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Finite Element Thermal Simulations for the Design of Mold Conformal Heating Channels Manufactured by 3D Printing Sand Casting for Molding of EPDM Rubber

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Abstract: This paper presents an application of Additive Manufacturing (AM) technology that is suitable for manufacturing molding tools with conformal heating channels to increase productivity for EPDM rubber molding. The design and the manufacturing of a molding tool by combining 3D sand printing and casting processes was analyzed. A simplified finite element thermal analysis was used to optimize the EPDM molding cycle time of an automotive hood seal. The simulation results showed that by using a mold with conformal heating channels manufactured by 3D printing sand casting, the cycle time process of EPDM can be reduced by 41.5%.

Keywords: 3D printing sand casting, Additive manufacturing (AM), Finite element simulation, Conformal heating, EPDM rubber molding.

1. INTRODUCTION

Molded foam rubber parts, that can be manufactured using either compression or injection molding, include NVH (Noise, Vibration and Harshness), gaskets and seals, and other miscellaneous products. EPDM (ethylene-propylene-diene monomer) is a synthetic rubber used in applications that will be subject to outdoor elements because of its resilience and versatility, resistance to heat, extreme temperatures and weather conditions, oxidation, corrosion and other damaging forces makes it ideal for such a range of applications [1-3]. Nearly all recently manufactured vehicles make use of EPDM rubber molding for door and window stripping as well as trunk and hood seals. As blowing agents, Azodicarbonamide-based chemicals (ADC) are frequently used in rubber processing [4]. Chemical blowing agents undergo thermal decomposition during processing and yield gases, which lead to an expansion of the material. The expansion process and the vulcanization reaction take place simultaneously in the curing unit [5]. Both reactions are thermally activated and interact regarding their kinetics [6]. The product quality of foamed rubber parts is strongly influenced by the time dependent process of the vulcanization and by the thermal decomposition reaction [7]. Injection molding cycle time is likely to be one of the biggest factors in the efficiency of an industrial process both from a time and a cost standpoint. Reducing the process time have become the primary objective of processors and the design of the thermal regulation system is of great importance to improve the process. The emergence of additive manufacturing systems offered mold designers a new way to tackle the problems related to the regulation system design. For example, in the injection molding of thermoplastics, effective cooling has been proved by using conformal cooling systems [8-10]. The additive manufacturing technology allowed the manufacture of complex conformal thermoregulation systems that follow the free form geometry inside the mold. Among Additive Manufacturing (AM) technologies, sand mold printing technology has the ability to produce rapid bespoke molds that can be used with traditional production metal casting techniques, with minimal change to the current casting industry; providing the user with key commercial and strategic advantages [11]. 3D sand mold printing fabricates pattern and core boxes without pattern mold. Existing technologies of 3D sand mold printing mainly are the following three methods: SLS (Selective Laser Sintering), 3DP (Three Dimensional Printing) and PCM (Patternless Casting Manufacture technology) [12-15].

This paper reports the results of finite element simulations undertaken to investigate the potential benefits of a 3D printed sand mold applied to injection molding of an EPDM compound. Of interest in this research was the ability of this AM technology to generate tooling with conformal heating channels, through which heated oil could be used to foam and

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cure the EPDM compound with optimal process cycle time.

2. MATERIALS AND METHODS

For the molding of foam EPDM (Ethylene-Propylene-Diene Monomer) automotive hood seal (Figure **1**), a two mold parts are designed (Figure **2**). Due to limitations of machining processes, the heating channels have to be straight. In conventional molding the heat to foam and cure the elastomer compound is provided through electrical platens from both sides of the mold. Using this heating method the cycle time to manufacture the EPDM component was 20 min for a mold temperature T=170°C. However, the key temperatures of the manufacturing cycle are: the expansion temperature of the foaming agent of the formulated mixture (T_{exp} = 140°C), and the vulcanization temperature (crosslinking of the polymer) (T_{vul} = 152°C). To optimize the molding process, a new mold made of AlSi9 aluminium alloy was manufactured by die casting. The mold is designed with heating conformal channels by means of a modern mold manufacturing technology: the 3D sand mold printing (Figure **3**).

