研究論文

GMAW 공정 중 용접 변수들이 용접 폭에 미치는 영향에 관한 연구

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The Effects of Welding Process Parameters on Weld Bead Width in GMAW Processes

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Key Word : GMAW(가스 금속 아크용접), Welding Process Parameter(용접변수), Welding Bead width(용접폭), Empirical Equation(실험식), Fractional Factorial Technique(분수의 계승방법), Multiple Regression Analysis(다 회기 해석)

Abstract

In recent years there has been a significant growth in the use of the automated and/or robotic welding system, carried out as a means of improving productivity and quality, reducing product costs and removing the operator from tedious and potentially hazardous environments. One of the major difficulties with the automated and/or robotic welding process is the inherent lack of mathematical models for determination of suitable welding process parameters. Partial-penetration, single-pass, bead-on-plate welds were fabricated in 12 mm AS 1204 mild steel flats employing five different welding process parameters. The experimental results were used to develop three empirical equations: curvilinear; polynomial; and linear equations.

The results were also employed to find the best mathematical equation under weld bead width to assist in the process control algorithms for the Gas Metal Arc Welding(GMAW) process and to correlate welding process parameters with weld bead width of bead-on-plates deposited. With the help of a standard statistical package program, SAS, multiple regression analysis was undertaken for investigating and modeling the GMAW process, and significance test techniques were applied for the interpretation of the experimental data.

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NOMENCLATURE

D	Wire diameter (mm)	t_1	Plate thickness (mm)
G	Gas flow rate (liter/min)	V	Welding voltage (V)
I	Arc current (A)	W	Weld bead width (mm)
L	Electrode extension (mm)	ρC_p	Volumetric heat capacity (J/cm^3 C^0)
Q	Rate of heat input to plate (J/sec)	λ	Thermal diffusivity (cm^2)
S	Welding speed (mm/min)	η	Heat input efficiency
T	Melting temperature-ambient temperature (C^0)		

1. INTRODUCTION

GMAW is generally accepted today as the preferred joining technique and commonly chosen for assembling most large metal structures such as bridges, automotive, aircraft, aerospace, shipbuilding and rolling stocks due to its joint strength, reliability, and low cost compared to other joint processes. An earlier attempt to procedure optimization, called a tolerance box, was developed to allow a rigorous determination of the effects on the quality of any modification of the welding process parameters, and to offer a well-informed choice of the welding process parameters in terms of the constraints imposed by the production process[1-2]. Nevertheless, this approach required a large number of tests and was found to be impractical for process control purpose when dealing with more than three welding process parameters. Such a work published before 1978 was summarized by Shinoda and Doherty[3]. McGlone[4] and McGlone and Charwick[5] reported the mathematical analysis of the relationship between arc welding variables and weld bead geometry for Submerged Arc Welding (SAW) of square edge close butts. The SAW variables in those studies included arc current, welding voltage, welding speed, bevel angle and electrode diameters. Similar mathematical relationship between arc welding variables and fillet weld geometry for the GMAW using flux-cored wire has also been reported[6].

The situation has been altered recently with the advent of increasing computer efficiency and better understanding of the usefulness of statistically designed experimentation based on factorial techniques[7] which can reduce cost and provide the required information about the main and the interaction effects on the response factor. Such techniques for establishing the relationship between welding process parameters and weld bead geometry have been reported for the arc welding in order to accomplish control over arc behavior for fully mechanized and automatic welding[8]. Raveendra and Parmar[9] presented a mathematical model for predicting weld bead geometry and shape for CO_2 shielded flux cored arc welding as functions of welding voltage, arc current, welding speed, nozzle to plate distance and gun angle by using fractional factorial method and a multiple regression technique. The experimental results have shown that a mathematical model can be a effective tool for prediction of weld bead geometry, and useful to predict the values of control variables for achieving a desired weld bead profile.

Chandel[10] first applied this technique to the GMAW process and investigated the relationship between welding process variables and weld bead geometry of bead-on-plate welds deposited by the GMAW process. These results showed that arc current has the greatest influence on weld bead geometry. However, there was no efforts to find the best empirical model which has been required development of automatic control system. Also, Yang et al. [11] carried out on experiment to determine the effects of the various process variables on the weld bead height for the SAW process. It was found that weld bead height is affecteed by the electrode polarity, electrode diameter, electrode extension, arc current, welding voltage and welding speed. A negative electrode polarity, a small electrode diameter, a large electrode extension, a high arc current or welding speed and a small welding voltage encourage a large weld bead height. Regression equations were represented for computing weld bead height from the welding process parameters, using both linear and curvilinear multiple regression techniques.

