estimation on a case-specific basis. The typical components of a cost estimate are as follows [12]:

1. Material cost (Filler material)
2. Labor cost (weld preparation time + actual weld time)
3. Power cost
4. Shielding gas cost
5. Machine cost (cost of the weld machine + pre-weld equipment cost + miscellaneous equipment cost)
6. Tooling cost

The cost of the filler materials (C_{ec}) is estimated by determining the types and amounts of filler material required in production. Allowances for waste, spoilage, and scrap should be included in the cost estimate.

The cost of labor (C_{lc}) is based on the weld preparation time, number of weld runs, and length of the weld. The rate of production and weld preparation time determines the number of working hours and the product of the hourly labor rate and the number of labor hours determines the labor cost. The model also includes the break time for which the operators are paid.

The cost of power (C_{pc}) includes the number of hours for which the welding machine works and the amount of power consumed.

The cost of the shielding gas (C_{gc}) is estimated by considering the amount of gas flow and the unit cost of the shielding gas.

The machine cost (C_{mc}) includes the cost for the welding equipment, weld preparation equipment, and special handling equipment. The hourly cost of the equipment is calculated from the costs for depreciation, interest, and maintenance, along with an estimate of the annual usage time.

The fixturing cost (C_{tc}) includes the costs for fixtures, which are specific to each joining process. The present cost estimation model does not include the costs of machining tools, sharpening tools, tool storage, etc.

The sum of all the component costs discussed above equals the total cost of the joint. This can be expressed mathematically as follows [12]:

$$C_{total} = C_{ec} + C_{lc} + C_{pc} + C_{gc} + C_{mc} + C_{tc} \qquad \text{……………} (1)$$

The cost components are simplified such that a specific cost can be calculated with minimal number of inputs. The inputs in this model include length of the weld, thickness of the base plate, type of weld, and number of weld passes. In practice, a range of input values are specified. For example, if a range is given for the length of a weld, then the model can calculate the cost for the minimum and maximum lengths specified. Therefore, the output cost is also a range, and a designer could easily specify the range for the cost incurred in producing the joint.

Cost component #1 (CC1): Filler material

The filler material cost is given by equation (2) [12]:

- Cost of electrode,

$$C_{ec} = P \times C_f$$

.... (2)

where

P = Pounds of the electrode or wire required (lb)

C_f = Unit cost of the filler material ($/lb)

- The weight of the welding electrode necessary to complete a given weld is as follows [12]:

$$P = \frac{WL}{E}$$

.... (3)

where

W = Weight per foot of weld metal (lb/ft)

L = Length of weld (inches)

Z = Thickness of base material (inches)

E = Deposition efficiency (95%)

- The weight of weld per foot is given as follows [12]:

$$W = A_S \times \rho$$

.... (4)

where

A_S = Cross-sectional area ($inch^2$)

ρ = Density of the base material ($lb/inch^3$)

The formulae for calculating the weight of welding electrodes required for different types of welded joints are given below [12]:

$$P = \begin{cases} \dfrac{(0.012192862 \times L)}{95\%} & \text{(Fillet weld)} \\ \dfrac{(0.04877 \times z^2 \times L)}{95\%} & \text{(Lap weld)} \\ \dfrac{(0.056315 \times z^2 + 0.00768 \times z^2) \times L}{95\%} & \text{(Full penetration butt weld)} \\ \dfrac{(0.056315 \times z^2 - 0.0011885 \times z - 0.00025557) \times L}{95\%} & \text{(Partial penetration butt weld)} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Assumptions:

- We used a broad classification of joint types that includes: Fillet weld, Lap weld, Full penetration butt weld and Partial penetration butt weld. Other joint types such as the T-joint or edge joint have been considered in the fillet weld equation. This assumption was made because the joint configurations of T-joints and edge joints are similar to fillet weld. This approximation facilitates ease of calculations.
- The cross section of the weld nugget is approximated to the nearest geometric shape to facilitate easy calculations.
- The height and width of the nugget in a fillet weld are assumed to be equal to the thickness of the base plate.
- The *MIG Welding handbook* [22] suggests a deposition efficiency of 95%, i.e., effectively 95% of the filler material used is deposited in the weld area and the remaining 5% is wasted in terms of filler material preparation and other operations.
- All welds are assumed to be continuous in nature.

Cost component #2 (CC2): Power cost

The variable power cost is given by the following equation [24]:

$$C_{pc} = \frac{I \times V \times C_p \times L}{1000 \times 60 \times S \times M}$$

…………………. (6)

where

I = Current (amps)

V = Voltage (volts)

S = Travel speed (inch/min)

= $\frac{S}{n}$ (n is the number of weld passes and S = 40 inches/min)

M = Machine efficiency (assuming 95%)

L = Length of the weld (inches)

C_p = Power cost ($/kWh)

- The variable power cost for different diameters of the electrode are given below [24]:

$$C_{pc} = \begin{cases} 3.509 \times 10^{-5} \times n \times V \times C_p \times L & \text{(0.3" dia. electrode)} \\ 5.7018 \times 10^{-5} \times n \times V \times C_p \times L & \text{(0.35" dia. electrode)} \\ 7.675 \times 10^{-5} \times n \times V \times C_p \times L & \text{(3/64" dia. electrode)} \\ 1.0088 \times 10^{-4} \times n \times V \times C_p \times L & \text{(1/16" dia. electrode)} \end{cases}$$

…………………. (7)

where

n = Number of weld passes

V = Voltage used (volts)

C_p = Unit cost of power ($/kWh)

L = Length of the weld (inches)

Assumptions:

- According to *Estimating and Costing for Metal Manufacturing Industries* [12], the normal weld torch travel speed for the MIG welding process is 40 inches/min.
- *Estimating and Costing for Metal Manufacturing Industries* [12] suggests a machine efficiency of 95% and an operating factor of 0.5.
- The required filler material diameter is chosen according to the thickness of the base metal as shown in Table 1.
- The typical operating current can be identified using Table 2.

Cost component #3 (CC3): Shielding gas cost

The equation for calculating the cost of the shielding gas is given below [24]:

$$C_{gc} = \frac{F_r \times C_g \times L}{S \times 60} \qquad \text{………………… (8)}$$

where

F_r = Gas flow rate (10 ft^3/hr, according to AWS standard)

S = Travel speed (inch/min)

= $\frac{S}{n}$ (n is the number of weld passes and S = 40 inches/min)

L = Length of the weld (inches)

C_g = Gas cost ($\$/ft^3$)

$$C_{gc} = 4.167 \times 10^{-3} \times n \times C_g \times L \qquad \text{………………… (9)}$$

where

n = Number of weld passes

C_g= Gas cost ($/ft^3)

L = Length of weld (inches)

Assumption:

- According to the *MIG welding handbook* [22], the gas flow rate is assumed to be 10 ft^3/hr.

Cost component #4 (CC4): Labor cost

The equation for calculating the labor cost is given below [24]:

$$C_{lc} = \left(\frac{L}{60 \times S} + W_t \right) \times \frac{C_L}{OF}$$

………………... (10)

where

S = Travel speed (inch/min)

L = Length of the weld (inches)

OF = Operating factor (0.5, for GMAW)

T_W = Time for the weld preparation is assumed to be 30 sec

C_L = Labor rate ($/hr)

$$C_{lc} = \left[4.166 \times 10^{-4} \times n \times L + \left(\frac{T_W}{3600} \right) \right] \times \frac{C_L}{OF}$$

………………… (11)

where

n = Number of weld passes

Cost component #5 (CC5): Machine cost

The machine cost is given by the following equation [12]:

$$C_{mc} = \frac{P \times C_M}{D_r \times OF}$$

………………… (12)

where

P = Amount of weld metal (lb)

OF = Operating factor (0.5)

D_r = Deposition rate (lb/min) = $60 \times S \times W$

S = Travel speed (inch/min)

W = Weight per foot of the weld metal (lb/ft)

C_M = Machine cost ($/hr)

$$C_{mc} = 8.772 \times 10^{-4} \times n \times C_M \times L$$

………………… (13)

where

n = Number of passes

C_M = Machine cost ($/hr)

L = Length of weld (inches)

Cost component #6 (CC6): Fixturing cost

The fixturing cost is not included in the cost estimate described in this paper.

Table 3 illustrates a detailed calculation using the mathematical model mentioned above. This example is taken from a joint provided in the case study considered for cost model development. Table 4 provides the cost of all the joints from the case study considered.

FRICTION STIR AND FRICTION STIR SPOT WELDING COST MODEL

This model considers various cost components involved in cost estimation of a FS welded joint. Analogous to MIG welding cost model, FS cost model is structured using the essential cost components. The typical components of a FSW cost estimate are listed below [11]:

1. Labor cost (weld preparation time + actual weld time)
2. Power cost
3. Machine cost
4. Tooling cost
5. Fixturing cost

The cost of labor is based on weld preparation time, number of weld runs and length of welds. The rate of production determines the number of working hours and the product of the hourly labor rate and the number of labor hours determines the cost of labor. The model also includes the break time for which the laborers are paid.

The cost of power includes the number of working hours of the welding machine and its power consumption. The power consumed depends on the power rating of each machine. Heavy machines usually tend to higher rates of power consumption. Hence, the power rating of each FSW machine is used to calculate the cost of power.

Machine cost includes the cost of welding equipment, weld preparation equipment, and special handling equipment. The hourly cost of the equipment is calculated from the costs for depreciation, interest, and maintenance, together with an estimate of the annual usage time.

The tooling cost provides the cost incurred in using a particular tool for making a joint. It also takes into consideration the life of the tool.

The fixturing cost includes the costs for fixtures, which are specific to each joining process. The present cost estimation model does not include the cost of machining tools, sharpening tools, tool storage cost, etc.

