Microstructure and Hardness of Compression Mold Fabricated by Fused Deposition Modeling Process

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Abstract— **Various rapid prototyping techniques have been developed for the growing industrial demands, which includes fabrication of compression molds for rubber products. The fused deposition modeling (FDM) process is one of the rapid prototyping techniques capable of producing molds with reduced cost and fabrication time. The FDM process employed in this study involves deposition of steel wires onto steel substrates, using MIG/MAG welding machine equipped with CNC milling machine. The steel wires were deposited layer by layer from bottom to top and milled for surface finish. Microstructure and hardness of the mold were examined using scanning electron microscope (SEM) and Rockwell hardness test. Results from microstructural analysis revealed that there was no appearance of macroscopic pore or crack in the substrates, the deposited wires and the interfaces between substrates and wires. Only micro or submicro-sized pores were observed. Average grain size of the substrate, the deposited wire and the interface areas were 26.1, 11.1 and 9.5 micrometers, while hardness of the same regions were 73.1, 70.8 and 77.5 HRB, respectively. Absence of macroscopic pore or crack as well as comparable hardness for all areas indicated that the deposition process was well controlled.**

Keywords— **Microstructure, Hardness, Fused Deposition Modeling, Mold**

I. INTRODUCTION

Fabrication of compression molds for rubber products requires a technology which accommodates short time processing. Rapid prototyping technology, such as fused deposition modeling (FDM), has been developed for the growing industrial demands. The FDM technique can facilitate fabrication of near-net-shape compression molds with reduced cost and fabrication time. The FDM technique employed in the mold fabrication process involves deposition of steel electrode wire onto a steel substrate layer by layer from bottom to top, using MIG/MAG welding machine.

One of the considerations in producing compression molds by FDM technique is microstructure of the molds. Uncontrolled deposition process can lead to residual porosity within the materials. Open pores with large size, in range of millimetre, can be detrimental to the rubber products. Macroscopic pores on the mold surface may result in surface roughness of the rubber products. In addition to the surface roughness, large pores can have detrimental effects on mechanical properties of molds. It has been reported that porosity in the weld metal could cause deteriorated mechanical properties [1-5].

Porosity in the weld metal is typically formed by gas entrapment during solidification. Formation of pores can also be attributed to the presence of contaminants, such as oil, dirt or moisture, in the welding zone. In addition, inappropriate welding parameters, such as current and welding speed, can lead to porosity. In order to eliminate porosity and to retain mechanical properties of the compression molds, it is therefore crucial to employ appropriate deposition parameters during the deposition process.

Grain size is also an important parameter to characterize the microstructure, since it strongly related to mechanical properties. It is generally accepted that yield strength of materials decreases with increasing grain sizes. Size of grains is greatly affected by heat; high temperature encourages grain growth. Since FDM involves high temperature processing, the process should be controlled to avoid excessive grain growth.

This study is aimed at investigating microstructure, specifically pores and grain sizes, of compression molds fabricated by the FDM process. Hardness of the molds was also examined. Results from microstuctural examination and hardness test were used in determining the appropriateness of the parameter employed in the mold fabrication process.

II. EXPERIMENTAL PROCEDURE.

A. Materials

In this study, a SS400 steel plate with dimension of 250 mm * 150 mm * 25 mm was used as substrate, while commercial steel wire ER70S-6 with diameter of 1.2 mm was used as electrode for deposition.

B. Deposition Process

Fabrication of core part of compression molds, shown as part #3 in Fig. 1, by fused deposition modeling employed a hybrid process that combines (a) material deposition process using MIG/MAG welding machine to form the shape layer by layer and (b) material removal process using CNC milling machine to enhance the surface finish.

Materials deposition process involved feeding of the electrode wire into the nozzle. The electrode was then melted and deposited onto the substrate. The motion of X-Y table, where the substrate located, was controlled to accommodate the deposition. When deposition of one layer was completed, the nozzle was elevated to compensate the height of the deposited layer. The electrode was deposited layer by layer from bottom to top. The deposition process was set up according to parameters given in Table 1.