Recently, Liu al. [12] examined experimentally the weld abilities of AA 1100 aluminum and AISI 409 stainless steel by the pulsed Nd:YAG laser welding process. The effects of Nd:YAG laser welding paramenters (laser pulse time and power intensity) and material dependent variables (absorptivity and thermophysical properties) on laser spot-weld characteristics, such as weld diameter, penetration, melt rate, melting ratio, porosity and surface crater have been studied. The experimental results showed that weld bead geometry was found to be influenced mostly by the power intensity of the laser beam and to lesser extent by the pulse duration. Yang et al. [13] first extended their study to the weld deposit area and presented the effects of electrode polarity, extension, electrode diameter, arc current, welding voltage, travel speed, power source characteristics and flux basicity on the weld deposit area. The results of their experiment indicated that a small-diameter electrode, long electrode extension, low voltage and high welding speed produce a large deposit area, whereas the power source and flux type do not seem to have any significant effect on the weld deposit area.

This paper presents the results obtained in detailed experimental study regarding the effects of five welding process parameters on the weld bead width in AS 1204 mild steel flats adopting the bead-on-plate technique. The objectives were to fully characterize welding process parameters in which accurate and reproducible outputs could be generated, and to develop the mathematical models which study the influence of welding process parameters on weld bead width and help the generation of process control algorithms. The empirical models developed will be useful for identifying the various problems that result from the GMAW process and establishing criteria for effective joint design.

2. EXPERIMENTAL WORK

The experimental materials for development of mathematical formulae were AS 1204 mild steel plates with chemical composition of C 0.25%, S 0.4% and P 0.04%. To optimize the GMAW process, two samples were taken for observation after discarding 50 mm on each side to eliminate the end effects, and both surfaces were cleaned to take off dirt and oxides. The selection of the welding electrode wire was based principally upon matching the mechanical properties and physical characteristics of the base metal, weld size, and existing electrode inventory. Steel wires with diameters of 0.9, 1.2 and 1.6 mm which have composition of C 0.07-0.5%, Mn 1.00-1.50%, Si 0.60-0.85%, S 0.035%max, P 0.025%max and Cu 0.55%max, were employed as the welding consumables.

The welding process parameters included in this study were three levels of wire diameters (0.9, 1.2 and 1.6mm), three levels of gas flow rate (6, 10 and 14 liter/min), three levels of welding speed

(250, 330 and 410 mm/min) and three levels of welding voltage (20, 25 and 30 V). The arc current levels selected for 0.9 mm wire diameter were 90, 190 and 250 A, whereas the levels for 1.2 and 1.6 mm wire diameters were 180, 260 and 360 A. All other parameters except these parameters under consideration were fixed. The welding facility at the Center for Advanced Manufacturing and Industrial and Automation (CAMIA) was chosen as the basis for the data collection and evaluation. The facility consists of a GMAW unit which included a welding power source, welder remote control unit and wire torch, and a process robot manipulator that has a robot control unit and robot teach box. Torch positioning and motion control were obtained using the six axis robot controller. Experimental test plates were located in the fixture jig by the robot controller and the required input weld conditions were fed for the particular weld steps in the robot path. With welder and argon shield gas turned on, the robot was initialized and welding was executed. This continued until the predetermined-fractional-factorial-experimental runs were completed. To measure the weld bead width, the transverse sections of each weld were cut using a power hacksaw from the mid-length position of welds, and the end faces were machined. Specimen end faces were polished and etched using a 2.5% nital solution to display weld bead width. The measurements of weld bead width as shown in Fig. 1 were made using a metallurgical microscope interfaced with an image analysis system. Images are represented by a 256 level Gray scale and the program can be employed to identify weld bead width. The fractional factorial matrix was assumed to link the mean values of the measured results with changes in the five welding process parameters for determining local features of the response surface. The experimental results were analyzed on the basis of the relationship between input and output parameters of the GMAW process.

