MODELLING, SIMULATION AND CONTROL OF GAS METAL ARC WELDING

Marjan Golob[1], Boris Tovornik[1]

[1]University of Maribor, Faculty of Electrical Engineering and Computer Science
2000 Maribor, Smetanova 17, Slovenia

mgolob@uni-mb.si (Marjan Golob)

Abstract

The objective in this paper is to combine the simulation of Gas Metal Arc Welding (GMAW) process models with the simulation models of inverter based power machines. The main goal of proposed approach is enhancing the hardware and software design of welding devices and research of new welding technologies. The GMAW process is considered as an electrical circuit and the mathematical model is based on physical descriptions of several parts of GMAW process, as are the electric circuit of power supply, the arc dynamics, and the electrode melting process. To establish the validity of the proposed GMAW model, a simple welding application was simulated in MATLAB SIMULINK. Welding parameters ware derived from several experimental conditions. Next, the dynamic behavior of full-bridge DC-DC converter is described and suitable discrete PI controller for welding current feedback control is proposed. Both models, the GMAW model and the inverter power supply model, are combined into simulation model of the GMAW process application together with the inverter based welding machine. Presented simulations are useful for study and research of new welding technologies, and for the rapid development of new control algorithms and design of new inverter control units as are power source circuits, and welding current or voltage controllers

Keywords: modeling, simulation, gas metal arc welding process, welding power source, inverter power supply.

Presenting Author's biography

Marjan Golob received his M.Sc. degree in electrical engineering from the University of Maribor, in 1991 and Ph.D. in electrical engineering from the University of Maribor, in 2000. In 1990 he joined the Department of Automation, Faculty of Electrical Engineering and Computer Science, University of Maribor as a Research Assistant and he is currently an Associate Professor. His research area of interest includes process modeling and control, fuzzy logic theory, and industrial automation. Currently he is involved in application research project Embedded intelligent systems for gas metal arc welding process.

1 Introduction

The gas metal arc welding process, also called the MIG/MAG welding process is almost substitute for the stick-electrode arc welding process in nowadays industry. This process is often used to weld aluminum with an inert shielding gas (MIG - metal inert gas) or to weld certain ferrous metals with active shielding gases (MAG). The GMAW is an economical process suitable for welding most of metals in all positions with the lover energy variations of the process. It is appropriate for use in semi-automatic or automatic welding applications applied in high production industry.

Today, in modern welding machines the inverter based transformer technologies are used for transformation a high voltage and a low current into a low voltage and a strong current. The main advantages are small volume, lightweight, excellent control performance and good dynamic characteristics, which allow fast adaptation ability to arc load's change. This is important for welding process stability and for possibility to realize different welding applications, as are pulsed DC welding, pulsed AC welding and others. The quality of output welding current and voltage of a GMAW power source has important influence on the quality of welding product. With the aim of maintaining a high quality of welding results, the output welding current and voltage must be controlled during the welding process. Furthermore, a real time control system is an important element of modern GMAW welding machine.

The modern GMAW equipment is combination of sophisticated power electronic device and high performance microprocessors based control systems. The development process of inverter based welding power source with the corresponding control system is a complex and expensive process, which require the large human and material resources. With using simulation technique the quality of design process can be improved and design cost can be reduced.

In this paper, mathematical model of GMAW process are first developed and the simulation program is used to illustrating the behavior of the GMAW process. A description of the electric arc is presented and all equations are combined into general model, which describing the GMAW process. The simulation model has been developed in Simulink.

With a view to understand the dynamic properties and requirements of inverter power supply, a simulation model of power supply is also realized in Simulink. The dynamic characteristics of full-bridge inverter circuits are illustrated with simulation results. Both models, the GMAW model and the inverter power supply model, are combined into simulation model of the GMAW welding application with the inverter based welding machine. Simulation results are very useful for rapid development of new control algorithms and design of the new inverter control units.

2 GMAW process model

In several research studies, from example [1], [2], [3], and [5], the GMAW process is considered as an electrical circuit.

2.1 Electrical circuit of the GMAW process

In Fig. 1 the electrical circuit of welding machine power source and principle of GMAW process are illustrated.