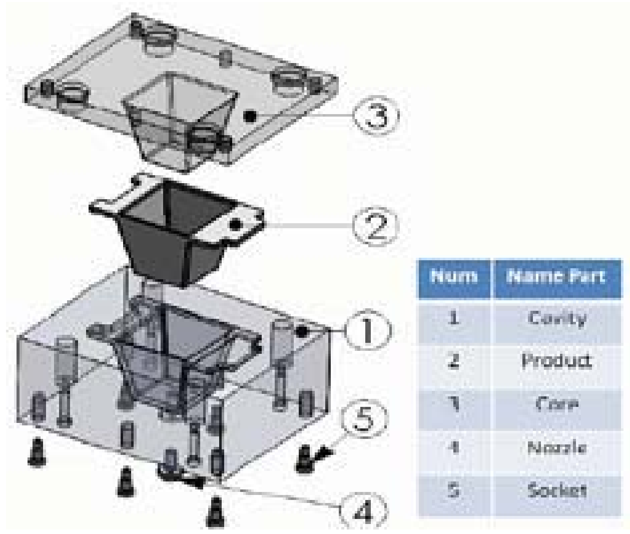

Fig. 1 Schematic presentation of compression mold, showing cavity part, rubber product, and core part designated with #1, 2 and 3, respectively

TABLE I
SUMMARY OF PARAMETERS EMPLOYED DURING THE DEPOSITION PROCESS

Shielding gas	Argon 70% CO_2 30%
Current (A)	150
Voltage (V)	19
Weld speed (m/min)	0.4
Nozzle-to-work distance (mm)	10
Electrode feeding speed (m/min)	2.5

C. Characterization

Macroscopic defects of the mold were investigated by radiographic examination, while microscopic defects were examined by scanning electron microscope (SEM) (Phillips XL30). Secondary electron mode was used to obtain microstructural images.

Sample preparation for the microstructural examination was achieved by slicing the mold into cross-section and cutting it into a rectangular-shaped sample with dimension of 38 mm * 60 mm by an Endmill, as shown in Fig. 2. The sample was then ground through 240-1200 grinding papers and etched in nitric acid for 15 seconds. Quantitative grain and pore size analysis of the sample was performed by using SEM micrographs. The sizes of grains and pores were analyzed by Scion Image Software. To obtain average values of grain and pore sizes, a minimum of 100 grains and 50 pores were used in the measurements.

Hardness of the sample was measured by Rockwell hardness testing machine (Indentec) with ball indenter (HRB, 1/16”). The load of 980.7 N was applied to the samples during the test.

Fig. 2 Cross section of core part of the mold, showing substrate and deposited electrode, designated as region A and B, respectively

III. RESULTS AND DISCUSSION

A. Macroscopic Defects

Visual examination was initially used in examination of macroscopic defects in the sample. The sample in Fig. 2 shows distinguished interfaces between the steel substrate and the electrode, designated as region A and B, respectively. Visual examination indicated that no large crack or pore were present in both substrate and electrode area.

Radiographic image, as shown in Fig 3, confirmed the trend in the visual observation. Cracks or pores have a higher radiographic density than the surrounding area. Therefore, cracks normally appear as dark lines, while pores appear as dark round, irregular spots or elongated holes in the radiographic image. The results obtained from the investigation appeared to be clean. There was no evidence of dark lines or spot in the samples which indicated that the sample contained no macroscopic cracks or pores

In addition, the radiographic analysis also revealed that the sample did not contain slag inclusion or incomplete fusion region, as there was no evidence of jagged asymmetrical shapes or dark line oriented in the direction of the joining seam in the radiographic image.

Fig. 3 Radiographic image of core part of the mold, showing substrate and deposited electrode, designated as region A and B, respectively

It is accepted that good-quality fusion-welded materials should meet following criterions: (i) there should be no evidence of surface breaking, cracks or incomplete fusion and (ii) large pores with size in millimetre range should not be detected. Results from visual and radiographic investigation, therefore, indicated that the mold was free from macroscopic defects and the deposition process was well-controlled.

