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Research Article

Design and Implementation of PLC Based Special Purpose Machine for Surface Coating

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Abstract

To improve the quality and efficiency of surface coating with the GTAW (Gas Tungsten Arc Welding) method a semi-automatic welding machine was designed based on PLC (Programmable Logic Controller) control. The control program using ladder logic can accomplish system management and control functions. This system could control welding travel speed up to 560 mm/min, measure and saves the current status of the surface temperature at the welding zone via infrared thermometer up to 1600 °C in real-time, has complete automatic fault diagnosis, modify the welding travel speed and save the inputted welding parameters. To evaluate the performance of the designed welding machine, several experiments have been conducted. Optical microscope (OM) and scanning electron microscope (SEM) methods were used for microstructure examinations. In addition, mechanical tests were carried out with the microhardness method. An average of 377.5 HV0.2 microhardness was obtained from the surface of SAE (AISI) 1040 materials used in the experiments to a depth of 1 mm via the coating powders containing 64 wt% FeCrC + 16 wt% FeTi and 20 wt% Ni. The results from the experiments have shown that the designed PLC-based semi-automatic welding machine could be effective in determining the optimum conditions for surface coating and different welding processes.

Keywords: Surface Coating, Welding, GTAW, PLC Control.

Yüzey Kaplama için PLC Tabanlı Özel Amaçlı Makina Tasarımı ve Uygulaması

Öz

GTAW (Gaz Tungsten Ark Kaynağı) yöntemi ile yüzey kaplamanın kalitesini ve verimliliğini artırmak için PLC (Programlanabilir Mantıksal Denetleyici) kontrollü yarı otomatik bir kaynak makinesi tasarlanmıştır. Ladder mantığını kullanan kontrol programı, sistem yönetimi ve kontrol fonksiyonlarını gerçekleştirebilir. Bu sistem, 560 mm/dk'ya kadar kaynak hareket hızını kontrol edebilir, gerçek zamanlı olarak 1600 °C'ye kadar kızılötesi termometre ile kaynak bölgesindeki yüzey sıcaklığının mevcut durumunu ölçer ve kaydeder, tam otomatik arıza teşhisine sahiptir, kaynak ilerleme hızını düzenler ve girilen kaynak parametrelerini kaydedebilir. Tasarlanan kaynak makinesinin performansını değerlendirmek için çeşitli deneyler yapılmıştır. Mikroyapı incelemelerinde optik mikroskop (OM) ve taramalı elektron mikroskobu (SEM) yöntemi kullanılmıştır. Ayrıca mikrosertlik ölçümleri ile mekanik testler gerçekleştirilmiştir. Deneylerde kullanılan SAE (AISI) 1040 malzemelerinin yüzeyinden ağırlıkça %64 FeCrC + ağırlıkça %16 FeTi ve ağırlıkça %20 Ni içeren kaplama tozları ile ortalama 377.5 HV0.2 mikrosertlik elde edilmiştir. Deneylerden elde edilen sonuçlar, tasarlanan PLC tabanlı yarı otomatik kaynak makinesinin, yüzey kaplama ve farklı kaynak işlemleri için optimum koşulların belirlenmesinde etkili olabileceğini göstermiştir.

Anahtar Kelimeler: Yüzey Kaplama, Kaynak, GTAW, PLC Kontrol.

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1. Introduction

Wear is one of the most common problems occurring in engineering parts. Various surface coating techniques are used to reduce wear on machine elements. Many researchers have used methods such as gas tungsten arc welding (GTAW) (Mithun, Sellamuthu & Saravanan, 2018; Chang, Chen, & Wu, 2010; Kumar, Saravanan, Sellamuthu & Narayanan, 2018; Nair, Sellamuthu & Saravanan, 2018; Shanmugasundaram, Arul & Sellamuthu, 2018; Amirsadeghi & Sohi, 2008; Ya-long et al., 2018; Dalmis, Teker & Yilmaz, 2018), manual metal arc welding (MMAW) (Jankauskas et al., 2015; Selvi, Sankaran & Srivatsavan, 2008; Kang, Singh & Cheema, 2017), laser cladding method (Bartkowski & Bartkowska, 2017; Kwok, Cheng & Man, 2000; Yang et al., 2020), thermal spray coating (Kang, Grewal, Jain & Kang, 2012) to reduce wear on machine elements. Among these methods, the GTAW method stands out because of its easy application and cheapness (Shanmugasundaram, Arul & Sellamuthu, 2018).

