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ADDITIVELY MANUFACTURED 2D MATRIX CODE DIRECT PART-MARKING CASTING REQUIREMENTS

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Abstract

Direct part-markings (DPMs) can be formed into metal castings, using additively manufactured two-dimensional matrix encoded tags (AM2D) placed in a sand or shell mold. It has been unclear how thin a part can be and yet form a readable DPM. There must be sufficient molten metal to burn away the tag, and sufficient feeding pressure to form the 2D matrix code dot pattern. Here the formability limit for the casting of any AM2D (polymer) tag is shown to be the smallest heat energy from the latent heat of condensation needed to raise the temperature of the tag to ignition to burn the tag from the mold. The minimal part thickness that can be utilized is thereby derived. The minimum thickness is calculated to predict a part of various materials and compared positively with experiments. This provides a means to compute required part metal thickness to positively form a DPM tag before casting.

Keywords: *sand casting, direct part-marking, matrix codes, industry 4.0, cast part tracking*

Introduction

Research is progressing to enable the industry 4.0 smart foundry, including research on IoT sensors and data analytics in the foundry. This includes research on process monitoring, part tracking, inspection, and quality control.[1,2] Studies are employing foundry data analytics based on machine learning to compute process diagnostics and adjustments. This is challenging in casting practice since it is difficult to track parts through early foundry processes and associate with monitored process variables.[3] Foundry surveys indicate that post-production part-marking methods have challenges, including high expense, complexity of operation and difficulty with early steps prior to shakeout. There is a need for an in-cast direct part-marking (DPM) approach for the sand and investment casting industry.[4]

One approach to marking parts is using additively manufactured two-dimensional (AM2D) polymer tags whose imprint can be cast directly into the part and thereby create a permanent DPM. The process of creating an AM2D tag and its implementation onto different castings have been studied and compared with methods such as laser marking, pin-type tooling methods, and classical alphanumeric labeling.[5] The DPM created by AM2D tags can be read very early, even at the shakeout before cleaning. The method has been shown for several industrial parts and a foundry part-marking and tracking system has been demonstrated for use in root cause analysis of defects and statistical quality control.[4,5]

Creating a DPM using an AM2D tag involves printing a uniquely coded polymer tag, inserting it into a mold, and then casting the metal part in which the molten metal raises the polymer tag above its ignition temperature and the tag burns away from the mold, leaving an imprinted DPM on the part. A problem with AM2D tags is that it is unclear how thick the metal part must be to raise the polymer to its ignition temperature and burn away the tag and provide a readable DPM. For parts and tags of various sizes and

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thicknesses, it is desirable to understand the required thickness of metal part-marking area. A thicker tag would provide deeper holes with a higher contrast, but this also requires higher metal thickness.

As an alternative to AM2D tag technology, laser etching is also used to mark metal castings for post-cast processes. For in-cast sand-based casting operations, laser technologies have been used to mark the sand molds or core boxes with alphanumerical character shapes. Another part-marking technology includes pin-type tooling, which enables direct part-markings in green sand permanent molding machines.[6] These other technologies are equipment put in line on the foundry and can be sensitive to the foundry environment.[5]

With AM2D tags, the DPM created involves additively manufacturing unique plastic tags for each cast part and placing them in the sand mold when casting. The sand casting process involves pattern preparation, sand molding, pattern removal, metal casting, cooling and shakeout, and finally, fettling and polishing. The tag is burned away by the molten metal in the casting process. Typical filling time and casting pressures are needed without any additional processing conditions. A challenge arises from the different and complex cast part designs and determining whether the tag will be properly burned away and shaped as a readable DPM or not. Sufficient heat energy in the metal is needed to burn out the tag. Different plastic or wax tag materials would require different levels of energy of the molten metal. For example, ABS (acrylonitrile butadiene styrene) plastic requires more molten metal energy than other plastics. Here, the more environmentally friendly PLA (polylactic acid) is used. PLA has a relatively low melting point, 150–160 °C, thus requiring less energy to print the material. In addition, PLA has been shown to be a safer alternative to the possibly toxic ABS or other plastics.[7]