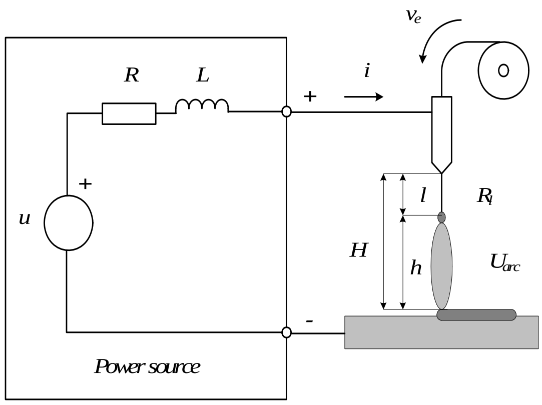

Fig. 1 Electrical circuit of the GMAW process

The GMAW process can be presented as an electrical circuit with control voltage u as the input variable. The circuit consists of the power source inductance L and resistance R, i is welding current, R_l is electrode stick-out resistance, and u_{arc} is arc voltage. Electrode stick-out resistance R_l is dependent on electrical resistivity of the electrode stick ρ, cross-sectional area of the electrode wire A, and electrode stick-out length $R_l = l\rho/A$. It is assumed that u, R, L, ρ, and A are constant parameters and i, l, u_{arc} are dependent variables. A model of the electrical circuit, presented on Fig.1, can be described with Eq. (1):

$$u = R \cdot i + L\frac{di}{dt} + i \cdot R_l + u_{arc} \qquad (1)$$

The electrode resistance R_l is depending on total length of the electrode stick-out length and drop $l=l_s+l_d$. The dynamics of l_s is depended by the feeding speed of electrode, melting speed v_m, and on the vertical velocity of the contact tip v_c. The contact tip to workpiece distance (CTWD) is indicated by H, so, if we ignoring the length of the drop ($l_d = 0$ and $l = l_s$), the following equation describe the length of the arc h:

$$h = H - l \qquad (2)$$

The dynamic of electrode stick-out could be given by Eq. (3):

$$\frac{dl}{dt} = v_e - v_m + v_c \tag{3}$$

With respect to (2) and (3) the arc length dynamics can be derived:

$$\frac{dh}{dt} = v_m - v_e - v_c \tag{4}$$

In the present model the dynamics of melting speed v_m and arc voltage u_{arc} should be described in greater detail.

2.2 Model of electrode melting speed

When the current flows through the electrode and the arc the electrode is heated by the current flowing through it. This heat is depended by resistance of the electrode. A numerous studies describe the physical background of this phenomenon. In [5] a research results of study of anode and cathode melting rate is presented and in [4] is reported the characteristic of melting rate as a function of current, type of gas, and other parameters. In those and other related works the expression for the total melting velocity v_m is :

$$v_m = k_1 \cdot i + k_2 \cdot i^2 \cdot l \tag{5}$$

K_1 and K_2 are empirical constants for given wire materials and sizes and l is the electrode stick-out.

2.3 Model of electrical arc

An arc appears during welding process between the electrode-stick (anode) and the workpiece (cathode). It can be presented as discharge of electricity between the electrodes, characterized by a high current density and a low voltage drop between electrodes. The simple model of electrical arc is a voltage equation:

$$u_{arc} = u_{a+c} + E \cdot h + i \cdot R_{arc} \tag{6}$$

The total arc voltage u_{arc}, is made up of three separate parts: the anode and cathode drop voltage u_{a+c}, the drop voltage in the arc column, which is function of the electric field strength E and the arc length h, and drop voltage, which depends on current i and arc resistance R_{arc}. In our model we suppose that u_{a+c} is constant.

2.4 Simple mathematical model of GMAW

The model of the consumable electrode GMAW process is composed by the equations (1), (4), (5) and (6). The voltage equation of electric circuit is now:

$$u = R \cdot i + L\frac{di}{dt} + i \cdot \frac{\rho}{A} \cdot l + u_{a+c} + E \cdot h + i \cdot R_{arc} \tag{7}$$

Further parts of GMAW process dynamics, for example the welding drop dynamics, or drop detachment process is also important, but in this model are neglected. They should be a subject of our further research and will be also included in simulation model.

3 GMAW process simulation

To establish the validity of the GMAW model, it was simulated in MATLAB SIMULINK. An automatic welding application was assumed. Parameters, which ware derived from experimental conditions are shown in Table 1

Tab. 1 GMAW process simulation parameters

R	0.07 Ω
L	0.02 *mH*
l	10 *mm*
ρ	1 *mΩ mm*
A	1.02 mm^2
E	0.675 Vmm^{-1}
u_{a+c}	11.55 V
R_{arc}	0.03 Ω
v_e	70 *mm/s*
K_1	0.626 *mm/As*
K_2	$7.55 \cdot 10^{-5}$ $A^{-2}s^{-1}$

The constant welding speed was supposed. The welding torch was positioned 16 mm (*H*) from work distance. Selected welding wire feed rate v_e 50 mm/s and the open circuit voltage u = 24 V ware set.