The Addtitive Manufacturing (AM) machine used to produce the 3D printed sand mold is a Voxeljet VX1000 machine providing a 1000 x 600 x 500 mm³ build space, with a print resolution (x,y) up to 600 dpi and a layer thickness of 300 µm. The molds are produced by applying a particle material in layers and selectively bonding it with a binder. Silica sand is used as the particulate material.

Figure 1: EPDM automotive hood seal.

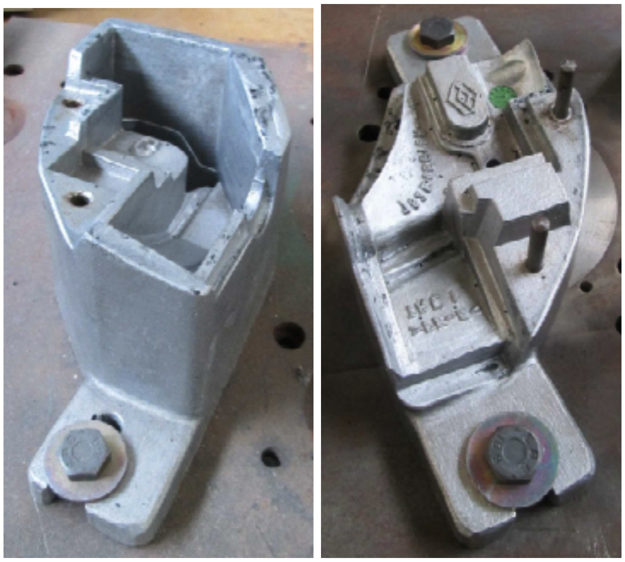

Figure 2: Two parts of the mold.

3. RESULTS AND DISCUSSION

In heating process, there are two kinds of chemical reactions that take place simultaneously: the

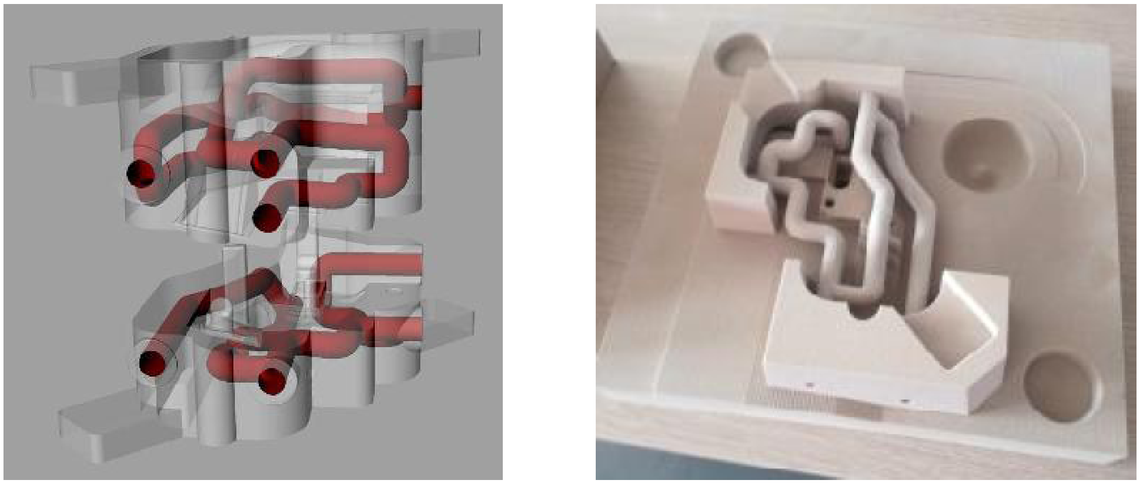

Figure 3: Design of conformal heating channels (left), and 3D printed sand half mold (right).

vulcanizing of the rubber and the decomposing of the blowing agents. To optimize the process cycle time, thermal simulations were performed on the new mold under different conditions.