Theory

A DPM is formed by the AM2D tag burning away upon contact of molten metal. We seek to drive the conditions for this to happen. The tag must be raised from initial room temperature to above its ignition temperature of the tag polymer material. The energy required to do this is the heat required,[8]

$$E_{\mathrm{required}} = \rho_{\mathrm{p}} A t_{\mathrm{p}} C_{\mathrm{p,p}} \left(T_{\mathrm{ig}} - T_{\infty}\right) \qquad \text{Eqn. 1}$$

where ρ_{p}, A, t_{p}, and $C_{\mathrm{p,p}}$ are the density, area, thickness and heat capacity of the polymer tag, respectively, T_{ig} is the ignition temperature of polymer tag, and T_{∞} is the initial room temperature. To provide this energy, it must be extracted from the molten metal. The energy available within the molten metal is the energy to lower the molten metal to its liquidus temperature and then solidify,

$$E_{\mathrm{metal}} = \rho_{\mathrm{m}} A t_{\mathrm{m}} C_{\mathrm{p,m}} \left(T_{\mathrm{cast}} - T_{\mathrm{liq}}\right) + L_{\mathrm{m}} \rho_{\mathrm{m}} A t_{\mathrm{m}} \qquad \text{Eqn. 2}$$

where ρ_{m}, and t_{m}, and $C_{\mathrm{p,m}}$ are the density, thickness and heat capacity of the molten metal, respectively, T_{cast} is the casting temperature of the metal, T_{liq} is the liquidus temperature, and L_{m} is the latent heat of solidification.

The conditions needed for the tag to be raised above its ignition temperature are that $E_{\mathrm{required}} \le E_{\mathrm{metal}}$. However, the available heat flow from the tag is only from half the molten metal material from the centerline of the molten metal, whereas the other half of the molten metal cools into the mold opposite the tag. Therefore, the required energy balance becomes

$$\rho_{\mathrm{p}} A t_{\mathrm{p}} C_{\mathrm{p,p}} \left(T_{\mathrm{ig}} - T_{\infty}\right) \le 2\left(\rho_{\mathrm{m}} A t_{\mathrm{m}} C_{\mathrm{p,m}} \left(T_{\mathrm{cast}} - T_{\mathrm{liq}}\right) + L_{\mathrm{m}} \rho_{\mathrm{m}} A t_{\mathrm{m}}\right) \qquad \text{Eqn. 3}$$

that is, expressed in terms of required molten metal thickness,

$$t_{\mathrm{m}} \ge \frac{\rho_{\mathrm{p}} t_{\mathrm{p}} C_{\mathrm{p,p}} \left(T_{\mathrm{ig}} - T_{\infty}\right)}{2\left(\rho_{\mathrm{m}} C_{\mathrm{p,m}} \left(T_{\mathrm{cast}} - T_{\mathrm{liq}}\right) + L_{\mathrm{m}} \rho_{\mathrm{m}}\right)} \qquad \text{Eqn. 4}$$

Eqn. 4 is therefore the formability constraint on required thickness for a suitable AM2D tag to form a DPM. This supposes also that the melting temperature T_{liq} is greater than the ignition temperature of the polymer Tag. Also, there must be sufficient gating and venting in the casting system.

Analysis and Experimentation

For a part-marking to be formed from an AM2D tag insert, there needs to be sufficient molten metal to burn away tag and fill the 2D matrix shape. To explore this necessary part thickness, an experimental part was designed as shown in Figure 1, with multiple stepped thicknesses. With a tag inserted each thickness layer, the minimum thickness required can be determined since the thin part sections are made sufficiently thin to not have enough molten material to burn away the tag and the thick sections with more than enough. Between these limits will be the minimum thickness to form a DPM.

The molten metal thickness required should relatively decrease with metals of higher density than those with a higher latent heat of condensation. Also, the molten metal thickness required should relatively increase with increased tag thickness.