First simulation was performed to find the welding current response when the CTWD was changed from 16 mm to 12 mm (at time 2,5 s) and back (at time 7,5 s). In addition, the electrode feeding speed v was changed from 50 mm/s to 75 mm/s at time t = 5 s. Fig. 2 shows the changes in the welding voltage and current time responses and the changes of the arc length.

The welding current rise and fall with the changes of H and v_e as we expected. From the first plot in Figure 2 it can be seen that the arc length h (doted curve) is decreased after the H is changing from 16 to 12 mm and then increased back to the previous length. Accordingly, the electrode length l changed from 11.25 mm to 7.5 mm which means that electrode melted with higher speed when current increased. On the second plot of Figure 2 the electrode feeding speed is increased from 50 mm/s do 70 mm/s. This leads to reduction of arc resistance and increasing of welding current.
The simulations show that the model describes only the basic behavior of the welding process. However

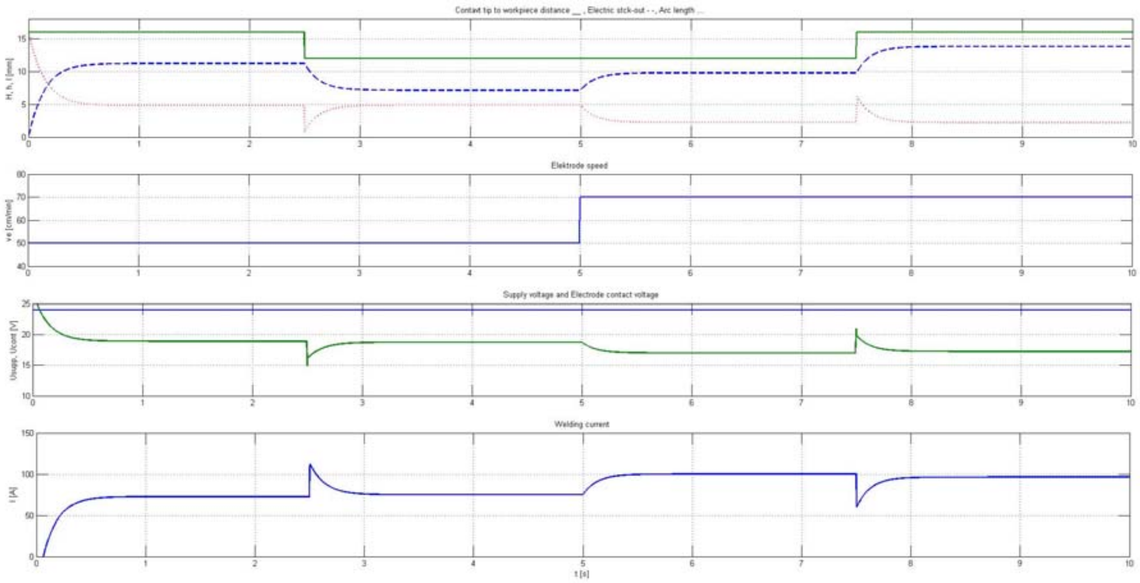

Fig. 2 Simulation response of the GMAW model when the CTWD was changed from 16 mm to 12 mm and the electrode feeding speed v_e was changed from 50 cm/min to 70 cm/min.

model should be used for design of the welding current control system in the modern inverter based welding power supply.

4 Model of inverter power supply

The inverter based welding power supply consists of a rectifier, an inverter switch circuit, a high frequency ferrite transformer, high frequency rectifier, and inductor as is presented in Figure 3.

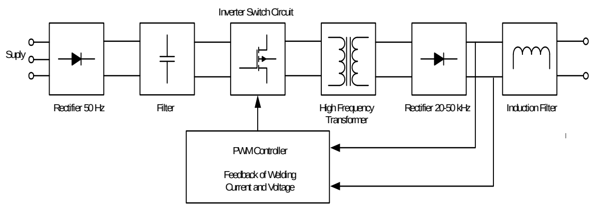

Fig. 3 Scheme of inverter based welding power supply.