Programmable logic controllers (PLCs) are widely used in many industries to control and monitor the production processes of industrial automation systems. PLCs are microprocessor-based control systems designed for automation processes. PLC-based automation systems deliver reliable, cost-effective, efficient, sustainable and flexible manufacturing systems. In the Industrial Automation System included two CNC (Computer Numerical Control) machines and a 6-axis industrial robot, PLC and artificial intelligence techniques are used together to compute the time to return to profitability Efe, Ozcan & Haklı, 2021). Welding is manually inappropriate and time-consuming in some situations. An automatic welding machine can be needed to improve welding quality and efficiency (Li et al., 2011). Controlling these welding machines is generally provided with PLC systems. PLCs are typically computer-based, solid-state, single-processor instruments that emulate the behavior of an electric ladder diagram (Patil et.al, 2014). Li et al. (2011) have conducted studies on an automatic welding machine having a PLCs control system used for the carbon dioxide gas welding. They have concluded that PLC controlled automatic welding machine is effective to enhance welding quality and efficiency. It also provides economic benefits. Rullán (1997) have studied a new MIG (Metal Inert Gas) welding approach applied in SPM based control system to weld a knuckle bracket on the circular shaft of the shock absorber. A Messung PLC has controlled the system and by this means welding process can be controlled as automatic. They have drawn attention to the importance of using PLC in their results. Alphonsus & Abdullah (2016) have reviewed applications of PLC in a variety of areas. In their results, they emphasized that PLCs have many benefits and can be used for all kinds of applications. They also stated that it might be used widely by researchers in the near future. Yufeng et al. (2018) have found the best welding parameter combination of heterogeneous high strength steel (HC550/DP780). They have chosen a ULCR-50 type CO_2 laser for this process. To control the laser welding process, PLC has been used. They have concluded that the results found can be useful for the optimization of welding technology and the improvement of welding efficiency of high-strength heterogeneous steel plates. The purpose of this paper is to describe the application of a semi-automatic welding machine and to compare and discuss its results with those of previous measurements. During the surface coating, some parameters such as welding rate, shielding gas flow rate, welding current are very important. Especially control welding rate is very difficult for welders. This study aims to avoid the time-consuming task of manual welding, reduce human efforts and increase the accuracy of welding. Therefore a new PLC-controlled welding machine has been proposed. This system has an infrared thermometer to measure temperatures between 385°C and 1600°C. The proposed system can save experimental parameters to a USB flash drive, which are important during welding operation such as welding rate, temperature, welding current and shielding gas flow rate through a human-machine interface (HMI). A surface coating process has been carried out to see the effectiveness of the welding machine. Since AISI 1040 steel is widely used in today's machinery manufacturing industry, it was used as the substrate material, and FeCrC, FeTi and Ni powders were used as coating powders.

2. Material and Method

2.1. Design of Semi-Automatic Welding Machine

The designed system has two linear movements. One of them is provided manually and the other is provided automatically. The vertical movement required to adjust the torch height is given by hand. The geared motor is operated with an inverter via the control signal coming from the PLC. Torque from the motor is transmitted to the nut through the ball screw. It turns into linear motion with the linear guides connected to the nut and torch movement is provided as linear. The screw step is 5 mm. The maximum rotational speed of the gear motor is 112 rpm and the maximum feed rate of the system for welding is 560 mm / min. A Fume extractor has been located on the machine for extracting welding fumes from the environment. All controls for adjusting the fume extractor during operation are located outside and no other additional part is required. A general view of the semi-automatic welding machine is shown in Figure 1.