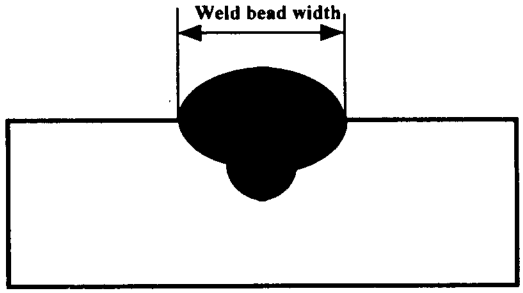

Fig. 1 Schematic representation of weld bead width

3. RESULTS AND DISCUSSION

3.1 Effects of Welding Process Parameters on Weld Bead Width

The weld bead width is determined by the amount of the wire melting and the manner in which this molten metal is spread over the workpiece surface. The factors that affect the melting rate, are arc current, wire diameter and electrode extension[2,9]. The mode of spreading over the workpiece surface is governed by welding voltage, wire diameter and welding speed[2,9]. The coupled effects of gas flow rate and wire diameter on the average weld bead width are represented in Fig. 2. The average weld bead widths were calculated by taking the average of all measured values with the same gas flow rate for a particular wire diameter, but without considering the effects of welding speed, arc current and welding voltage. It is evident that a higher weld bead width is obtained with a larger wire diameter, while the effect of gas flow rate on weld bead width seems to have little significance. Fig. 3 shows the average weld bead width against welding speed for wire diameters of 0.9, 1.2 and 1.6 mm.

Weld bead widths were produced by taking the average of all values for welds deposited with the same welding speed for a given wire diameter, but ignoring the effects of gas flow rate, arc current