The sum of all the component costs discussed above results in the total cost of the joint and can be expressed mathematically as follows [11, 12]:

$$C_{total} = C_L + C_M + C_P + C_T \qquad \text{.....................} (14)$$

Cost component #1 (CC1): Labor cost

The time taken to weld a joint (W_T) is given as follows:

$$= \frac{\text{Weld path length (L)}}{\text{Feed rate (F)}} + \frac{\text{Depth of plunge (d)}}{\text{Plunge feed rate }(\text{F}_\text{p})} + \text{Dwell time }(\text{T}_\text{d})$$

(Friction Stir Continuous Welding) .... (15)

$$= \frac{\text{Depth of plunge (d)}}{\text{Feed rate (F)}} + \text{Dwell time }(\text{T}_\text{d})$$

(Friction Stir Spot Welding) .... (16)

where

L= Length of weld (inches)

F = Feed rate (inches/min)

n = Number of weld passes

d = Depth of plunge (inches)

T_d = Dwell time (min)

The equation for calculating the labor cost is given below,

- Labor cost,

$$C_{lc} = \left(\frac{W_T \times n}{OF} + T_W \right) \times \frac{C_L}{60}$$

………………... (17)

where

W_T = Time to weld (min)

n = Number of weld passes

OF = Operating factor (0.5, for GMAW)

T_W = Time for weld preparation (min)

C_L = Labor rate (\$/hr)

Assumptions:

- All the welds are assumed to be continuous.

Uncertainties arising due to approximations made during calculations have not been considered.

Cost component #2 (CC2): Machine cost

The machine cost is given by the following equation,

- Machine cost,

$$C_{mc} = \frac{[(W_T \times n) + T_S + T_{Ch}] \times C_M}{MR \times 60}$$

………………… (18)

where

T_S = Setup time (min)

T_{Ch} = Tool change-over time (min)

MR = Machine reliability (assuming 95% assumed)

C_M= Machine rate ($/hr)

n = Number of passes

Cost component #3 (CC3): Power cost

The variable power cost is given by the following equation,

- Variable power cost,

$$C_{pc} = \frac{0.8 \times PR \times C_P \times W_T \times n}{1000 \times 60 \times MR}$$

………………… (19)

where

PR = Power rating (KVA)

C_P = Power cost ($/kwhr)

W_T = Time to weld (min)

n = number of weld passes

V = Tool traverse speed (inches/min)

MR = Machine reliability (assuming 95%)

Cost component #4 (CC4): Tool cost

Initially, a tool is selected from the table based on the joint configuration. The thicknesses of the materials are used to select the appropriate tool.

As stated in [15],

Tool life, T = $Q \times \left[\frac{60 \times C_T}{C_{MR}} + t_{ch} \right] \times \left(\frac{1 - n'}{n'} \right)$ ………………… (20)

Cutting fraction, Q = $(\theta / 360) \times (L / L_{tot})$ ………………… (21)

The tool cost per joint is given by the following equation:

Tool cost, $C_t = \dfrac{C_T \times Q \times W_T \times n}{T}$ ………………… (22)

where

L = Length of the weld (inches)

C_T = Unit tool cost ($/tool)

C_M = Machine rate ($/hr)

θ = Angle of engagement (degrees)

L_{tot} = Length of weld + Lead + Over travel (inches) = Length of weld + Diameter of the shoulder

T_{Ch} = Time for tool change (min)

n' = Taylor's tool life exponent (assuming 0.1)

n_t = Tool changes/unit = $\dfrac{Q \times W_T}{T}$ (interrupted welding) ………………… (23)

$= \dfrac{Q \times W_T}{T}$ (Uninterrupted welding) ………………… (24)

Cost component #5 (CC5): Fixturing cost

The fixturing cost is not included in the cost estimate described in this report.

RESULTS AND DISCUSSION

The MIG cost model stated in this paper provides the joint costs using the MIG welding process. Figure 4 illustrates the cost distribution for the example shown in Table 3. It has been found that the cost of labor is the major contributor towards the total cost of a joint. The filler material cost is the second major contributor to the total cost. The results for a case study using this model were reasonable. Simultaneously, a set of cost estimates are generated based on welder's experience. A similar trend is identified in the cost distribution. Figures 5 and 6 depict the cost distribution with respect to the length of weld and thickness of the base plate. In Figure 5, a cluster of data points can be seen for lengths less than 20 inches as several weld joints fall into this region in the case study considered. In Figure 6, different cost values are observed for weld joints with similar base plate thickness. This shows that the cost of the joint for these thicknesses varies with the length of the weld and not with the thickness of base plate. We can conclude that the cost of a joint depends predominantly on the length of the weld for joints considered. Along with the length of weld, and thickness of the base plate, the material of the joints is also varying. Hence, the peaks and valleys can be observed in the cost function plots.

Monti Carlo Simulation (MCS) is used to address the uncertainties in input variables for the cost models by converting them into probability distributions. The probability of the output is achieved by combining the distributions and randomly selecting the values to recalculate the simulated model several times. The input values, mean and variance values for all the cost components, are derived from the auto case study. Table 4 lists all the cost values of 42 MIG joints identified in the case study. Assuming the MIG cost model to be normally distributed, these values are used to drive the probability and reliability values for the cost function. Considering the mean values of each cost component, the following MIG cost model is evaluated using MCS for a sample of 100,000 trial runs.

Table 5 provides the summary statistics of the output with reliability. The results suggest that this model is 99.993% reliable with a mean value of \$0.45 as the total cost of the joint for a given failure point of \$1. Figure 7 and the statistics in Table 5 refer to the design in terms of the financial risk involved in the joints used. Such type of analysis aids in determining the financial risk involved in using these types of joints and also provides an opportunity to improve the design robustness. Moreover the reliability also depends on the point of failure selected which in turn depends on the designer.

The shaded region in Figure 7 shows the probable region of success for given mean and range values of the total cost of the weld joint, while Figure 8 presents the cumulative distribution function (CDF) of the MIG cost model. The reliability of this model can be further improved by shifting the mean and variance values of the samples. Figure 8 also shows the degree of uncertainty in the inputs variables for the MIG cost model assuming the model is normally distributed.

Figure 9 provides information flow in the basic cost framework developed for FSW process. It presents details about each cost component and the prerequisites required for calculating these component costs. Milling machining process provided the base for developing a FSW cost model. This model is entirely based on the physics involved in the process.

Figure 10 shows the cost distribution for weld joint fabricated using FSW process. Unlike MIG welding, the labor cost and machine cost shares here are almost equal due to the fact that FSW machines are costlier than MIG and also due to the uncertainties in the assumptions. Assumptions are made to display working of the cost model.

Similar to MIG cost model, a probabilistic approach is followed for checking the reliability of the model. Figures 11 and 12 describe the behavior of the model under normally distributed condition. The shaded region in Figure 11 represents the probable success region for the FSW cost model discussed in this paper.

CFSP laboratory at UMR provided sample examples to evaluate this model [33]. The input values, mean and variance values for all the cost components are derived from these examples. Table 7 lists all the cost values of various FSW joints collected. Similar to MIG welding, these cost values are used to run MCS for a sample of 100,000 trial runs. The results yielded the reliability and probability of failure values for this model.

Table 8 provides the summary statistics of the output with reliability. The results suggest that this model is 96.43% reliable with a mean total weld joint cost value of $1.26 as for given failure point of $1.6 and given input variables. The reliability of this model can be improved by feeding in pool of data. Data for FSW is hard to come by as it is a novel technology. Examining the data gives the privilege to shift the mean and variance values resulting in an improved FSW cost model reliability and also suggests appropriate mean and variance values for the input cost components.

This study aids the user in decision making process while opting to choose the suitable fabrication process for a given task and also aids in checking the amount of financial risk involved in the design for the joints prepared for MIG and FS welding joining processes. The reliability study supports these models to be used for cost estimation process and also to check for the design robustness by referring the financial risk involved in the joint design. This study also helps in determining the failure point for the given cost models, thereby setting the limits to use which in-turn aids in selecting appropriate model for cost estimation.

FUTURE WORK AND CONCLUSIONS

The cost models, mentioned in this paper, are used to develop e-design tool in collaboration with Center for E-Design (CED) at Virginia Tech. This tool is equipped with various joint examples and a user can input a query to find the solution for it. This tool is developed for MIG, FS and FSS welding processes using the cost models presented in this paper. The cost models are initially validated as mentioned and later used to develop the e-design cost tool. MIG welding cost model could be validated with the real time data but FSW and FSSW cost models, in this paper, still needs to be validated. Even though efforts are made in the direction of validating the cost models using probabilistic engineering approach, complete solution for FSW could not be realized due to lack of case examples.

The central idea behind generation of cost model for FSW is to have a comparative study between FSW and other competing joining processes. Cost comparison with other processes such as laser welding, riveting, etc., will provide a comprehensive comparative scope for this technology. This paper provides cost models for MIG, FSW and FSSW processes only. Many automotive industries use robotic welding process; hence, an economic comparative study between FSW and robotic welding process would be interesting. Many industries are looking to insert FSW in the manufacturing process due to its high technical advantages, such as high joint strength with no material addition etc. Therefore, it is necessary to upgrade the proposed e-design tool to accommodate robotic welding process. Substantial work in other metal joining process areas will provide a broader view to compare with FSW and thereby check the economic feasibility of FSW application.

This paper includes a dataset of sample FSW joints and further investigation can be made to improve the cost modeling by building a dataset pool. The FSW cost model in this paper includes uncertainties in the assumptions due to the novelty in the process.

Further study and case examples will help in refining the model which ensures in increased in reliability. Increased in reliability will increase the accuracy of the model.