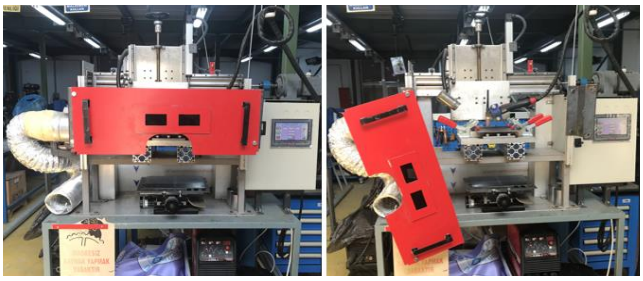

Figure 1. General view of the semi-automatic welding machine

2.2. Control System

The semi-automatic welding machine will be equipped with a PLC-based control system. Figure 2 represents a block diagram of the designed control system.

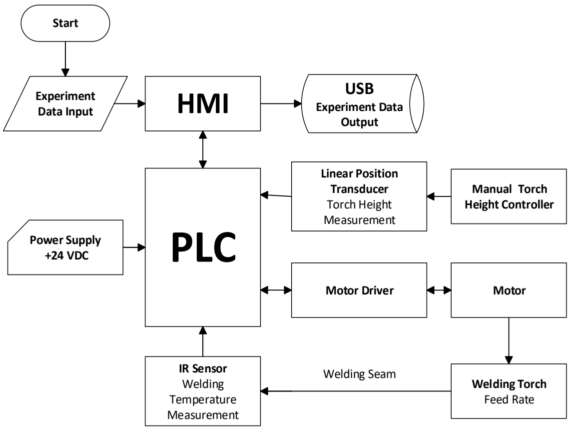

Figure 2. Block diagram of the designed control system

The system consists of hardware and software units. A PC runs programs called GMTSoft and ENDA.EOP, which are used to write a control program for the PLC and a graphical screen design for the HMI. The control program is downloaded to the PLC through the ethernet communication cable. The HMI program is downloaded to the HMI via USB cable.

Enda GLC 386RT PLC CPU module was used as a control device. The PLC control unit supports 4 relay outputs, 2 pulse outputs (12,5kHz), 1 analogue input (0-10VDC, 10 bit resolution) and 1 analogue output(0-10VDC, 14 bit resolution), 1 port RS232, 1 port RS485, 1 port Ethernet, RTC (real-time clock). tconsumption is 3W max. Its control program was written in Ladder Diagram (Figure 3).

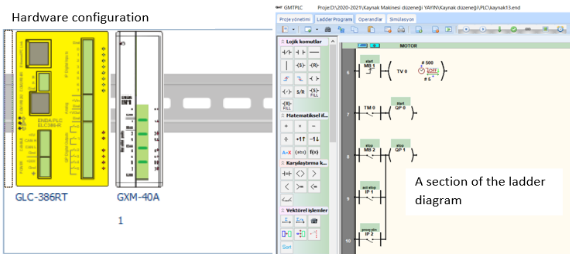

Figure 3. Control system of PLC based special-purpose machine and ladder diagram

GMT CNT GXM-40A analog module was used as a data acquisition device. The analog input module takes analog values produced by the temperature sensor and converts them to digital signals for the PLC CPU module. The data (temperature) are also sent to a USB flash drive plugged into the HMI USB port. An analog module is snapped onto the rail next to the CPU on the right and is electrically and mechanically connected to the CPU by plugging its male connector into the receptacle on the side of the CPU. This device offers software-selectable analog input ranges for 0-10V, 0-20mA and 4-20mA. It has a resolution of 16-bits with a measurement accuracy of 0.5%. Its read speed is up to 1 kHz for every single channel.

An inverter was used as a motor driver. The inverter is connected to the PLC via the programming terminal of the drive communication cable. The inverter functions as an interface between the PLC and the motor. PLC sends out a control signal to the inverter for the driving motor. The inverter converts the corresponding analog input voltage (0-10VDC) to the required output frequency. The control signal to the inverter is an analog signal representing the desired inverter output frequency.

Human Machine Interface (HMI) provides a user interface to humans for interacting with machines. In this study, Enda GOP41-070ETE HMI is used to monitor and control various welding variables such as temperature, torch height, shielding gas flow rate, welding current and experiment number. It is connected to PLC by an RS232 cable. In this system, HMI provides information with welding speed, operating temperature, torch height, shielding gas flow rate, welding current and experiment number (Figure 4).

