EFFECT OF PROCESS PARAMETERS ON DISTORTION AND RESIDUAL STRESS IN HIGH-PRESSURE DIE CAST AZ91D COMPONENTS AFTER CLEAN BLASTING AND PAINTING

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Abstract

A high-pressure die-casting process was employed to produce AZ91D components. These cast components were exposed to three different post-treatments: (1) clean blasting, (2) clean blasting and painting, and (3) painting (without clean blasting). The influence of the process parameters first phase injection speed, temperature of fixed half of the die, cooling time, and intensification pressure on distortion and residual stress of the components after each

post-treatment were investigated. The results showed that intensification pressure was the most significant factor among the four parameters.

Keywords: High pressure die casting, Magnesium, Distortion, Residual stress, Component casting

Introduction

The use of magnesium (Mg) alloys for structural applications in industries such as automobile equipment, aerospace, and hand-tool components is growing. The combination of attractive properties such as low density, high specific strength, and excellent castability is reasons for its growing use in these industries. One of the most developed and used Mg-alloys is AZ91D, which is the most used alloys in structural applications in these industries.¹

The high-pressure die-casting (HPDC) method is preferred manufacturing process for the AZ91D components thanks to excellent shape replication, dimensional accuracy, and short cycle times resulting in high productivity.¹ However, the influence of the HPDC process parameters upon the quality of the finished products is a critical issue to consider. The typical variables are mold temperature, dosage volume, first and second phase injection speed, cooling time, intensification pressure, as well as chemical composition and liquid metal temperature.² If these parameters are not adequately controlled, various defects, such as

porosity or component distortion, are expected to be generated.

The role of process parameters on porosity formation in pressure die casting of magnesium alloys has been well studied. It has been understood that the molten metal temperature heavily influences the amount of gas porosity and the degree of turbulence during filling, while shrinkage porosity is mainly affected by casting design, which alters feeding and the effect of intensification pressure.³ Lee et al.⁴ showed that the application of intensification pressure significantly reduces the total volume of gas porosity, and a decrease in the gate velocity decreases the total porosity (the gas porosity and the shrinkage porosity).

On the other hand, a component may exceed the accepted tolerance allowance due to distortion. Hofer et al.⁵ reported that the variation of section thickness and/or variation of cooling rates in different regimes might lead to distortion in castings. The distortions may generate residual stresses in the components,⁶ which may have a negative influence on, for instance, fatigue life.⁷ Besides, there is a possibility that at high temperatures, residual stress may relax, resulting in

Figure 1. Illustration of the experimental setup for each test setting. For each cast condition, distortion and residual stress were measured after three different post-processes of: (1) as-clean blasted, (2) as-clean blasted and painted (through bake cycle), and (3) as-painted (no clean blasted).

part distortion.⁸ In the recent work by the authors,⁹ the effect of HPDC process parameters on both distortion and residual stress response of an AZ91D component was studied. It was understood that the application of intensification pressure significantly reduced the component's distortion, but significantly increased the residual stress near the surface. A decrease in the temperature difference between the two die halves reduced the distortion. However, increasing the moving side temperature decreased the residual stress near the surface, suggesting that stress relaxation may take place.⁹

It has been well established that the state of the surface roughness obtained at the final stage of the cast component has a great effect on fatigue strength. This knowledge is vital as-clean blasting (using cut wire grit) is a common form of surface conditioning before painting and has strong similarities to shot peening resulting in significant compressive stress generation. In the assessment of residual stress level, magnitude, and type of stress (tensile or compressive) are critical factors. A surface with tensile residual stress induced by the casting process is more prone to fatigue failure than a surface with compressive residual stress. Hence, the geometric state of the surface and the strengthening of the surface layer due to finishing are significant factors for controlling residual stresses in the component.¹⁰ Accordingly, a surface treatment like shot peening is applied to improve residual stress balance at the cast surface. There are very few publications on the surface strengthening of magnesium alloys, while the focus in all of these publications is comparing the effects of different intensity peening on fatigue strength. For instance, Zhang et al.¹¹ studied the influence of roll and ball burnishing on fatigue behavior of the wrought magnesium alloy AZ80.