ACKNOWLEDGMENTS

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NOMENCLATURE

ρ	Density of the Aluminum (lb/inch^3)
A_s	Cross-sectional area (inch^2)
C_f	Unit cost of the filler material ($/lb)
C_g	Unit gas cost ($/ft^3)
C_L	Unit labor cost ($/hr)
C_M	Unit machine cost ($/hr)
C_{OR}	Unit overhead cost ($/hr)
C_P	Unit cost of power ($/kWh)
C_T	Unit cost of tool ($/tool)
C_{ec}	Cost of electrode per joint ($)
C_{pc}	Variable power cost per joint ($)
C_{gc}	Cost of shielding gas per joint ($)

C_{lc}	Labor cost per joint ($)
C_{oc}	Overhead cost per joint ($)
C_{mc}	Machine cost per joint ($)
C_t	Tool cost per joint ($)
C_{fc}	Fixturing cost per joint ($)
C_{total}	Total cost of the joint ($)
CF	Cubic feet
E	Deposition efficiency
F	Tool feed rate (inches/min)
F_p	Tool plunge feed rate (inches/min)
F_r	Gas flow rate (ft^3/hr)
I	Current (amps)
L	Length of the weld (inches)
n	Number of weld passes
OF	Operating factor
P	Pounds of electrode or wire required (lb)
PR	Power rating (KVA)
S	Travel speed (inches/min)
T_{Ch}	Tool change-over time (min)
T_d	Dwell time (min)
T_S	Setup time (min)
T_W	Weld preparation time (min)
V	Voltage used (volts)

W Weight per foot of weld metal (lb/ft.)

Z Thickness of the base material (inches)

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ANNEXURE A

A Few MIG welding machines, costs and capabilities

<table>
<tr><th colspan="9">MIG WELDING MACHINES</th></tr>
<tr><th colspan="2" rowspan="2">ITEM</th><th rowspan="2">PRICE ($)</th><th colspan="3">RATED OUTPUT</th><th rowspan="2">SOLID WIRE SIZE RANGE</th><th rowspan="2">WIRE FEED SPEED RANGE</th></tr>
<tr><th>Current (Amps)</th><th>Voltage (Volts)</th><th>Duty cycle</th></tr>
<tr><td>K24 70-1</td><td>Power MIG 140T MIG/Flux-Cored Wire Feeder Welder</td><td>509.95</td><td>90</td><td>19.5</td><td>20%</td><td>0.035”</td><td>50-500</td></tr>
<tr><td>K24 71-1</td><td>Power MIG 140C MIG/Flux-Cored Wire Feeder Welder</td><td>577.00</td><td>90</td><td>19.5</td><td>20%</td><td>0.035”</td><td>50-500</td></tr>
<tr><td>K24 72-1</td><td>Power MIG 180T MIG/Flux-Cored Wire Feeder Welder</td><td>620.95</td><td>130</td><td>20</td><td>30%</td><td>0.035” – 0.045”</td><td>50-500</td></tr>
<tr><td>K24 73-1</td><td>Power MIG 180C MIG/Flux-Cored Wire Feeder</td><td>699.00</td><td>130</td><td>20</td><td>30%</td><td>0.035” – 0.045”</td><td>50-500</td></tr>
</table>

	Welder						
K23 26-1	Power MIG - 215	1,279.9 5	215 190 170	22 23 24	30% 40% 60%	0.035” – 0.045”	50-700
K24 16-1	Power MIG – 255C 208/230/1/60	1,785.9 5	250	26	4%	0.035” – 0.045”	50-700
K24 16-2	Power MIG – 255C 230/460/575/1 /60	1,818.9 5	250	26	40%	0.035” – 0.045”	50-700
K24 17-1	Power MIG – 255C One-Pak w/ Spool Gun	2,524.9 5	250	26	40%	0.035” – 0.045”	50-700
K24 03-1	Power MIG – 350MP	3,295.9 5	300	32	60%	0.035” – 0.045”	50-700
K24 51-1	Power MIG – 350MP Push-Pull w/Python Plus	4,869.9 5	300	32	60%	0.035” – 0.045”	50-700

SOURCE: www.weldingsupply.com (last visited 11/30/2006)

ANNEXURE B

Commonly used filler material types and their price

Diameter of filler material	Type of filler material	Price
0.03"	Aluminum – 4043	$5.29/lb
0.035"	Aluminum – 4043	$4.58/lb
3/64"	Aluminum – 4043	$4.34/lb
1/16"	Aluminum – 4043	$3.52/lb
Diameter of filler material	**Type of filler material**	**Price**
0.03"	Aluminum – 5356	$5.44/lb
0.035"	Aluminum – 5356	$5.00/lb
3/64"	Aluminum – 5356	$4.59/lb
1/16"	Aluminum – 5356	$3.72/lb

SOURCE: www.weldingsupply.com (last visited 11/30/2006)

ANNEXURE C

Commonly used shielding gas proportion, quantities and their price

Item		Price
20-AR75CD	75% Argon 25% Carbon Dioxide (20 CF)	$ 18
40-AR75CD	75% Argon 25% Carbon Dioxide (40 CF)	$ 20
Q-AR75CD	75% Argon 25% Carbon Dioxide (80 CF)	$ 25
S-AR75CD	75% Argon 25% Carbon Dioxide (130 CF)	$ 27
T-AR75CD	75% Argon 25% Carbon Dioxide (375 CF)	$ 30
PB-AR75CD	75% Argon 25% Carbon Dioxide (4,032 CF)	$ 225
T-AR80CD	80% Argon 20% Carbon Dioxide (375 CF)	$ 75

SOURCE: www.weldingsupply.com (last visited 11/30/2006)

ANNEXURE D

Average hourly wage of a labor

Labor Cost	**Avg. hourly wage**	
	GMAW welding process	$15.52 /hr
	Milling and other machining processes	$14.91 /hr

SOURCE: http://www.bls.gov/oes/current/oes514121.htm (last visited 09/12/2006)

(U.S. Department of Labor Bureau of Labor Statistics)

ANNEXURE E

Average electric power cost in different states of USA

State	Average cost of electric power	State	Average cost of electric power
Alaska	$0.10/kWh	Alabama	$0.06/kWh
Arkansas	$0.06/kWh	Arizona	$0.07/kWh
California	$0.13/kWh	Colorado	$0.06/kWh
Connecticut	$0.10/kWh	Delaware	$0.07/kWh
Florida	$0.07/kWh	Georgia	$0.06/kWh
Hawaii	$0.13/kWh	Iowa	$0.06/kWh
Idaho	$0.06/kWh	Illinois	$0.07/kWh
Indiana	$0.05/kWh	Kansas	$0.06/kWh
Kentucky	$0.04/kWh	Louisiana	$0.06/kWh
Massachusetts	$0.10/kWh	Maryland	$0.06/kWh
Maine	$0.11/kWh	Michigan	$0.07/kWh
Minnesota	$0.06/kWh	Missouri	$0.06/kWh
Mississippi	$0.06/kWh	Montana	$0.06/kWh
North Carolina	$0.07/kWh	North Dakota	$0.05/kWh
Nebraska	$0.06/kWh	New Hampshire	$0.10/kWh
New Jersey	$0.09/kWh	New Mexico	$0.07/kWh
Nevada	$0.08/kWh	New York	$0.11/kWh
Ohio	$0.07/kWh	Oklahoma	$0.06/kWh
Oregon	$0.06/kWh	Pennsylvania	$0.08/kWh
Rhode Island	$0.09/kWh	South Carolina	$0.06/kWh
South Dakota	$0.06/kWh	Tennessee	$0.06/kWh
Texas	$0.07/kWh	Utah	$0.05/kWh
Virginia	$0.06/kWh	Vermont	$0.11/kWh
Washington	$0.05/kWh	Wisconsin	$0.06/kWh
West Virginia	$0.05/kWh	Wyoming	$0.05/kWh

SOURCE: www.eere.energy.gov/states/state_specific_statistics.cfm/state=MI[2] (last visited 11/30/2006)

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[2] Prices are collected from US Department of Energy efficiency and renewable energy. Average unit prices are based on data collected from 1980 - 2001

ANNEXURE F

Modified Accelerated Cost Recovery System's depreciation table

Recovery year	**3-year class**	**5-year class**	**7-year class**	**10-year class**
1	33.33	20	14.29	10
2	44.45	32	24.49	18
3	14.81	19.2	17.49	14.4
4	7.41	11.52	12.49	11.52
5		11.52	8.93	9.22
6		5.76	8.92	7.37
7			8.93	6.56
8			4.46	6.55
9				6.55
10				6.55
11				3.28

SOURCE: Creese R.C., Adithan M., Pabla B.S., *Estimating and costing for the metal manufacturing Industries*.

ANNEXURE G

Price list of generally used tools and weld preparation equipment

Tools	Price
3/32" collets, collet bodies, #7 alumina nozzles, 3 of each for type, 2 series gmaw torch	$18.21
Tool box	$10.00
Victor #00 weld tip for 100FC torch body	$25.00
Welding gas hose reel	$460.99

Price list of generally used safety equipment

Safety Equipment	Price
Leather Jacket	$ 50.00
Leather Chaps	$ 25.00
Leather Gloves (Heavy, for arc, 2 pairs)	$ 16.00
Leather Gloves (Light, for gas, gtaw)	$ 12.00
Leather Boots	$ 45.00
Welding Cap (2)	$ 10.00
Welding hood, HornellSpeedglass 9000V	$270.00
Pkg of 10 replacement lens for 9000V	$ 25.00
Gas Welding Goggles	$ 10.00
Safety glasses	$ 3.46

SOURCE:

http://www.olympic.edu/Students/AcadDivDept/BusinessAndTechnology/WeldingTechnology (last visited 11/30/2006)

ANNEXURE H

Currently used tools at UMR

Tool ID	Material	Tool Features	Tool geometry			
			Pin Diameter (mm)	Pin Length (mm)	Shoulder Diameter (mm)	Shoulder feature
A227	densimet	Conical Threaded	2.97	2.98	14.90	concave
D120	densimet	Conical triflute pin	3.88	2.26	12.42	concave
A221	densimet	Conical Threaded	3	1.80	12.00	concave
A216	densimet	Conical Threaded	4.5(root)	0.80	12.00	concave
A217	densimet	Conical Threaded	4.5(root)	1.00	12.00	concave
A218	densimet	Conical Threaded	4.5(root)	1.20	12.00	concave
A219	densimet	Conical Threaded	4.5(root)	1.40	12.00	concave
A220	densimet	Conical Threaded	4.5(root)	1.60	12.00	concave
A142	densimet	Conical Threaded	4.5(root)	1.50	12.00	concave
A143	densimet	Conical Threaded	4.5(root)	2.00	12.00	concave
A193-s	densimet	Conical pin	4.5(root)	1.77	10.00	concave