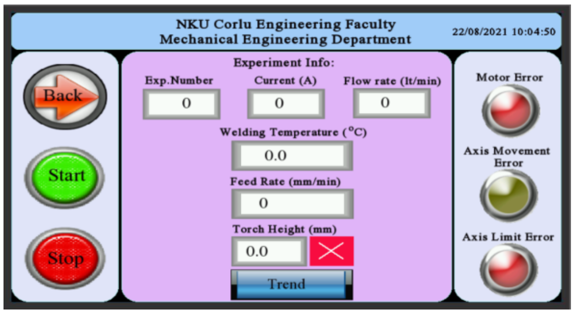

Figure 4. HMI Screen of the developed control system

2.3. Temperature Measures

An infrared thermometer (IR) has been used to measure operating temperature (Figure 5). High peak temperatures and cooling rates are some of the most important parameters for the welding process (Yufeng, Sili & Changwei, 2018). Knowing the cooling rates in the heat-affected zone during the surface coating process is an important criterion in determining the internal structure of the material. The formation of brittle structures such as martensite in most steels is related to the high cooling rates. By controlling the temperature and cooling rate, martensite formation can be prevented (Taysom, & Sorensen, 2020). Infrared (IR) temperature measurement has been widely used in the fields of welding. A non-contact IR thermometer (Micro-Epsilon thermometer CTLM-2HSF300-C3) was used to measure surface (operating) temperature during the welding process, which is applicable in the temperature range of 385–1600 °C. It was mechanically placed at a distance of 200 mm height from the welding zone and focused 10 mm forward to the welding region. After the first installation of the infrared thermometer, the desired temperatures can be measured easily from each point.

Figure 5. Infrared thermometer (IR) to measure temperature profiles

In order to draw the surface temperature curve, the temperature was measured by the infrared thermometer in the designed semi-automatic welding machine. The temperature cycle can be measured in any different points of the weld and so we can obtain peak temperatures, cooling rates and find the best welding parameter combination for GTAW surface coating.

2.4. Surface Coating

A surface coating application has been made to illustrate the effectiveness of the designed semi-automatic welding machine (Figure 6). Hot rolled plate AISI 1040 steel (100 x 30 x 10 mm in size) was used as substrate and alloyed by GTAW processes (Dalmis, Teker & Yilmaz, 2018).

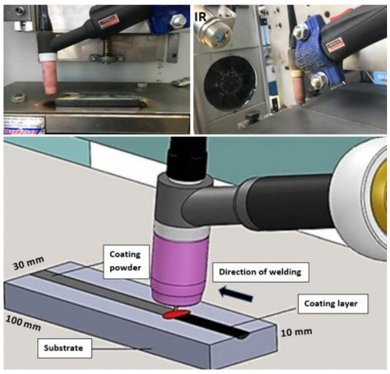

Figure 6. Surface coating application by GTAW and temperature measuring by infrared thermometer

Prior to coating processes, the surface of samples was ground with emery paper followed by cleaning with acetone to remove dirt and rust from their surfaces. The coating powders containing 64 wt% FeCrC + 16 wt% FeTi and 20 wt% Ni were mixed with the binder (sodium silicate) and pre-placed to the channels with a width of 10 mm and depth of 0.3 mm. The chemical composition of the coating powders and substrate material SAE (AISI) 1040 steel is shown in Table 1. Finally, they were dried in a heat treatment oven at 100 °C for 30 minutes to remove the moisture which is harmful to the welding process. A thoriated tungsten electrode with a diameter of 3.2 mm was used and the arc distance from the surface of the substrate was 2 mm during the process. An argon gas at a flow rate of 12 l/min was supplied as shielding to protect the processes zone from the harmful effects of the atmosphere. The current used for the GTAW (Lincoln Invertec V205-T AC/DC) melting is 150A and process speed is 60 mm/min. GTAW process parameters are shown in Table 2. The surface and cross-sectional morphologies of samples were observed by optical microscope (Optika B-500 MET) and SEM (Quanta FEG 250). To determine the depth of the clad layers, microhardness test analysis was performed with an HV hardness scale under 200 g loads at 0.5 mm intervals by MICROBUL 1000-DN test device.