For the thermal simulations, unsteady state heat transfer were performed to determine the temperature distribution during the process. The filling stage of the injection molding process was not simulated and the thermal effect of the EPDM in contact with the mold is approximated by a flux density calculated from the ratio of the amount of heat produced during the injection molding process and the contact surface between the mold and the elastomer [16].

3.1. Thermal Simulation with Constant Heating Conditions

Thermal simulation of the initial mold was performed with ABAQUS software (Version 6.13). Unstructured mesh of 10-node quadratic tetrahedral elements of type DC3D10 was generated consisting of: 228850 elements for the lower part of the mold, 219553 elements for the upper part of the mold and 112062 elements for the EPDM part. The mold is made of AlSi9 aluminium alloy with density 2800 kg/m^3, specific heat 960 J/kg/K and thermal conductivity 182 W/m/K, these values were linearly extrapolated from the results of Angadi *et al*. [17]. Governing equation describing the unsteady state heat transfer was solved in ABAQUS. Four boundary conditions were set as shown in Figure **5**.

- Heat exchange with EPDM is the heat flux density needed by EPDM to reach the desired temperature during the process defined as [16]:

$$q_P = \frac{Q_P}{t_{cycle} S_P} \tag{1}$$

The time cycle t_{cycle} was optimized after some trials and errors in the non-regulated mold.

with:

$$Q_P = \left(\left(T_{mold} - T_{EPDM} \right) C_p \right) \rho_P V_P \tag{2}$$

The parameters in equations (1) and (2) are defined in Table **1**.

Table 1: Parameters for Evaluation of the Flux Density Needed by EPDM to Reach the Desired Temperature

Parameter	Definition	Value
T_{mold}	Mold temperature	170°C
T_{EPDM}	EPDM initial temperature	110°C
S_P	Mold surface in contact with EPDM	35254 mm^2
ρ_P	EPDM density	1400 kg/m^3
V_P	Volume of polymer in contact with the mold	192000 mm^3
C_p	Specific heat of EPDM	2000 J/kg/K
t_{cycle}	cycle time	20 min

- Heat exchange by convection with air:

$$q_{air} = h_{air} \left(T - T_{mold} \right) \tag{3}$$

where h_{air} = 25 W/m^2/K is the convective heat transfer coefficient for air [18].

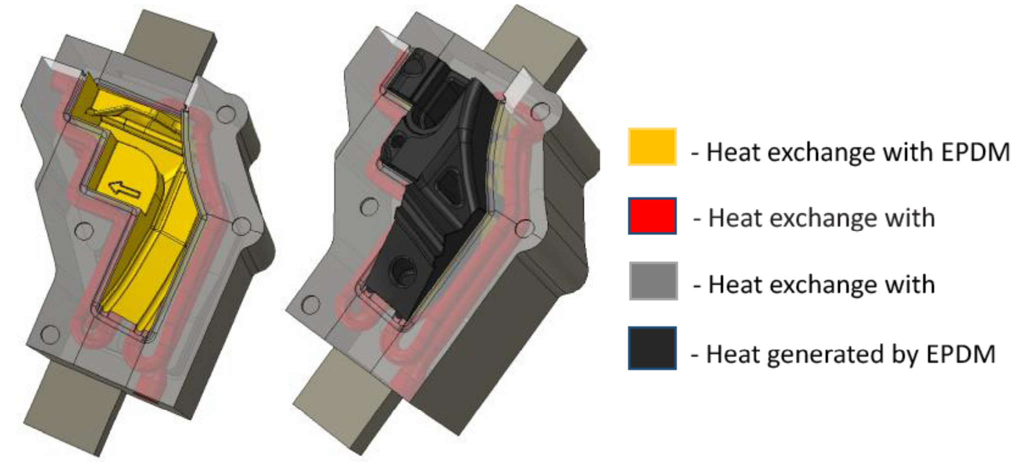

Figure 5: Thermal boundary conditions.