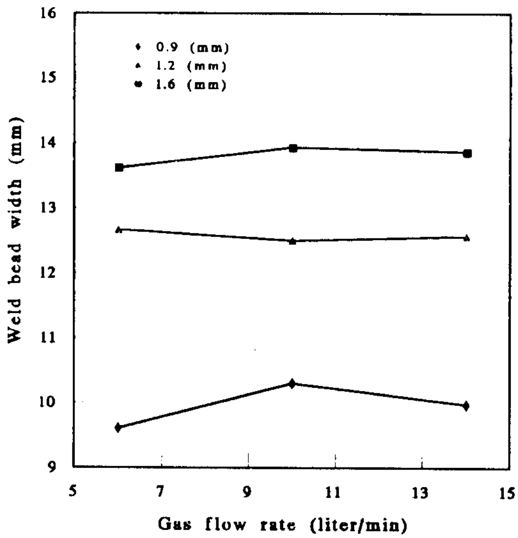

Fig. 2 The effect of gas flow rate on average weld bead width

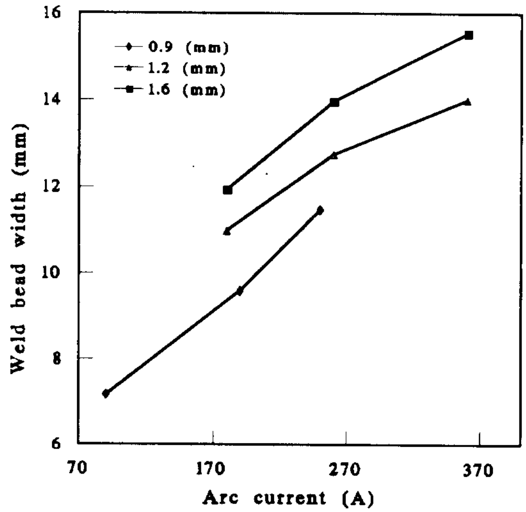

Fig. 4 The effect of arc current on average weld bead width

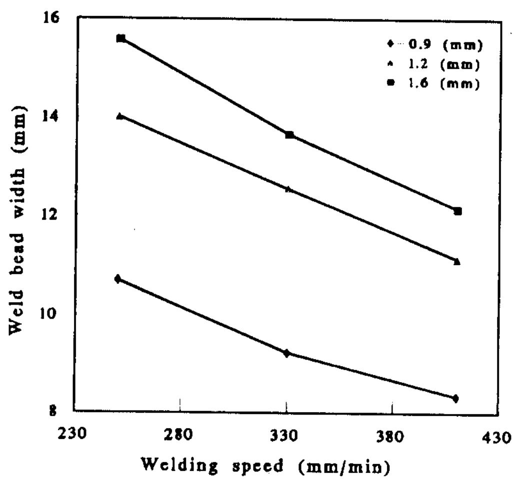

Fig. 3 The effect of welding speed on average weld bead width

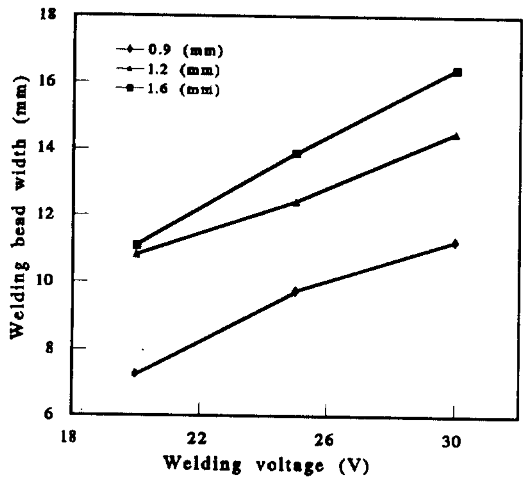

Fig. 5 The effect of welding voltage on average weld bead width

and welding voltage. It is noted that there is a decrease in weld bead width as welding speed increases. Fig. 4 presents the effect of arc current on weld bead width for three different wire diameters, respectively. The average weld bead widths were found by taking the avarage of all measured values with the same arc current for a particular wire diameter, without taking account of the effects of gas flow rate, welding speed and welding voltage. It can be seen from Fig. 4 that the weld bead width increases as arc current increases. The effect of welding voltage on weld bead width is shown in Fig. 5. The average weld bead widths were produced by taking the average of all measured values with the same welding voltage for a specific wire diameter, yet ignoring the effects of gas flow rate, welding speed and arc current. It is apparent from Fig. 5 that the weld bead width increases when there is an increase in welding voltage.

3.2 Comparing Between Theoretical and Experimental Results

Theoretical prediction of weld bead width can be predicted from conductive heat transfer studies. This assumes that the weld completely penetrates the plate being welded and heat is conducted only in the plane of the plate. Roberts and Wells[14] have estimated the weld bead width to be given by:

$$W = \frac{1}{2}\,\frac{Q}{St_1}\,\frac{1}{\rho C_p}\,\frac{1}{T_m} - \frac{4}{5}\,\frac{\lambda}{S} \tag{1}$$

Values of the material parameters were assumed to be λ=0.091 cm^2, ρC_P=4.5 J/cm^3C^0, T_m=1500 C^0 and t_l=12 mm. In GMAW, the rate of heat input to plate is given by the product of ηV and I. Heat input efficiency for the GMAW process employed to weld steel plates is based on welding process parameters such as welding voltage, arc current, electrode extension and type of shielding gas. It was assumed to be 68% for the comparisons made below. The scatter graphs of measured and calculated values of weld bead width are illustrated in Fig. 6. The line of best fit for the plotted points was drawn using linear regression computation. From Fig. 6, it is found that the weld bead width was overall slightly larger than the values obtained during experimentation. Christensen et al.[15] have presented similar findings. Also, Friedman and Glickstein[16] have analytically shown that a larger heat source tends to increase weld bead width in stationary Gas Tungsten Arc Welding (GTAW). In

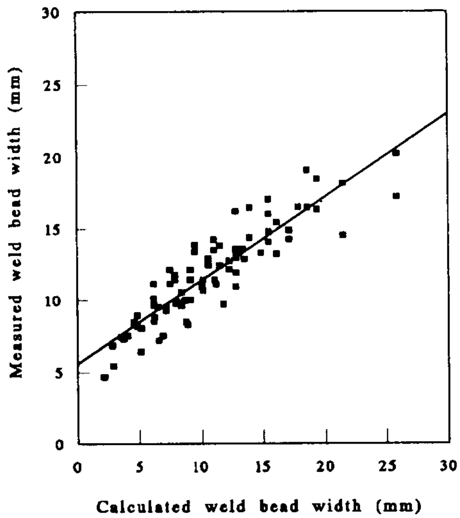

Fig. 6 Comparision of measured and calculated weld bead width

addition, it is quite evident from the above comparison that prediction of weld bead width with reasonable accuracy, based on various models, requires adjustments in order to achieve better agreement with experimental results. Since conductive, convective, radiative heat transfer and mass transfer in the GMAW process all take their toll, the development of an accurate analytical model can be complicated and perhaps inappropriate for either closed loop or adaptive control purpose. Instread, a regression model for weld bead width should be considered.