Most of inverter switch circuits are realized with full-bridge DC-DC converters based on semiconductor power elements as are MOSFETs, or IGBT transistors. Switch circuits are controlled by microprocessor based PWM controller units. The Simulink simulation model of full-bridge DC-DC converter is shown in Fig. 4.

The conventional DC-DC converter operates with Pulse Width Modulation (PWM) current controller. The DC-DC converter operates at constant switching frequency, which is usually limited to 20 - 50 kHz. The amplitude of welding current is depended by change of the phase shift between the transistors Q1, Q2 and Q3, Q4. The PWM signals are generated with simple circuit and are used for driving four transistors by changing the duty cycle.

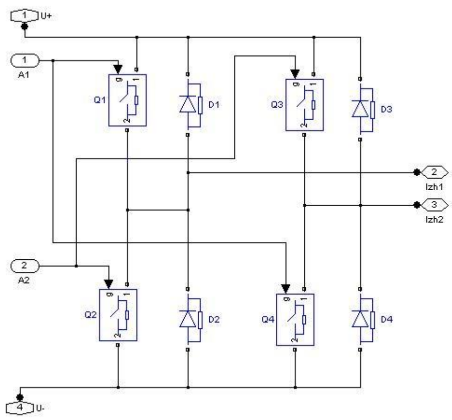

Fig. 4 Simulation model of full-bridge DC-DC converter welding power supply.

The duty cycle are usually controlled with simple feedback controller (voltage, current, or both). In Figure 5, the simple discrete PI controller is presented. The controller is realized as a simulation subsystem with common simulation blocks.

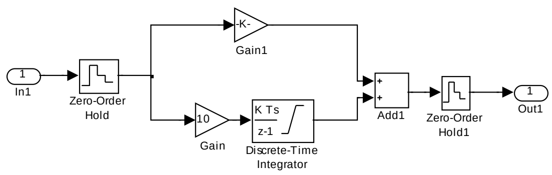

Fig. 5 Simulation model of PI controller welding power supply.

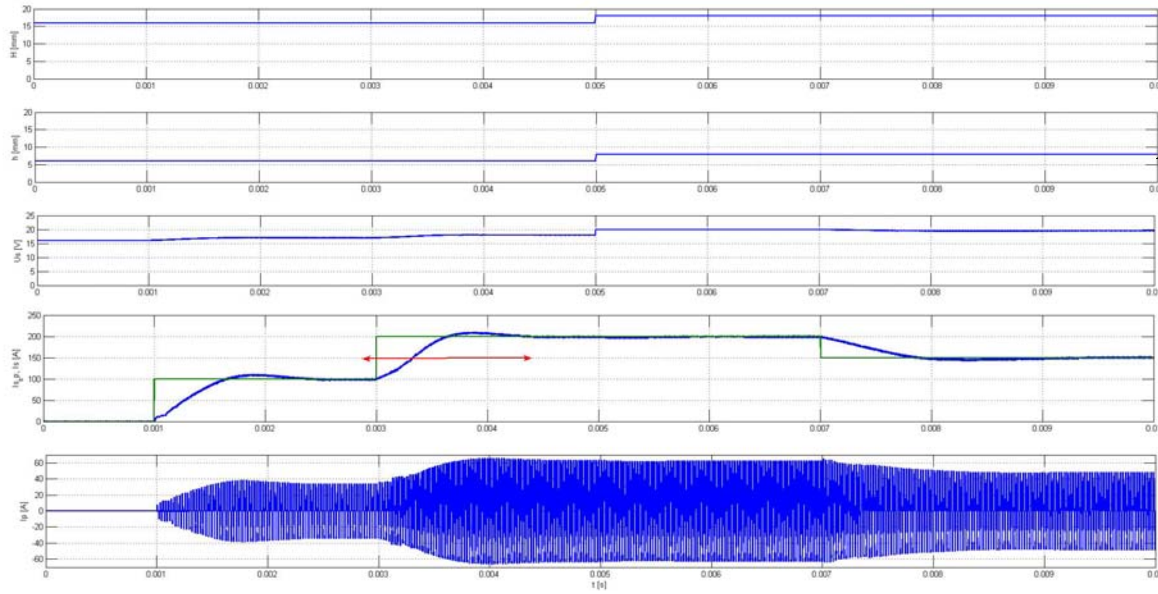

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Fig. 6 Simulation results of the welding with current control feedback and PWM full-bridge DC-DC converter