- Heat exchange with the heating fluid: a convective heat exchange with the heating oil is defined as:

$$q_{oil} = h_{oil}\left(T - T_{oil}\right) \tag{4}$$

where T_{oil} = 170°C is the temperature of the heating fluid, and h_{oil} = 7734 W/m^2/K is the convective heat transfer coefficient for the oil estimated by the Colburn correlation [19].

- Heat generated by EPDM during expansion and vulcanization:

$$Q_{EPDM} = m\left(Q_{Exp} + Q_{Vul}\right) \tag{5}$$

where Q_{Exp} = 776670 J/kg is the total heat of decomposition, Q_{Vul} = 6600 J/kg is the total heat of vulcanization for the EPDM system [20] and m = 268 g is the total mass of EPDM.

Figure **6** shows the distribution of temperatures in view cut of the whole model. Three points are defined to monitor the temperature: Point 1 is inside the EPDM part, Point2 is at the interface between the EPDM part and the mold and Point3 is at the interface between the mold and the channels. Figure **7** shows the temperature evolution during the process for constant temperature of heating fluid (T_{oil} = 170°C). It is clear from these curves that the required time to reach the vulcanization temperature (T_{vul} = 152°C) is 20 min. Point1 is the last point that reaches this temperature.

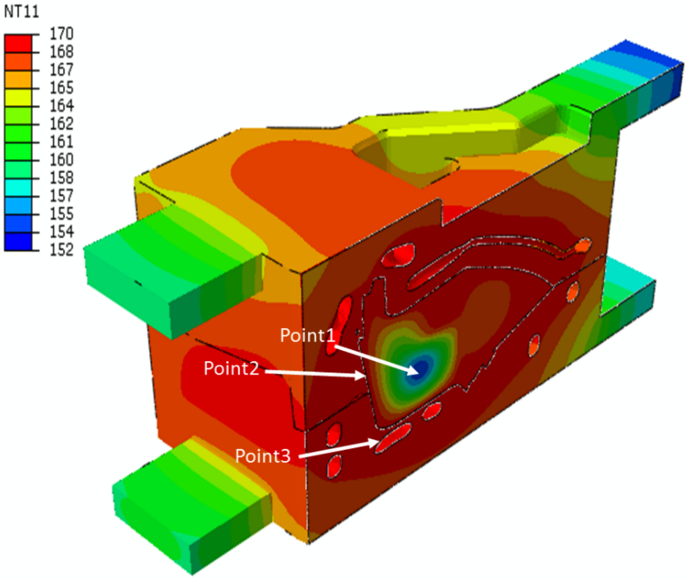

Figure 6: Distribution of temperatures in view cut of the whole model.

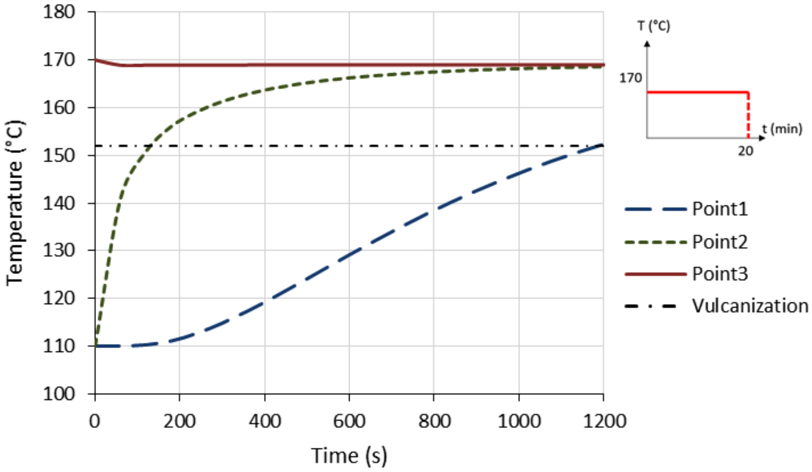

Figure 7: Temperature evolution during the process for constant temperature of heating fluid (T_{oil} = 170°C).