The empirical equation reported by Chandel[10] for the GMAW process was employed to predict weld bead width and presented as following:

$$W = \frac{(D)^{0.567}(L)^{0.0106}(I)^{0.181}(V)^{0.86}}{(S)^{0.614}} \times \frac{1}{(10)^{0.218}} \tag{2}$$

The welding process parameters employed to produce the 81 weld runs for fitting equation (2) were input into the Chandel's equation to provide theoretical results for weld bead width. This allowed the accuracy of Chandel's equation to be validated using experimental findings extracted during the course of this study. Results were plotted using a scatter graph for each weld bead width. Fig. 7 were produced for experimental versus theoretical results using Chandel's equation. The line of best fit for the plotted points was also drawn using regression computation. It is evident from these results that the model's accuracy is questionable and its universal applicability is limited. The conclusions from the results of this analysis show that theoretical results may not predict the experimental values with any consistent accuracy.

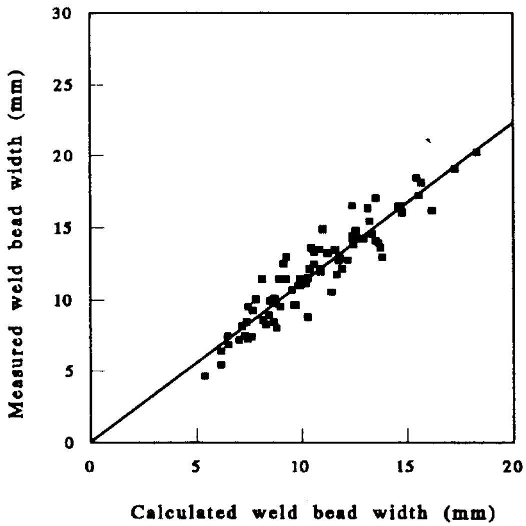

Fig. 7 Comparision of measured and calculated weld bead width using Chandel equation

3.3 Development of Empirical Models

The experimental results have shown that weld bead width is influenced by wire diameter, gas flow rate, welding speed, arc current and welding voltage. It was therefore thought that a formalized approach for development of process control algorithms could successfully establish combinations of welding process parameters which would produce welds of a given quality standard. With five welding process parameters, the response parameter (Y) could be weld bead width under considerations and express as follows:

$$Y = f(D,\ G,\ S,\ I,\ V) \tag{3}$$

Best fit equations for investigating the interrelation between the five welding process parameters and weld bead width were computed by using the standard statistical techniques such as multiple regression analysis[17-18]. These analyses were employed a standard statistical package program, SAS[19]. The following curvilinear, polynomial and linear equations for predicting weld bead width and correlating weld process parameters with weld bead width were obtained from the experimental results:

For curvilinear equation:

$$W_{cur} = \frac{D^{0.3647}\, I^{0.4151}\, V^{0.9273}}{S^{0.4873}\, 10^{0.0097}} \tag{4}$$

For polynomial equation:

$$\begin{aligned} W_{pol} = {} & 5.0102 - 0.2283D - 0.0035G - 0.0179S \\ & + 0.0098I + 0.4105V + 0.1497DV \\ & + 0.0005IV \end{aligned} \tag{5}$$

For linear equation:

$$\begin{aligned} W_{lin} = {} & -2.3053 + 3.5131D - 0.0035G - 0.0179S \\ & + 0.0213I + 0.4331V \end{aligned} \tag{6}$$

where subscrip (cur)=curvilinear regression analysis; subscript (pol)=polynomial regression analysis; and subscript (lin)=linear regression analysis.

The variance technique was employed to analyze and check the adequacies of the developed mathematical models. The Standard Error of

Table 1. Analysis of variance tests for mathematical models for weld bead width

No. of equation	Standard error of estimate	Coefficient of multiple correlation	Coefficient of determination
Equation (4)	0.712	0.9810	96.24
Equation (5)	0.791	0.9734	94.76
Equation (6)	0.832	0.9697	94.04

Estimate (SEE), coefficient of multiple correlation (R) and coefficient of determination (100 R^2) for equations (4) to (6) given in Table 1 indicate that the value of coefficient of multiple correlation of equation (5) is higher than those of equations (4) and (6), but all equations are equally useful for prediction of weld bead width due to small differences. To ensure the accuracy of the developed equations and to survey the spread of the values, three graphs (Figs 8 to 10) were produced for experimental versus theoretical results using the developed equations. Fig. 8 shows a plot of the measured weld bead width versus the calculated values obtained using curvilinear equation, whereas Fig. 9 presents a plot of the measured weld bead width versus the calculated values obtained using polynomial equation. Fig. 10 displays a plot of the measured weld bead width versus the calculated values obtained using linear equation. It is evident from these results that the mathematical models yield more accurate weld bead width and provides better prediction of the dimensions.