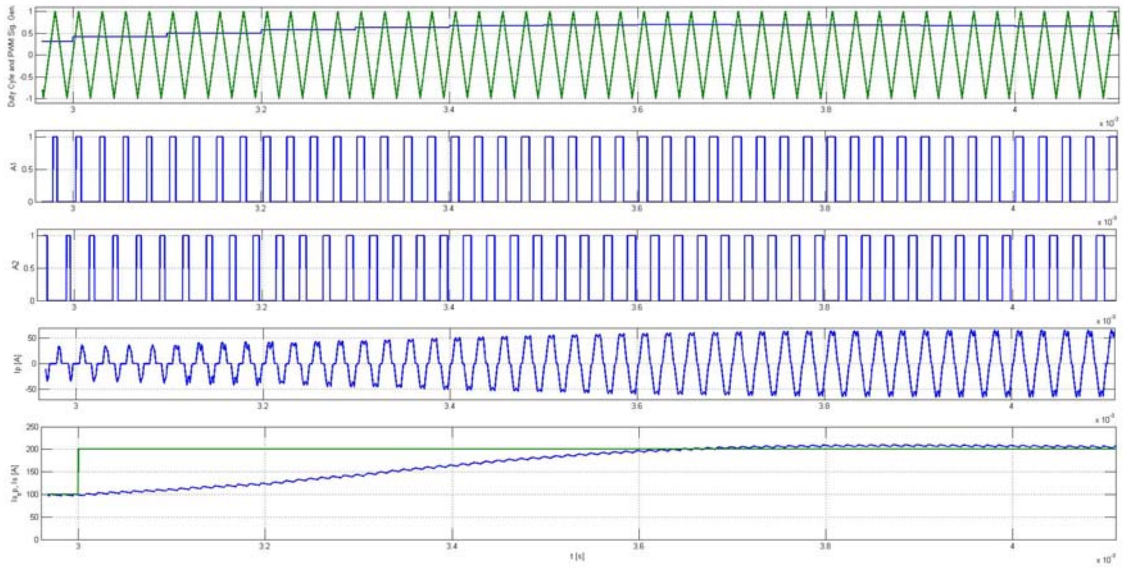

Fig. 7 Simulation results of generated PWM signals which are depends on the duty cycle controlled with simple PI controller.

5 Inverter power supply and GMAW process simulation results

A full-bridge circuit is simulated as the topology of the main inverter circuit. Load of the inverter is depending on GMAW simulation model and is continuously changing. Simulation results of the welding with current control feedback and PWM full-bridge DC-DC converter are shown in Fig. 6.

The constant welding speed was supposed. The welding torch was positioned 16 mm (*H*) from work distance (CTWD) and after 5 ms *H* was increased to 18 mm. Welding wire fed rate v_e was set to 70 mm/s. After 1 ms the welding current set point was increased to 100 A, after 3 ms to 200 A, and finally after 7 ms 150 A. The forth plot on Fig. 2 presents the current control system transient response, which is stable with small overshoot and sufficiently fast. On the fifth plot the time response of primary current is shown. For better presentation of generated PWM signals the same simulation results are plotted in time window from about 3 to 4 ms. On the first plot in Figure 7 the PWM frequency generator is compared with current controller output (duty cycle). On second and third plot the PWM signals for driving the full-bridge DC-DC converter switches are presented. Periods of pulses A1 and A2 are changing depends on duty cycle determinate by discrete PI controller. The maximum simulation step size was 0.1 μs and discrete PI controller sample time was 100 μs.

6 Conclusion

A simulation application for simulating the GMAW process and inverter based welding source has been developed. The mathematical model is based on physical descriptions of several parts of GMAW process, as are the electric circuit of power supply, the arc dynamics, the electrode melting process, etc. Further process parts, for example the welding drop dynamics and drop detachment process will be a subject of our further research and should be also included in simulation model of GMAW process.

A simulation of simple inverter power source for welding power supply has been proposed and tested together with GMAW simulation model. The simulation results shows that the conventional full-bridge DC-DC converter with appropriate current feedback controller makes the output welding current follow the setting references. The proposed models and simulations, which combine together simulation of power source circuits with simulations of GMAW process, are suitable for development and testing new power source circuits, for example the resonant converters. By establishing appropriate models of GMAW process and full-bridge DC-DC converter model, simulation can be also an effective tool for investigation of new welding technologies, for example the Surface Tension Transfer welding process (STT).

Simulation results could be very useful for rapid development of new control algorithms and for the design of new inverter control units.

7 References

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