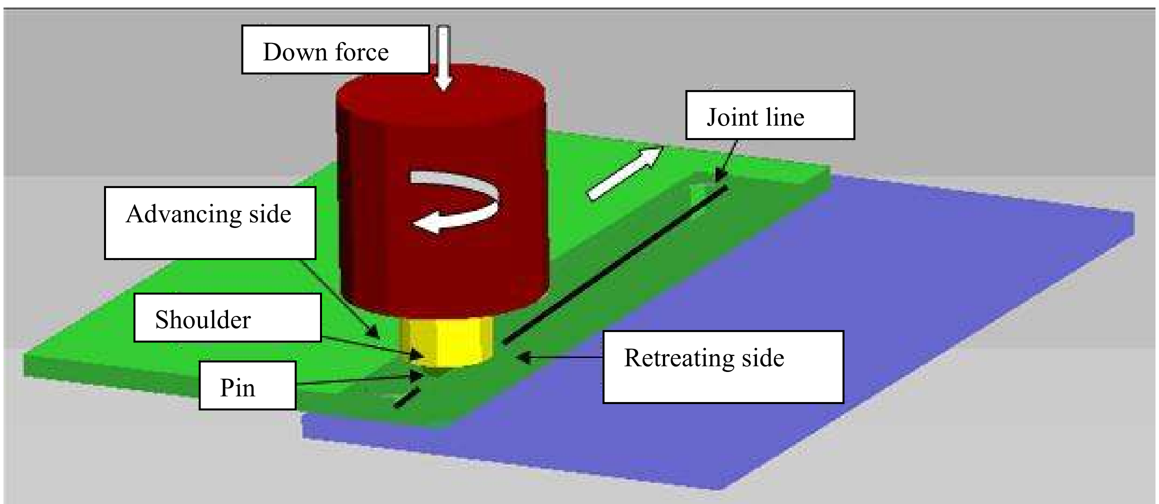


Figure 1. Friction stir welding process

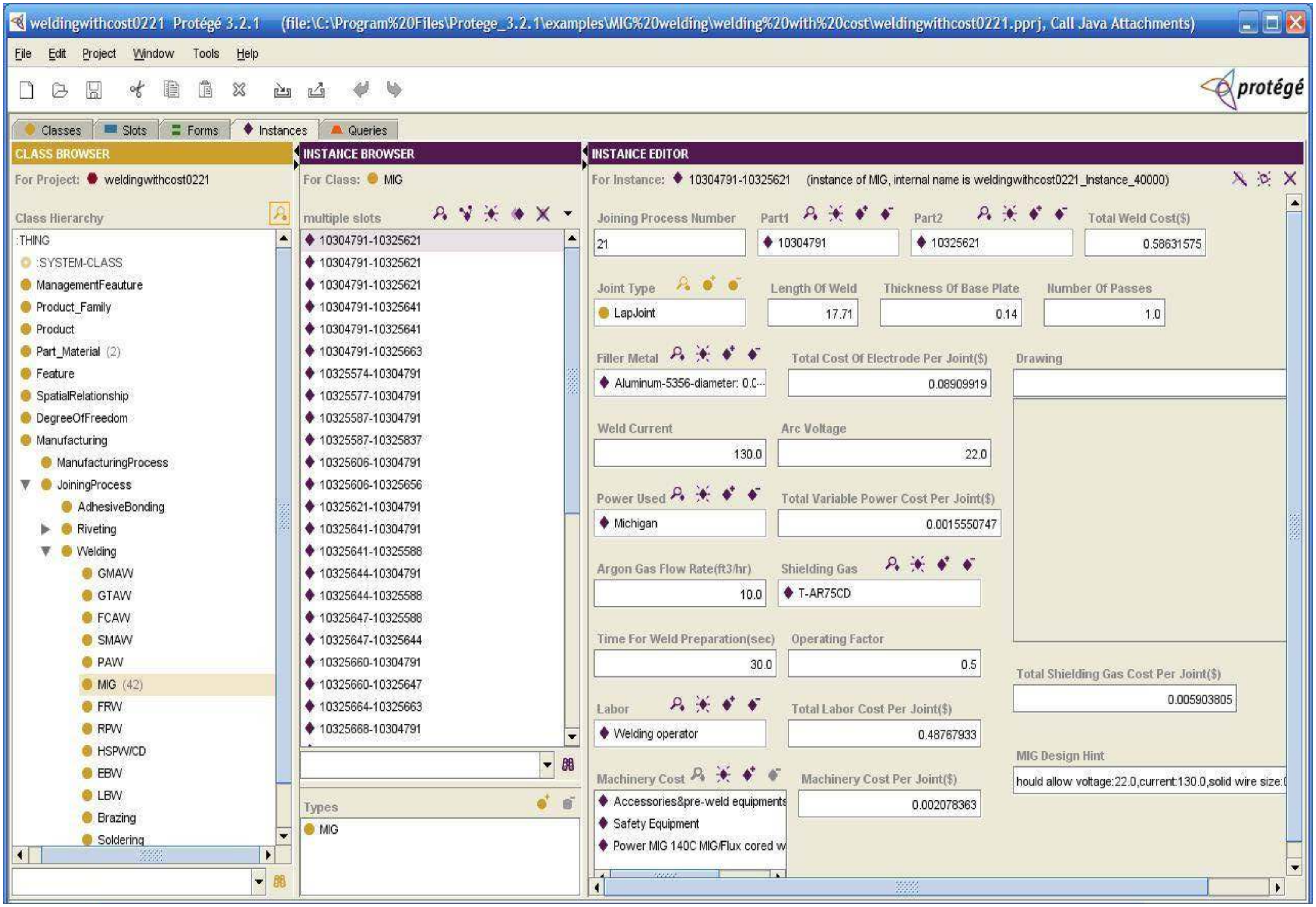


Figure 2. E-design tool developed by Virginia Tech. in collaboration with UMR

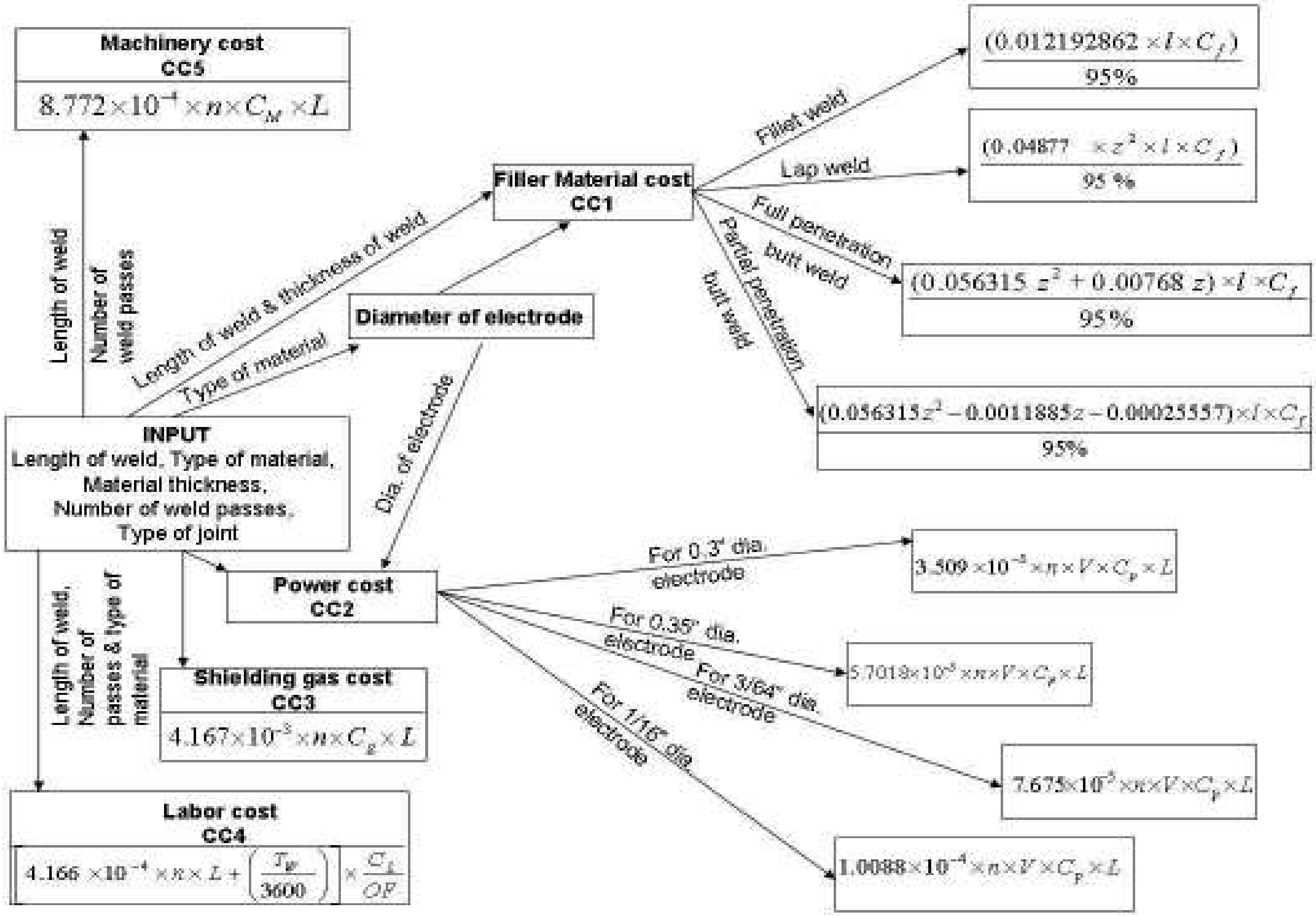


Figure 3. A block diagram depicting the information flow and various costs and their respective equations in the MIG cost model