B. Microstructure

1) Porosity: Microscopic defects in the sample were examined by scanning electron microscope. The SEM micrographs revealed that spherical pores were present in the sample, as shown in Fig 4. Quantitative pore analysis indicated that the pores observed in the sample had average diameter of 8.96 µm, while porosity of the sample was estimated to be 0.49% by area

Porosity is one of parameters listed in acceptance criteria of the welded materials. The acceptable level of porosity should not exceed 5%. Large size of the pores contributes to the higher porosity level. Nevertheless, materials with small sized pore are not affected by the acceptance criteria. According to D. Rybicki, porosity and inclusions with diameter less than 0.25 mm (250 µm) do not need to be considered for the inspection [6]. In addition, it has been reported that spherical pores with sizes smaller than 0.5 mm has no effect on tensile properties or toughness [7].

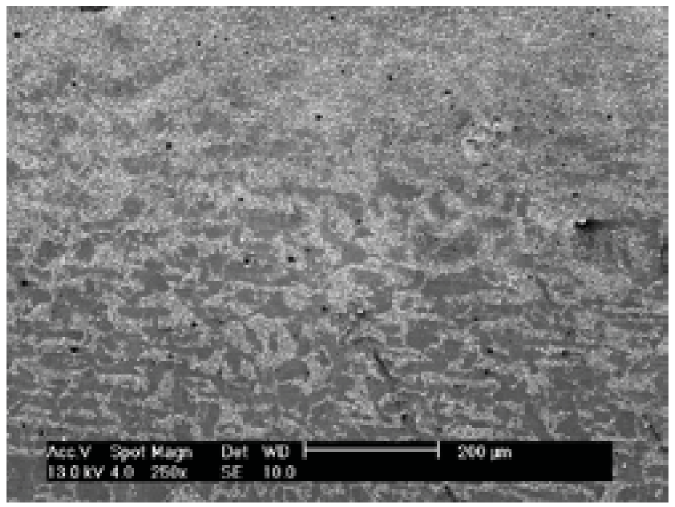

Fig. 4 SEM micrograph of the mold showing small pores in the sample

The porosity analysis suggested that the mold satisfied acceptance criteria in terms of porosity. The low porosity in the mold may be attributed to appropriate deposition parameters, such as arc length, welding current, composition of shielding gas, welding speed, or absence of contaminants such as oil, dirt or moisture in the welding zone.

Another factor contributed to the low porosity level is deposition technique. The FDM process used in this study involves deposition of materials and milling the surface of deposited layer prior to deposition of another layer. Milling is believed to enhance surface finish of each deposited layer, which resulted in good contact between adjacent layers. This contributed to low level of porosity.

2) Grain Size: Microstructure of steel substrate, interface between the substrate and electrode wire and electrode wire consisted of ferrite and pearlite, as shown in Fig 5-7. Nearly equiaxed ferrite grains with lamella pearlite structure along grain boundaries were evident in the micrographs. The ferrite-pearlite type of microstructure is common in welded low carbon steel, especially in SS400 and ER70S-6.