Table 1. Chemical composition of SAE (AISI) 1040 steel and coating powders

	C	Fe	Mn	P	S	Si	Cr	Ti	Al	Ni
AISI 1040	0.4	Balance	0.6	0.04	0.05					
FeCrC	6.2	Balance		0.03	0.02	1.5	64			
FeTi	0.11	Balance			0.008	0.05		70.35	3.86	
Ni										99.99

Table 2. GTAW parameters used for surface alloying

Current (A)	Electrode Tip Angle (°)	Travel Speed (mm/s)	Stand-off Distance (mm)	Electrode Diameter (mm)
150	180	1	2	2.4

3. Results and Discussion

Tests were performed with the welding machine designed to examine thermal events during welding. During these tests, welding heats which are important for the welding process are examined. Thermal events important for surface coating are taken from the infrared thermometer and information is recorded by means of a USB flash drive. Figure 7 shows macrographs of FeCrC based composite clad layers and thermal events occurring at a distance of 10 mm from the heat-affected zone (HAZ) at a rate of 60 mm / min and a current of 150 A by GTAW. Visual inspection is the most common non-destructive testing (NDT) method of evaluating surface weld quality without using any testing method. The experimental results show that the tracking welding of the flat steel weld was realized by the automatic welding system based on PLC control. The weld is well-formed when the welding speed is 1 mm/s, which ensures the welding quality. The feasibility and reliability of the automatic welding system based on PLC control was illustrated by the experimental results (Liu, Ye & Niu, 2019).

After GTAW surface coating, the re-solidified layer was studied to observe the microstructure. Figure 8 represents optical images of the cladding layer. When the figure is examined, it is seen that dendritic solidification was observed and carbides in the structure are homogeneously distributed. The achievement of homogeneity shows the efficiency of the coating process and welding machine.

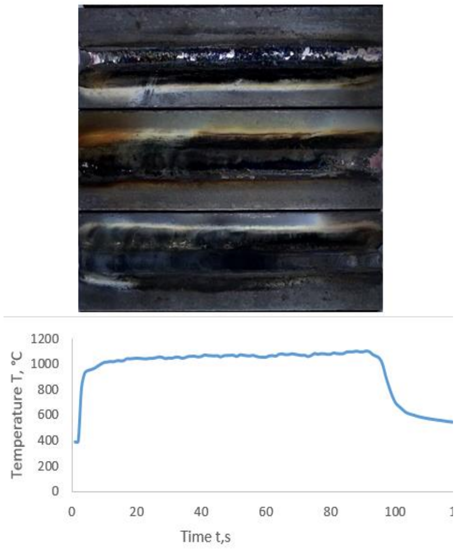

Figure 7. Macrographs of FeCrC based composite coatings and welding thermal cycle

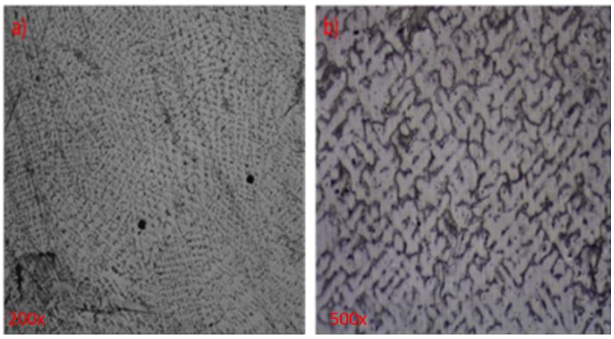

Figure 8. Optical microscope images of cladding layer a) 200x b) 500x

Figure 9 shows the SEM image of the transition zone between the covered layer and substrate material. It was seen that the martensite phase was formed with the effect of rapid cooling in the structure.