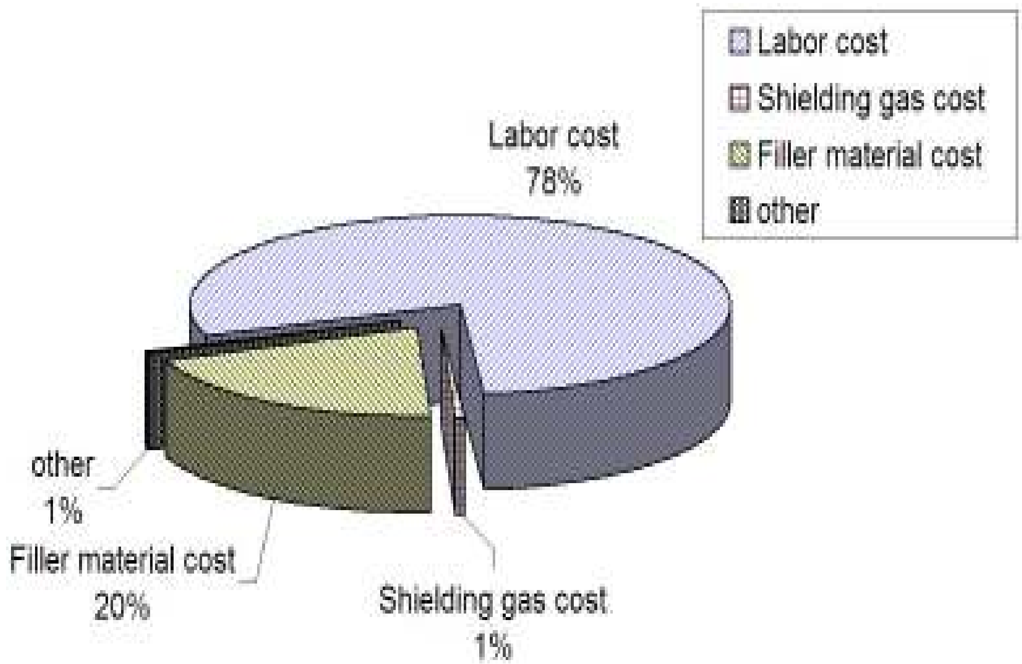


Figure 4. Distribution of cost components of MIG welding process *

* This figure is based on the example shown in Table 3.

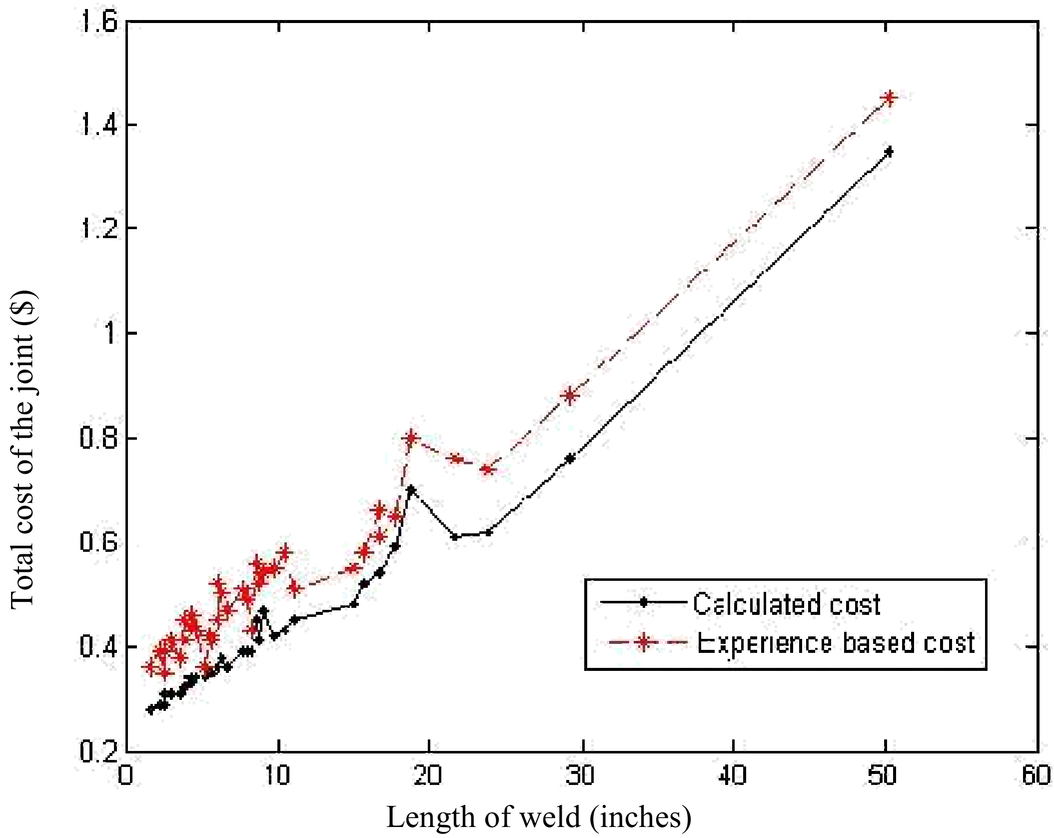


Figure 5. Distribution of calculated and experience based costs with respect to the length of the weld

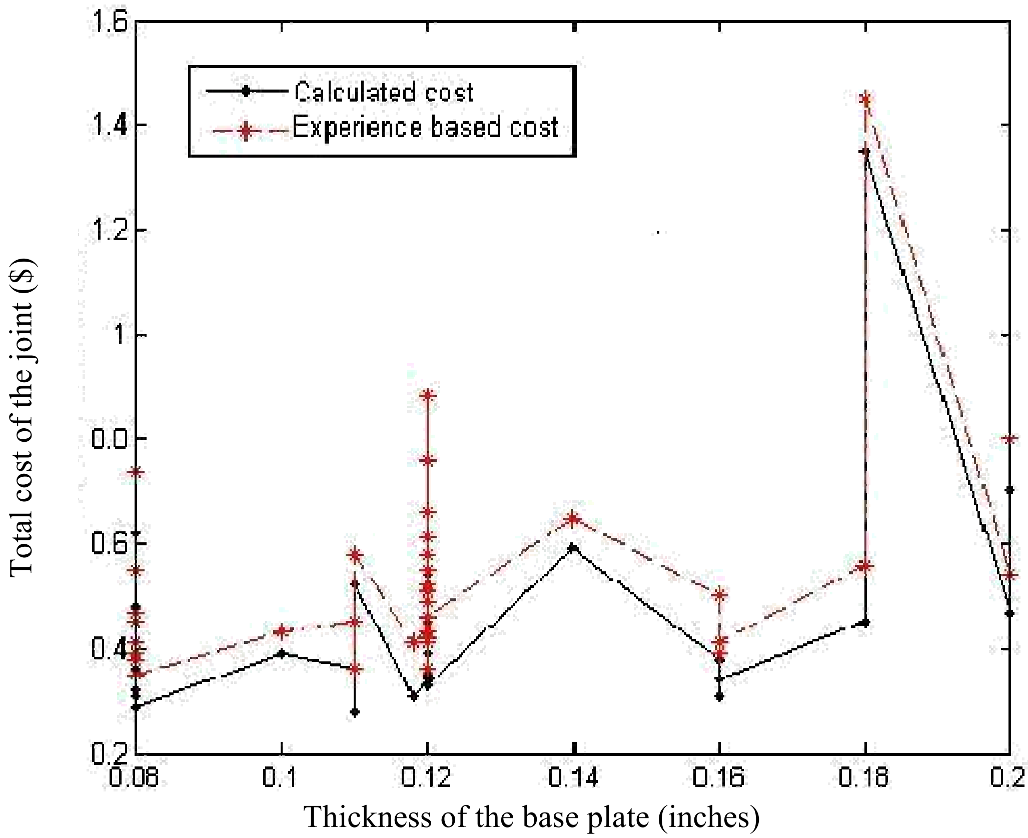


Figure 6. Distribution of calculated and experience based costs with respect to the thickness of the base plate

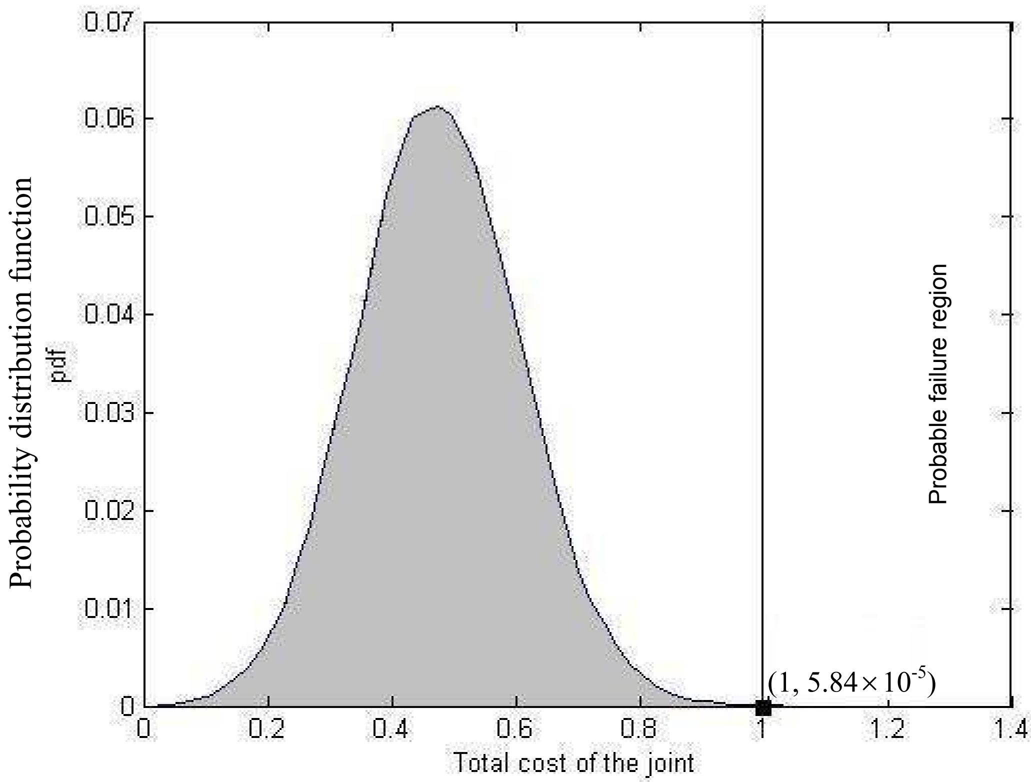


Figure 7. Degree of uncertainty in MIG cost model assuming it to be distributed normally