This cycle time is too high and therefore not compatible with mass production in the automotive industry.

3.2. Thermal Simulations with Variable Heating Conditions

To reduce the cycle time, the conformal heating can be used by varying the temperature regulation of the mold. The EPDM rubber foams around 140°C and cures after 152°C. However, the initiating time of vulcanization is earlier than that of blowing and the end time later than that of blowing which is less than 3 min [21]. In the following, we have varied the set temperature of the mold to reduce the cycle time. We have monitored the evolution of the temperature of the three points defined in the previous section.

Figure **8** shows the temperature evolution during the process for variable temperature of heating fluid: T_{oil} = 170°C for 3 min and T_{oil} = 200°C for the remaining time. In this case, Point1 reaches the vulcanization temperature after 14 min. The cycle time can be reduced by 6 min corresponding to 30% reduction compared to the reference cycle time. We can also notice that the interface between the mold and the channels (Point3) takes 2 min to switch between the set temperature of 170°C and that of 200°C.

Figure **9** shows the temperature evolution during the process for variable temperature of heating fluid: T_{oil} = 170°C for 3 min and T_{oil} = 220°C for the remaining time. In this case, Point1 reaches the vulcanization temperature after 12.5 min. The cycle time can be

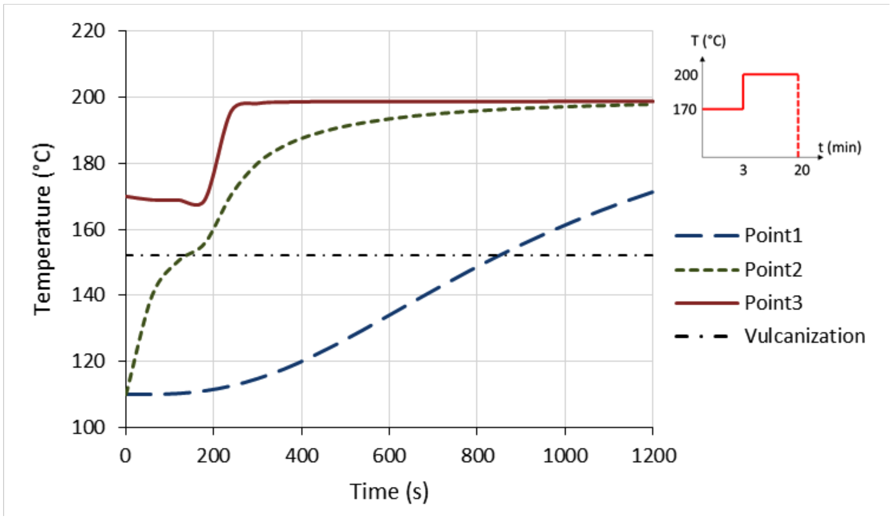

Figure 8: Temperature evolution during the process for variable temperature of heating fluid (T_{oil} = 170°C - T_{oil} = 200°C).