To test for formability, five experimental samples were fabricated as detailed in Table 1. This included three different metals, three different tag sizes, and different casting

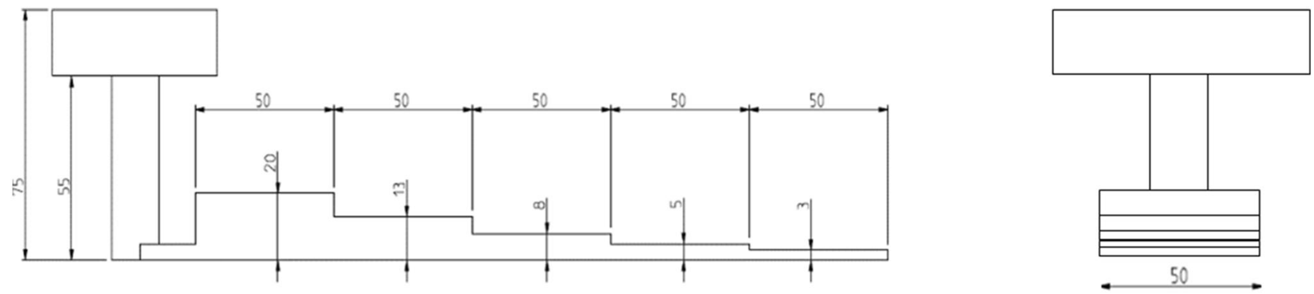

Figure 1. Experimental part dimensions showing incremental thickness of the pattern (mm) on side view (right) and front view (left).

Table 1. Summary Results

Material	Tag thickness (mm]	Cast temp. (°C)	Min. DPM forming thick. (mm)	Metal thickness (mm)	Predicted formed	Formed?
$AlSi_2$	0.70	740	4.7	20.00	Yes	Yes
				13.00	Yes	Yes
				8.00	Yes	Yes
				5.00	Yes	Barely
				3.00	No	No
	0.50		3.4	20.00	Yes	Yes
				13.00	Yes	Yes
				8.00	Yes	Yes
				5.00	Yes	Yes
				3.00	No	Barely
		700	4.8	20.00	Yes	Yes
				13.00	Yes	Yes
				8.00	Yes	Yes
				5.00	Yes	Yes
				3.00	No	No
CuSn	1.70	1160	5.1	20.00	Yes	Yes
				13.00	Yes	Yes
				8.00	Yes	Barely
				5.00	No	No
				3.00	No	No
	0.50		1.5	20.00	Yes	Yes
				13.00	Yes	Yes
				8.00	Yes	Yes
				5.00	Yes	Yes
				3.00	Yes	No
ZA-12	0.50	500	NA	20.00	No	No

temperatures. The idea was that some of the thinner sections on the part would not form DPM, whereas other thicker sections on the part would. Similarly, thicker tags may not be formable, whereas thinner ones would. Lastly, increasing the temperature would also promote forming. Here, predictions are made using the minimum forming thickness equation above (Eqn. 4) and compared to the experimental results on the stepped part. The experimental parts were fabricated as a pattern by taping the tags to the pattern and then sand-molded. In the molding process, the