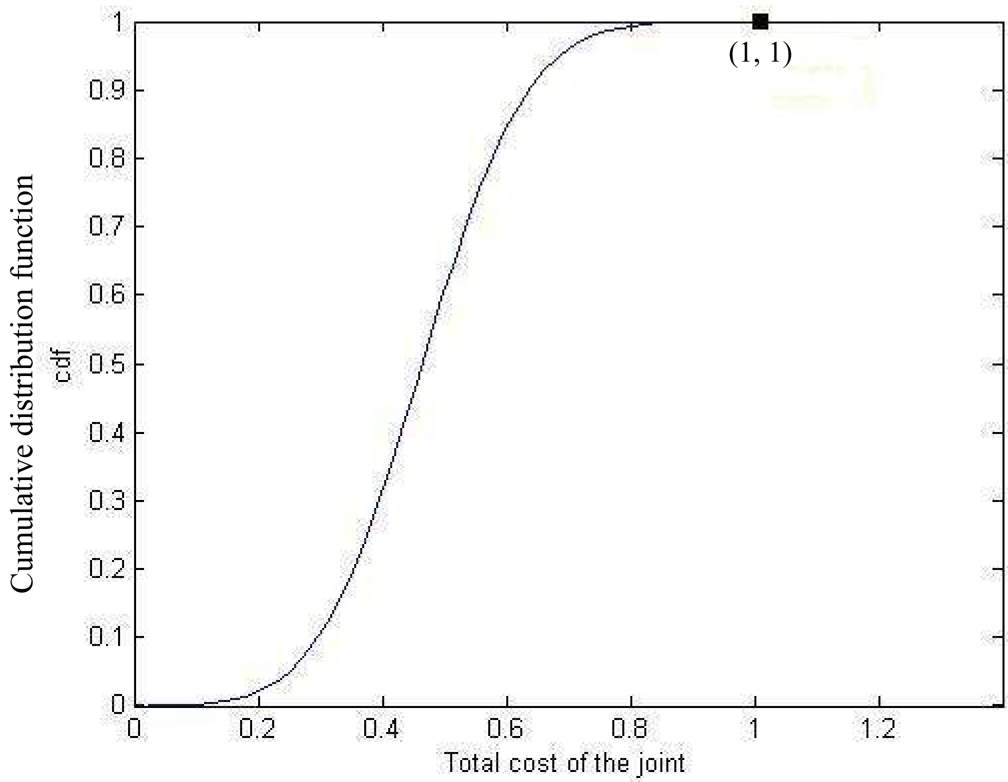


Figure 8. CDF function generated using the data from Monte Carlo simulation for MIG welding cost model

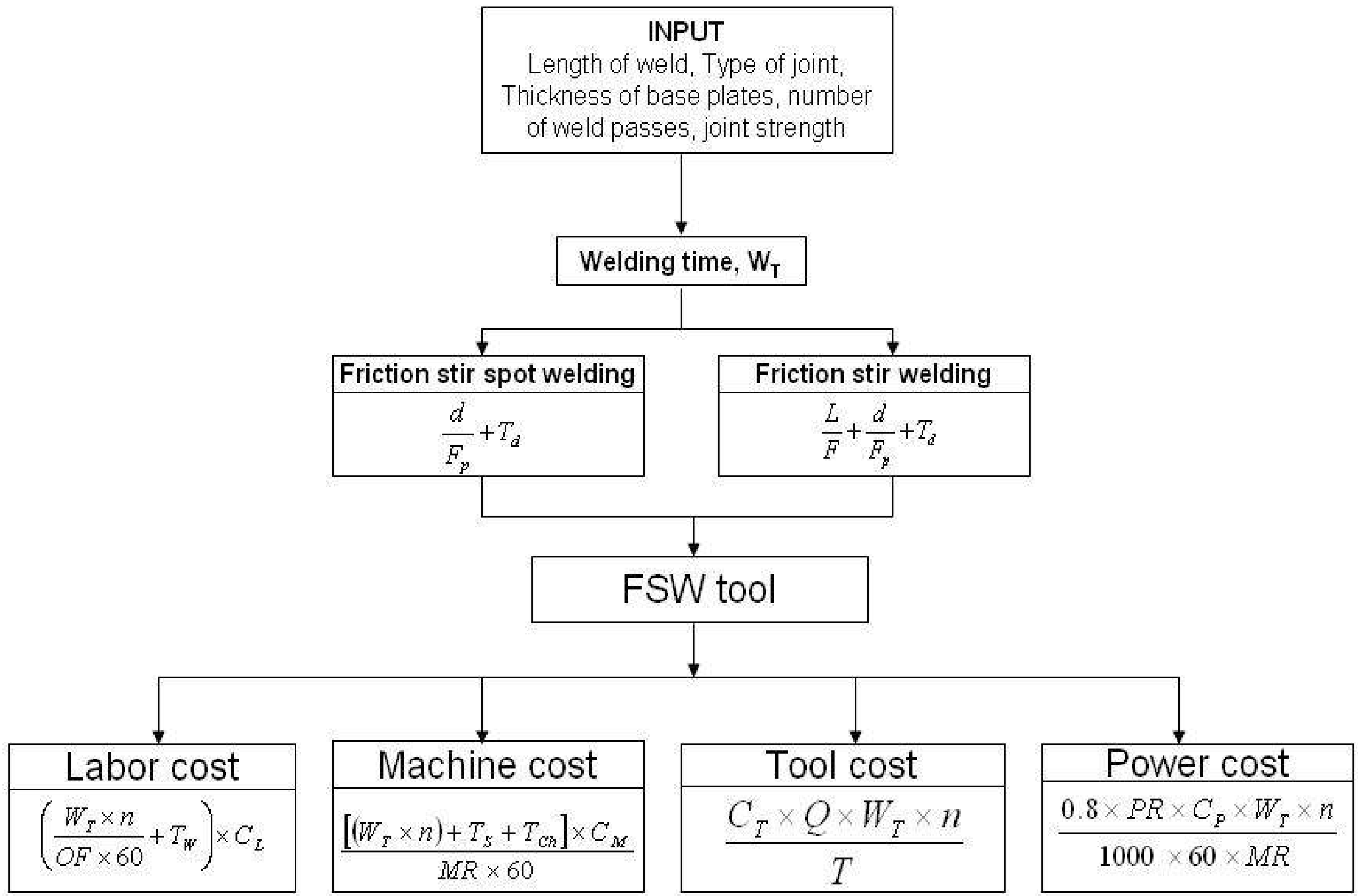


Figure 9. A block diagram depicting the information flow and various costs and their respective equations in the FSW cost model

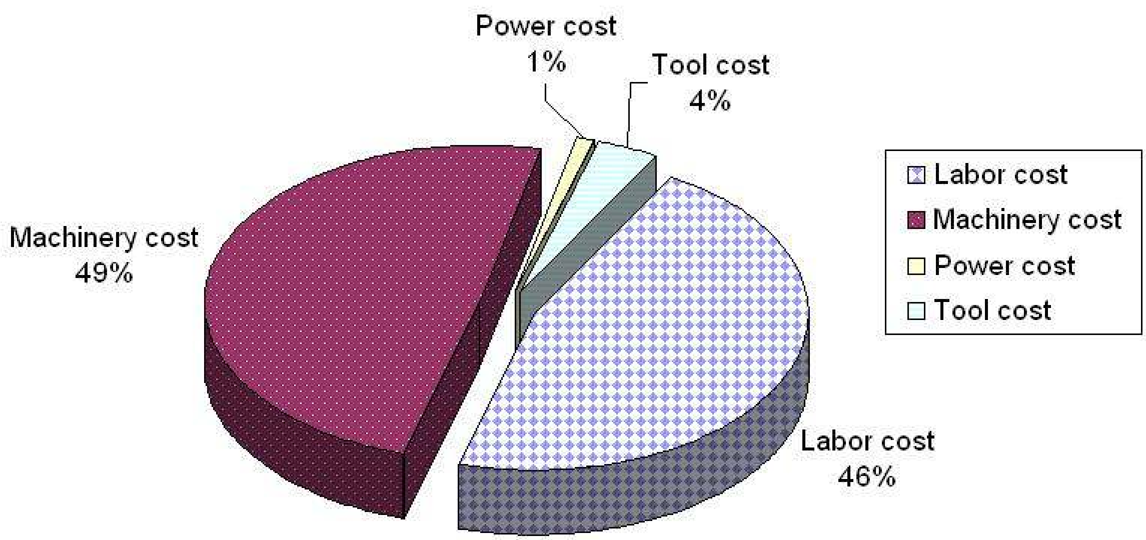


Figure 10. Distribution of cost components of FSW process*

* This figure is based on the example shown in Table 6.