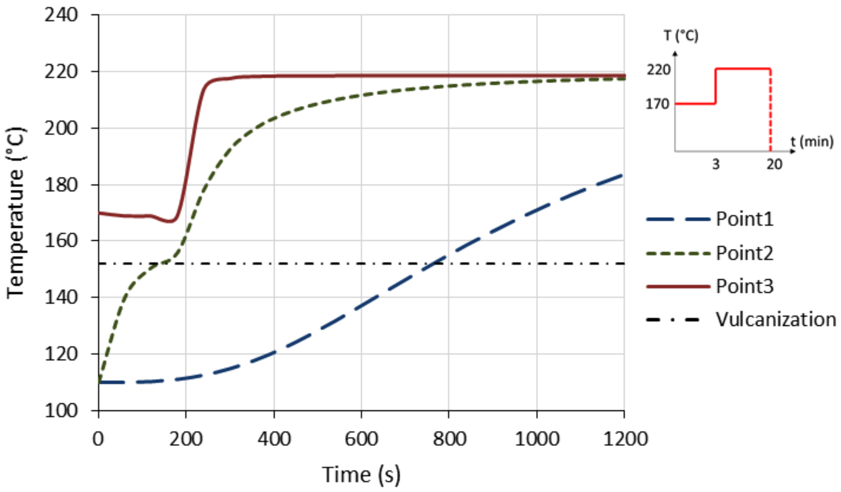

Figure 9: Temperature evolution during the process for variable temperature of heating fluid (T_{oil} = 170°C - T_{oil} = 220°C).

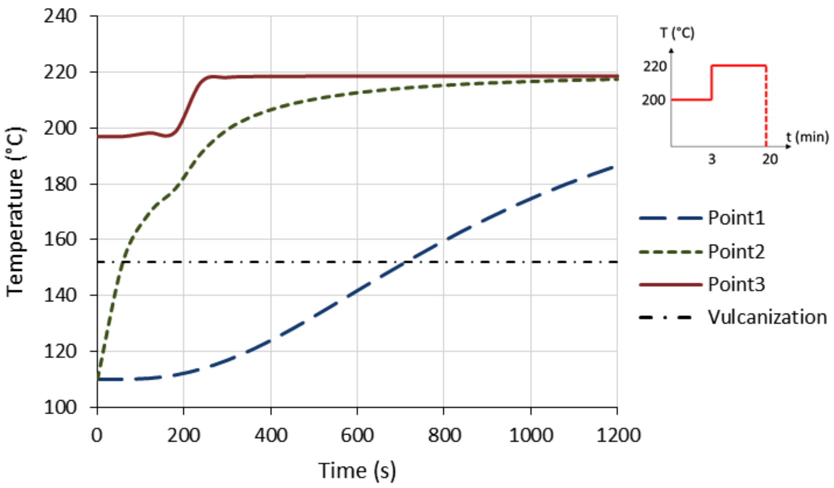

Figure 10: Temperature evolution during the process for variable temperature of heating fluid (T_{oil} = 200°C - T_{oil} = 220°C).

reduced by 7.5 min corresponding to 37.5% reduction compared to the reference solution. We can also notice that the interface between the mold and the channels (Point3) takes 2.5 min to switch between the set temperature of 170°C and that of 220°C. This switching time is higher because the difference between the two temperatures is greater than in the previous case.

Figure **10** shows the temperature evolution during the process for variable temperature of heating fluid: T_{oil} = 200°C for 3 min and T_{oil} = 220°C for the remaining time. In this case, Point1 reaches the vulcanization temperature after 11.7 min. The cycle time can be reduced by 8.3 min corresponding to 41.5% reduction compared to the reference solution. We can also notice that the interface between the mold and the channels (Point3) takes less than 2 min to switch between the set temperature of 200°C and that of 220°C. This solution was successfully implemented in industrial conditions.

CONCLUSIONS

EPDM rubber injection molding is one of frequently used processing technologies to manufacture automotive parts for door and window stripping as well as trunk and hood seals. In order to improve productivity and part quality, optimal thermal regulation of injection mold is an essential step in the mold design. A conformal heating system is one of the best solution to reduce the cycle time. In this paper, we presented a simply applicable finite element simulation to analyze the thermal efficiency of conformal heating channels manufactured by 3D printing sand casting for molding of EPDM rubber. The cycle time of EPDM rubber molding was significantly improved with the proposed conformal heating channels. The cycle time was reduced by 41.5 % compared to the reference solution. The proposed solution with optimal cycle time was successfully used in mass production of automotive hood seals. The proposed methodology can be easily applied on any other mold with conformal heating/cooling made by AM technologies in order to optimize the process cycle time.

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