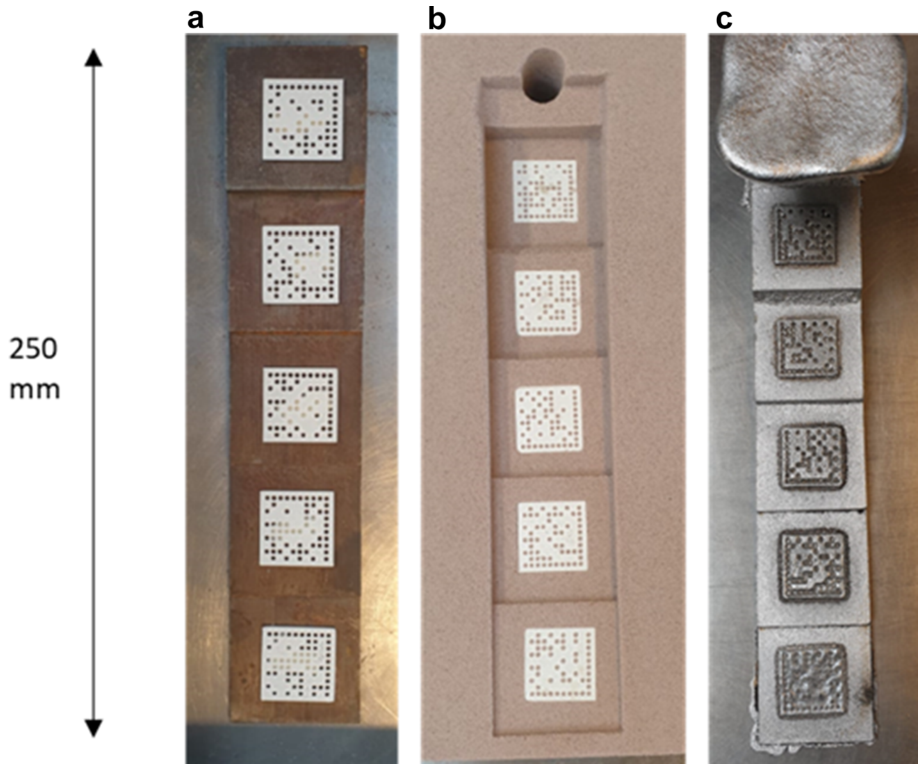

Figure 2. Aluminum step casting results. (a) Pattern with added AM2D tags, (b) sand mold with tags embedded, (c) resulting casting.

Figure 3. Example casting result with bronze and 1.7 mm tags.

tags remain stuck to the mold and thereby separated from the pattern and remained in the mold. During casting, the tags were then burned away.

Result and Discussion

Given all these variables, Eqn. 4 can be used to predict the thickness where tags will be formed. Bronze has a lower latent heat of condensation 270 kJ/kg and high density of 8000 kg/m^3 compared to aluminum with 520 kJ/kg and 2900 kg/m^3. The equation predicts the thickness required to get a readable tag in aluminum is 5-mm bronze, whereas bronze requires above 8.5 mm.

Examples of the pattern, mold cast parts resulting from the experiments with aluminum, are shown in Figure 2. Metal part thicknesses less than 5 mm failed to produce a readable DPM, and thicknesses above 5 mm produced DPMs that were all readable. For aluminum, 5 mm is the minimum part thickness for a readable DPM when using a 0.7-mm-thick AM2D tag.

Bronze was also tested, and the casting result with bronze is shown in Figure 3. The results indicate that the DPM in the third step (8mm thick) was barely formed and not readable as predicted. The 10 mm thickness and above produced readable DPMs. The same results for other thicknesses and materials are shown in Table 1.

Overall, the results shown in Table 1 include the minimum thickness predicted using Eqn. 4. Note that the thickness prediction worked well to determine whether the tags would be formable or not at the various thicknesses of the part. The aluminum-alloyed parts were predicted formable at 3.7–4.8 mm depending on tag thickness and casting temperature and the results agreed. Similarly, the bronze step casting were predicted at 1.5 and 5.1 mm formable DPMs and the results mostly agreed. Lastly, we cast with zinc that failed because the melting temperature was too low compared to ignition temperature of the PLA.

Conclusion

We show here that unique AM2D codes can be directly formed in metal sand castings, and there is a minimum thickness required for any particular tag to ensure sufficient metal thickness and temperature to burn the tag away and create a readable DPM. The formability conditions required are provided by Eqn. 4. For the DPM casting to be properly formed, there must be sufficient molten metal to ignite and burn the plastic tag. We show here the required metal thickness for various tag thicknesses and materials with various casting metals. The equation ensures adequate heat content in the molten metal to burn the tag. Additionally, to ensure the burn tag gases escape, proper gating and venting are needed.[5] Future work would include developing 3D printing of DPM patterns directly on the 3D sand mold for small parts, and the impact of the burned ash in the local surface vicinity of the tag. Overall, we have developed here a prediction equation, which can be used in any part to ensure the formability of the DPM using the AM2D tag.

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