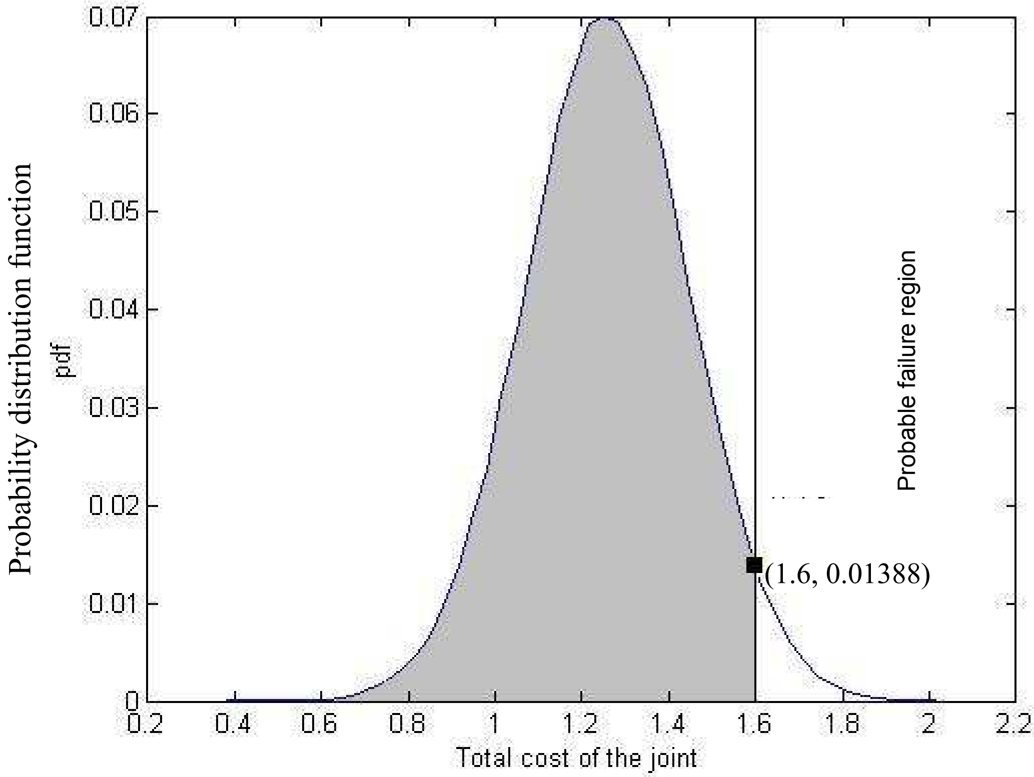


Figure 11. Degree of uncertainty in FSW cost model assuming it to be distributed normally

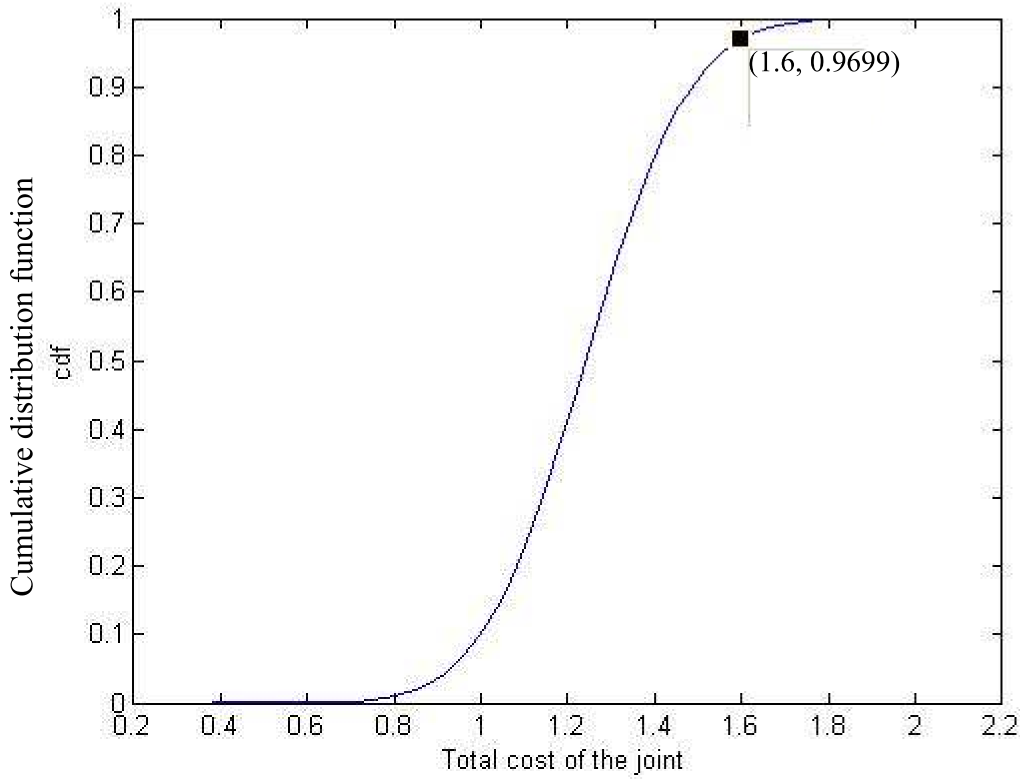


Figure 12. CDF function generated using the data from Monte Carlo simulation for FSW cost model

Table 1. Relation between amperage and filler or wire diameter[3]

Filler or wire diameter	0.03”	0.035”	3/64”	1/16”
Current (Amps)	60-100	100-160	150-200	180-280

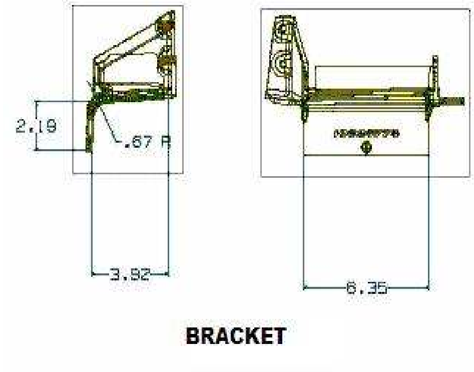
Table 2. Relation between the metal thickness and filler or wire diameter[4]

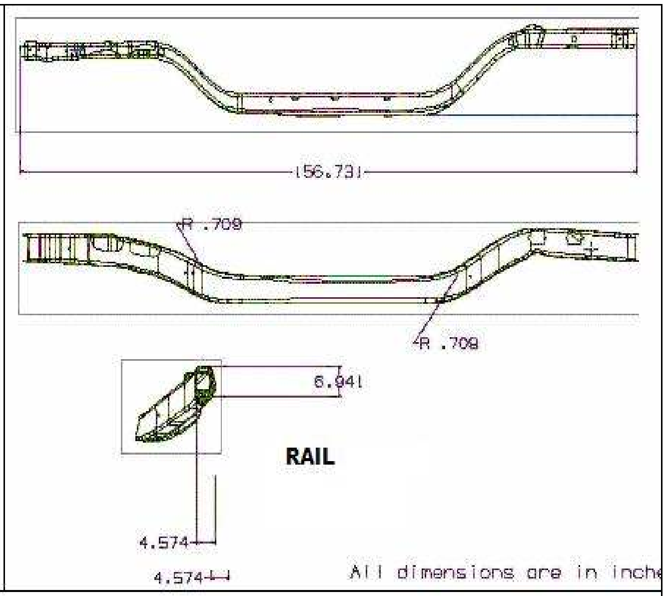
Metal thickness	**Filler material / wire diameter**
1/16”	0.03”
1/8”	0.03”, 0.035”, 3/64”
3/16”	0.03”, 0.035”, 3/64”
¼”	3/64”, 1/16”
3/8”	1/16”

[3] www.jwharris.com

[4] www.airgas.com

Table 3. An illustration of MIG mathematical cost model





This figure illustrates parts (Rail & Bracket) of a car chassis. A MIG welded lap joint between the two parts was considered. The numbers represent various dimensions of the parts.

Inputs:

Type of weld: LAP JOINT

Length of the weld, L: 9”

Thickness of the base plate, z: 0.2”

Number of weld passes, n: 1 (Assumed)

CC1: Filler material cost:

Type of material used: Aluminum 5356

Diameter of the weld wire used: 0.035”

Unit cost of the filler material, C_f: \$5.00/lb

Total cost of electrode per joint: $\frac{(0.04877 * z^2 * L)}{95\%} * C_f$ = \$0.0924 / joint

Table 3. An illustration of MIG mathematical cost model (cont.)

CC2: Variable power cost: Weld current assumed, I: 130 amps Arc voltage assumed, V: 22 volts Diameter of the weld wire used: 0.035” Average unit cost of power, C_p: \$ 0.07/kWhr (Assuming the plant site is in Michigan) Total variable power cost per joint: 5.7018* 10^{-5}*n*V*C_p*L = \$ 0.00079 / joint
CC3: Shielding gas cost: Gas flow rate assumed, F_r: 10ft^3/hr Unit gas cost, C_g: \$0.08/ft^3 (Assuming that a shielding gas with 75% argon gas and 25% carbon dioxide of 4,032ft^3 capacity is used) Total shielding gas cost per joint: 4.167*10^{-3}*n*C_g*L = \$0.003 /joint
CC4: Labor cost: Time for the weld preparation, T_W = 30 sec (Assumed) Operating factor, OF: 0.5 Unit cost of the labor, C_L: \$15.52 / hr Total labor cost per joint: $\left[4.166\times10^{-4}\times n\times L+\left(\frac{T_W}{3600}\right)\right]\times\frac{C_L}{OF}$ = \$ 0.37 / joint
CC5: Machinery cost: Power MIG 140C MIG/Flux cored wire feeder welder : \$577 Accessories & pre-weld equipments: \$514.20 Safety Equipment: \$466.46 (Let us assume the class life of the machine to be 5 yrs.) Machinery cost per joint= 8.772*10^{-4}*n*C_M*L = \$ 0.0012 / joint
CC6: Tooling cost: Not included
Total cost of the joint: C_{total} = \$ 0.47 / joint