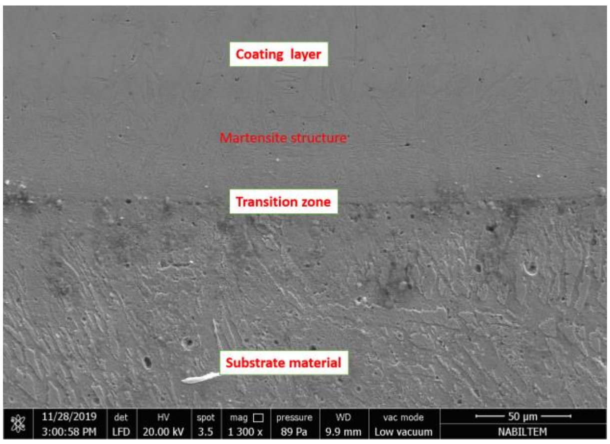

Figure 9. SEM image of transition zone (2500x)

Figure 10 illustrates the hardness profile of the cladding layer. The increase in hardness compared to the substrate material is related to the carbide formation in the structure (Dalmis, Teker & Yilmaz, 2018).

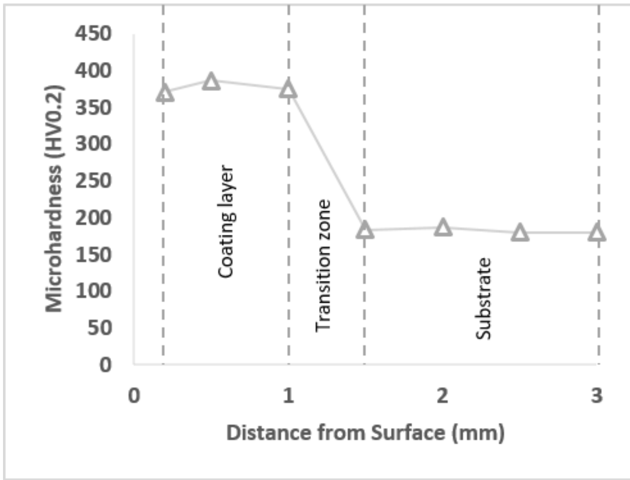

Figure 10. Hardness profile of cladding layer and substrate

It is thought that nickel has pushed chromium to the grain boundaries in the structure and hard complex carbides are formed due to the increasing chromium concentration in the grain boundaries.

In addition, titanium from ferrotitanium powders is predicted to form a TiC compound with carbon, which is thought to be among the factors that increase hardness (Xiao, Zhang, Wu, Qiu, Zhou, ... & Zeng, 2021).

4. Conclusions and Recommendations

Experimental results show that the semi-automatic welding machine is simple and effective at improving welding quality and efficiency for surface coating. PLC based control system provided a significant advantage over manual welding. The developed prototype machine was able to perform the coating processes at the specified input speeds. The linear movements of the machine took place smoothly on the linear beds. Limit switches worked flawlessly.

As a result, welding seams were obtained with the expected linearity in visual inspections. As we can measure temperatures from any point, the designed system is more outstanding than systems having thermocouples. It is thought to be effective in determining the optimum conditions in the coating processes as it is faster and more reliable. The developed semi-automatic welding machine can be used in both welding and surface modification (coating) applications. With the developed system, welding parameters and application temperatures can be recorded. The success of the application can be evaluated by converting the obtained data into graphics.

The regularity of the welding heat input directly affects the coating quality. The temperature graphs of the welding process measured by the developed setup give us an idea about the welding and coating qualities.

The success of the machine was also seen in hardness measurements. In the micro-hardness measurements, a coating zone with a hardness of over 370 HV0.2 was obtained from the coating surface of the main material to a depth of 1 mm. As can be seen from previous literature studies, the increase in hardness is due to alloying elements and formed carbides. In addition, from the microstructure images, it has seen that the phases in the structure have been homogeneously distributed and there has been no fluctuation in the hardness results.

Due to the high carbon content in the substrate material, martensite formation has been observed due to the heat effect and rapid cooling.

It is important to determine the suitability of the machine developed in the research by making trials in different welding applications. The next stage of the research is aimed to make the torch height automatically controlled. Thus, automatic welding applications would be made in different geometries.

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