To make effective use of the automated and/or robotic arc welding, it is imperative that mathematical models which can be programmed easily and fed to the robot controller having a high degree of confidence, are developed. They should also cover a wide range of material thicknesses and be applied for all position welding. For the automatic welding system to use these data, the data must be available in the form of mathematical equations. It was in the light of these concluding remarks and suggestions for further developments outlined by previous researchers that the work in this paper was undertaken.

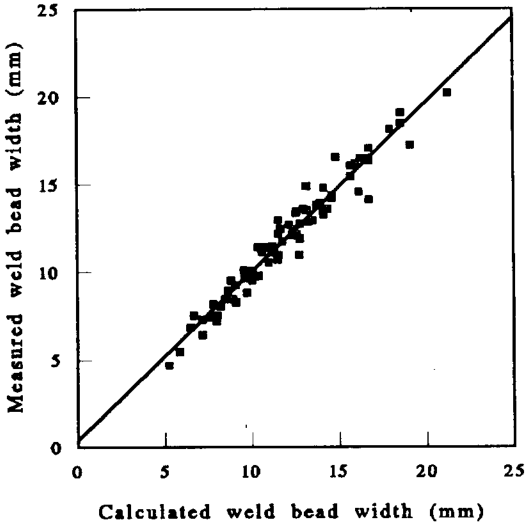

Fig. 8 Comparision of measured and calculated weld bead width using curvilinear equation

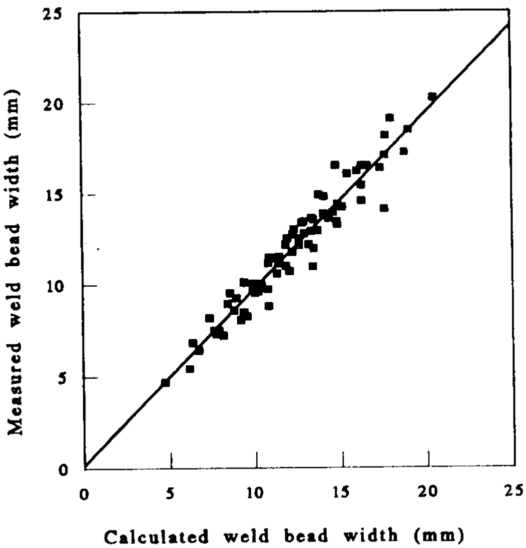

Fig. 9 Comparision of measured and calculated weld bead width using polynomial equation

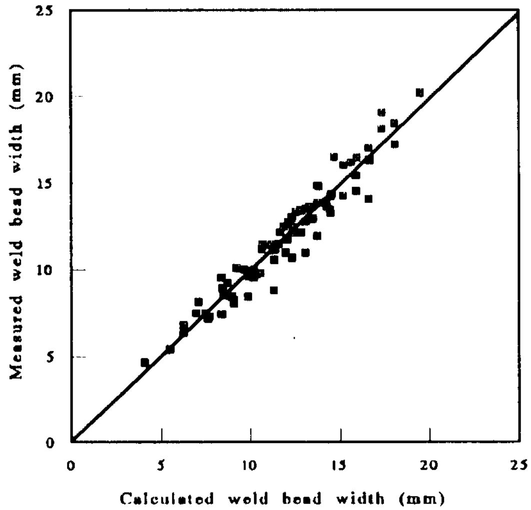

Fig. 10 Comparision of measured and calculated weld bead width using linear equation

4. CONCLUSIONS

The effects of welding process parameters on weld bead width when bead-on-plate welds are deposited using the GMAW process have been studied and the following conclusions reached.

1. Experimental results show that the weld bead width in the GMAW process is affected by wire diameter, gas flow rate, welding speed, arc current and welding voltage.
2. The weld bead width increases with an increase in wire diameter, arc current and welding voltage, but there is a decrease in weld bead width with an increase in welding speed.
3. The effect of gas flow rate on weld bead width does not seem to have any significance.
4. Mathematical models developed from experimental results can be used to investigate the relationship between welding process variables and weld bead width and predict the weld bead width with reasonable accuracy.
5. The comparison of coefficient of multiple correlation for curvilinear, polynomial and linear regression equations make no difference, which indicates that all equations are reasonably suitable.

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