Table 4. Cost of 42 MIG welded joints from the case study

Type of joint	Length of weld (inches)	Thickness of base plate (inches)	CC1 ($)	CC2 ($)	CC3 ($)	CC4 ($)	CC5 ($)	Total cost of the joint ($)
Lap joint	3	0.118	0.011	0.000263	0.001	0.3	0.000395	0.31
Lap joint	6.7	0.08	0.012	0.00033	0.002234	0.35	0.000823	0.36
Lap joint	6	0.11	0.019	0.0005269	0.002	0.34	0.00079	0.36
Lap joint	3.5	0.08	0.006256	0.000172	0.001167	0.3	0.00043	0.31
Lap joint	6.3	0.16	0.0414	0.0005532	0.0021	0.34	0.000829	0.38
Lap joint	2.6	0.16	0.0156	0.0002283	0.0008667	0.29	0.0003421	0.31
Lap joint	4.4	0.12	0.015	0.0003864	0.0015	0.32	0.0005404	0.34
Lap joint	4	0.16	0.0263	0.00035	0.0013	0.31	0.000526	0.34
Lap joint	8.68	0.18	0.0722	0.00076	0.0029	0.37	0.0011	0.45
Lap joint	4.6	0.12	0.017	0.000404	0.0015	0.32	0.000605	0.34
Lap joint	8.75	0.12	0.0323	0.000768	0.0029	0.37	0.0012	0.41
Lap joint	16.68	0.12	0.062	0.0015	0.0056	0.47	0.0022	0.54
Lap joint	9	0.2	0.0924	0.00079	0.003	0.37	0.0012	0.47
Lap joint	50.2	0.18	0.418	0.0044	0.0167	0.9	0.0066	1.35
Lap joint	29.29	0.12	0.1083	0.0026	0.0098	0.64	0.0039	0.76
Lap joint	3.9	0.08	0.007	0.000342	0.0013	0.31	0.000479	0.32
Lap joint	1.57	0.11	0.00488	0.000138	0.000523	0.28	0.00021	0.28
Lap joint	2.3	0.08	0.0041	0.000202	0.00077	0.29	0.00028	0.29
Lap joint	9.78	0.12	0.0362	0.000859	0.0033	0.38	0.0013	0.42
Lap joint	17.71	0.14	0.0891	0.0016	0.0059	0.49	0.0023	0.59
Lap joint	7.94	0.12	0.0293	0.000697	0.0026	0.36	0.001	0.39
Lap joint	5.2	0.12	0.0192	0.0004566	0.0017	0.32	0.0006842	0.34
Lap joint	15.75	0.11	0.0489	0.0014	0.0053	0.46	0.0021	0.52
Lap joint	5.55	0.12	0.0205	0.000487	0.0019	0.33	0.00073	0.35

Table 4. Cost of 42 MIG welded joints from the case study (cont.)

Lap joint	23.78	0.08	0.0425	0.0021	0.0079	0.57	0.0029	0.62
Lap joint	15	0.08	0.0268	0.0013	0.005	0.45	0.0018	0.48
Lap joint	3.78	0.08	0.0068	0.0003319	0.0013	0.31	0.000464	0.32
Lap joint	2.52	0.08	0.0045	0.0002213	0.00084	0.29	0.00031	0.29
Lap joint	8.19	0.1	0.0229	0.000719	0.0027	0.36	0.001	0.39
Lap joint	21.58	0.12	0.0798	0.0019	0.0072	0.54	0.0028	0.61
Lap joint	11.06	0.12	0.0409	0.00097	0.0037	0.4	0.0015	0.45
Lap joint	6.08	0.12	0.0225	0.000534	0.002	0.34	0.0008	0.36
Lap joint	5.64	0.12	0.0208	0.000495	0.0019	0.33	0.000742	0.35
Lap joint	7.73	0.12	0.0286	0.00068	0.0026	0.36	0.001	0.39
Lap joint	10.39	0.12	0.0384	0.000912	0.0035	0.39	0.0014	0.43
Lap joint	16.69	0.12	0.0617	0.0015	0.0056	0.47	0.0022	0.54
Lap joint	18.72	0.2	0.1922	0.0016	0.0062	0.5	0.0025	0.7
Lap joint	5.52	0.12	0.0204	0.00048	0.0018	0.33	0.000726	0.35
Lap joint	4.4	0.12	0.015	0.000386	0.0015	0.31	0.00058	0.33
Edge joint	23.622	0.08	0.0399	0.0016	0.0079	0.56	0.0029	0.61
Tee joint	5.85	0.12	0.3439	0.000514	0.002	0.33	0.00077	0.68
Tee joint	4.9	0.18	0.029	0.00043	0.0016	0.32	0.000645	0.35

Table 5. Monte Carlo Simulation summary statistics for MIG cost model

Cost function (g)	**Mean**	0.4493
	Variance	0.14428
PDF		0.0019
CDF		0.9999
Reliability		0.99993
Probability of failure		7.0000e-005

Table 6. An illustration of FSW mathematical cost model

Joint type	**TUBE – TUBE CONTINUOUS WELD**
Type of alloy	**6061 – 6061**

Inputs:

Type of weld: BUTT JOINT

Length of weld, L: 2.05”

Plunge depth: 0.084”

Thickness of first tube, t_1: 0.125”

Thickness of second tube, t_2: 0.125”

Number of weld passes, n: 1 (Assumed)

Type of weld: Continuous

CC1: Labor cost: Suggested Pin height = 0.073”

Diameter of the pin, D_p = 0.47”

Feed rate, F = 2.5inches/min

Plunge feed rate = 0.2inches/min

Time for weld preparation, T_{WP} = 0.5min (Assumed)

Operating factor, OF: 0.8

Unit cost of labor, C_{LR}: $14.91/ hr

Total labor cost per joint: $C_L = \left(\frac{W_T \times n}{OF \times 60} + T_{WP} \right) \times C_{LR}$ = $ 0.56/ joint

CC2: Machinery cost:

Robot ware – OS4.0, 3HAC 16640-1/M2000/Rev., IRB 940 Tricept : $350,000

Machine rate, C_{MR} = $16/hr (Let us assume the class life of the machine to be 10yrs.)

Machine reliability, MR = 95%

Setup time, T_S = 0.5 min (Assumed)

Tool change-over time, T_{Ch} = 0.5min (Assumed)

Machinery cost per joint, $C_M = \frac{[(W_T \times n) + T_S + T_{Ch}] \times C_{MR}}{MR \times 60}$ = $ 0.64/ joint

Table 6. An illustration of FSW mathematical cost model (cont.)

CC3: Variable power cost: Power rating of the weld machine, PR: 8.3KVA Time to weld, W_T: 1.84 min (From previous calculations) Machine reliability: 95% Average unit cost of power, C_{PR}: \$ 0.07/kWhr Total variable power cost per joint: $C_P = \dfrac{0.8 \times PR \times C_{PR} \times W_T \times n}{1000 \times 60 \times MR}$ = \$ 0.0105/ joint
CC4: Tool cost: Cutting fraction, Q: 0.8 (Assumed) Unit tool cost, C_t: \$800 / tool Taylor's tool life exponent, n' : 0.1 (Assumed) Tool life, T: 21603.6 min Total tool cost per joint: $C_T = \dfrac{C_t \times Q \times W_T \times n}{T}$ = \$ 0.0382/joint
CC5: Fixturing cost: Not included
Total cost of the joint: C_{total} = \$ 1.25/ joint

Table 7. Cost values of various FSW samples

Type of joint	Length of weld (inches)	Plunge depth (inches)	Feed rate (IPM)	Plunge feed rate (IPM)	CC1	CC2	CC3	CC4	Total cost of the joint ($)
					($)	($)	($)	($)	
Butt	2.55	0.07	2.5	0.1	0.71	0.78	0.014	0.0524	1.55
Butt	2.05	0.084	2.5	0.2	0.56	0.64	0.0105	0.0382	1.25
Butt	2.05	0.07	2.5	0.2	0.53	0.62	0.0099	0.0361	1.2
Butt	1.55	0.084	2.5	0.2	0.49	0.59	0.0089	0.0323	1.12
Butt	1.55	0.07	2.5	0.2	0.47	0.57	0.0083	0.0302	1.08
Butt &Lap	2.55	0.14	2.5	0.2	0.71	0.78	0.0144	0.0524	1.55
Butt &Lap	2.55	0.115	2.5	0.2	0.67	0.74	0.0134	0.0487	1.47
Butt &Lap	1.55	0.14	2.5	0.2	0.58	0.67	0.0112	0.0406	1.3
Butt &Lap	1.55	0.115	2.5	0.2	0.54	0.63	0.0102	0.0369	1.22
Lap	0.75	0.138	2.5	0.2	0.48	0.57	0.0085	0.0308	1.09
Lap	0.75	0.138	2.5	0.2	0.48	0.57	0.0085	0.0308	1.09
Lap	7	0.065	15	1.182	0.33	0.44	0.0047	0.0169	0.8

Table 7. Cost of various FSW samples (cont.)

Lap	7	0.065	10	1.182	0.41	0.51	0.0066	0.0238	0.94
Lap	7	0.065	7.5	1.182	0.48	0.57	0.0085	0.0308	1.09
Lap	7	0.065	5	1.182	0.62	0.7	0.0123	0.0446	1.38
Lap	7	0.065	3	1.182	0.91	0.97	0.0199	0.0722	1.97

Table 8. Monte Carlo Simulation summary statistics for FSW cost model

Cost function (g)	**Mean**	1.2577
	Variance	0.18964
PDF		0.087111
CDF		0.83574
Reliability		0.9643
Probability of failure		0.0357

VITA

"*E-Design Tools for Friction Stir Welding and Processing: Cost Estimation Tool*" is a thesis authored by Mr. Pradeep K Tipaji, beneficial to him in obtaining his Master of Science Degree from the University of Missouri – Rolla, USA in December 2007.

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