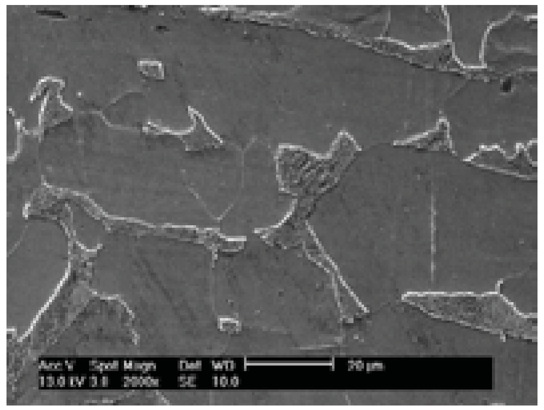

Fig. 5 SEM micrograph of the mold, showing grain in the S400 substrate area

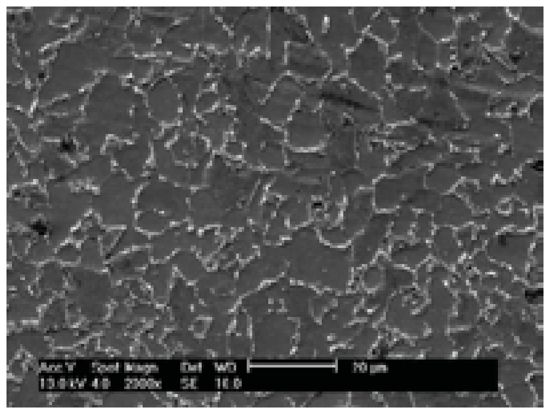

Fig. 6 SEM micrograph of the mold, showing grain in the interface area

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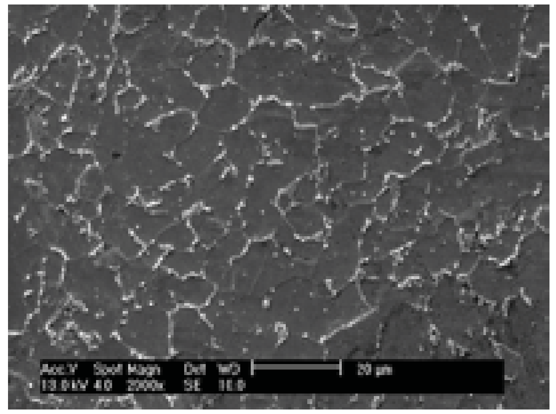

Fig. 7 SEM micrograph of the mold, showing grain in the electrode area

Grain size is a critical parameter to characterize the microstructure, as it is strongly related to mechanical properties. Since strength increases with decreasing grain size, excessive grain growth should be avoided to prevent deterioration of mechanical properties.

Microstructural analysis revealed that the mold contained relatively small ferrite grains. The average grain sizes of 26.1, 9.5 and 11.1 µm were observed in steel substrate, electrode wire and interface, as shown in Table II. The values observed in this study were small compared to other study. It has been reported that average grain size in the heat affected zone of SS400 steel could be as large as 127 µm [8]. Our results indicated that no excessive grain growth occurred during the deposition. This is attributed to the appropriate applied voltage and current, which consequently results in proper welding heat input.

TABLE II
AVERAGE GRAIN SIZE OF FERRITE INVESTIGATED IN DIFFERENT AREAS

Investigated Areas	Average Grain Size (µm)
SS400 steel substrate	26.1 ± 10.4
Interface between substrates and electrode	9.5 ± 2.6
ER70S-6 electrode wire	11.1 ± 3.1

C. Hardness

Welding heat input can affect hardness of the sample, Undesirable hard microstructures susceptible to cracking and brittle fracture and excessively soft microstructures susceptible failure under load can be originated from inappropriate welding heat input. Low heat input usually results in rapid cooling, which consequently lead to hardening of the materials. On the contrary, high heat input results in slow cooling rates and softening of the materials.

Average hardness values obtained from the hardness test of the sample ranged from 70.8 to 77.5 (in HRB scale), as listed in Table III. It was observed that the values were nearly the same in every area. Hardness values obtained after the deposition were in the same range as the hardness values of the original material; there was no evidence of excessive hardening or softening. The result, therefore, suggested that welding heat input applied to the material was appropriate for the deposition process.

TABLE III
AVERAGE HARDNESS INVESTIGATED IN DIFFERENT AREAS

Investigated Areas	Hardness (HRB)
SS400 steel substrate	73.1 ± 2.0
Interface between substrates and electrode	77.5 ± 1.4
ER70S-6 electrode wire	70.8 ± 3.2

IV. CONCLUSIONS

Investigation of microstructure and mechanical property of compression molds fabricated by fused deposition modeling (FDM) process was conducted.

Results from microstuctural examination revealed that no macroscopic crack, pore or inclusion were present in the sample. Only microscopic pores with the average size of 8.96 µm were observed. The sample had low porosity, less than 0.5% by area, indicating that appropriate deposition parameters, such as arc length, welding current, composition of shielding gas and welding speed, were employed during the deposition.

Small grain sizes, in the rage of 9.5 to 26.1 µm, were observed, which indicated that no excessive grain growth occurred during the deposition. In addition, hardness values of the samples were in the same range as the hardness values of the original material, which indicated that there was no evidence of excessive hardening or softening. The results suggested that the sample was deposited with proper welding heat input.

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