Moreover, in another study, the same authors carried out a similar investigation on AZ80 alloy, but they applied glass balls.¹² Other works by Hilpert et al.¹³ showed improvement in fatigue strength of AM50 and AZ91D alloys by using ball peening. Korzynski et al.¹⁰ compared the states of the surface texture and the fatigue strength of specimens made of an AZ91D alloy after turning and peening. Shot peening was applied to improve the fatigue strength of irregularly shaped components, through balancing the residual stresses. However, to the best knowledge of authors there is no clear data about how the HPDC process parameters influence the clean blasting outcome in terms of distortion and residual stress of a cast component.

Furthermore, the component distortion that may occur during the paint bake cycle when the component reaches 200 °C could lead to residual stress as a potential culprit. Since temperatures reached during paint baking exceed those that have been shown to initiate creep in Mg–Al alloys, it is feasible that residual stresses present before paint bake could cause dimensional changes in components.⁸ Hence, quantifying the distortion response and residual stress generation in an AZ91D component through the paint cycle is important.

This study aimed to quantify the effect of the HPDC processing parameters on distortion and residual stress creation after clean blasting and painting in AZ91D HPDC castings. This study was made as a continuation of a previous study on the influence of HPDC processing parameters in the as-cast state on the distortion, and residual responses were of the main interest.⁹ The current study focuses on four different HPDC process parameters found relevant (a) first phase injection speed, (b) the temperature

Table 1. Experimental Layout Using a Quadratic Foundation in the Design of Experiment (DOE) and a D-Optimal Approach

EXP no.	A (m/s)	B (°C)	C (s)	D (kBar)
1	3.07	220	15.0	0.68
2	1.50	220	15.0	1.1
3	4.50	220	5.00	1.1
4	1.50	220	5.00	0.45
5	4.50	220	9.75	0.45
6	1.50	206	10.5	0.75
7	4.50	197	15.0	1.1
8	4.50	197	15.0	1.1
9	2.67	173	8.85	1.1
10	1.50	162	15.0	0.45
11	1.50	162	15.0	0.45
12	4.50	158	5.00	0.68
13	1.98	154	5.00	0.75
14	3.88	148	12.0	0.78
15	4.50	100	15.0	0.45
16	4.50	100	6.80	1.1
17	2.10	100	15.0	1.1
18	4.50	100	15.0	0.45
19	1.50	100	5.00	1.1
20	1.50	100	10.25	0.69
21	2.91	100	5.00	0.45

Parameters are A, first phase injection speed; B, temperature of fixed half of the die; C, cooling time; D, intensification pressure.

difference between the two die halves through variation of the temperature of fixed half of the die, (c) cooling time, and (d) intensification pressure. The most crucial understanding to generate was to understand how the HPDC processing parameters can be traced through the post-processing sequence as residual stress and distortion.

Experimental Work

In present work, the distortion and residual stress values of HPDC components were studied after applying three different post-processes: (1) as-clean blasted, (2) as-clean blasted, and painted (through bake cycle), and (3) as-painted (no clean blasted). Figure 1 shows the over-all

experimental planning for each test condition (run) for each completed cycle. Distortion was measured for 315 components at 5 different locations for each component, subjected to 21 different test conditions, see Table 1. Each condition was evaluated, taking 5 samples for each of the post-treatment processing states. Residual stresses were measured for 63 components at 2 different locations for each component, having 7 different run conditions with 3 samples taken after each of the post-treatment process steps. It should be mentioned that the distortion and residual stress values at the as-cast state were reported earlier.⁹

Alloy Composition

Chemical composition of AZ91D alloy was determined using optical emission spectroscopy (OES) (SpectroMaxCCD LMXM3, SPECTRO Analytical Instruments Inc, Germany) metal analyzer. Table 2 gives average alloy composition from three OES analyses.

Component Geometry

The component was a “chain saw crankcase” made from AZ91D. Figure 2 shows the geometry of the crankcase used in this study. For the distortion and residual stress assessments, critical regions of this component were chosen, as shown in Figure 2.

Casting

Components were produced using a high-pressure die-casting machine (Buhler SC-D42 machine with 4000 kN locking force), and the protecting gas was a mixture of 0.5% SO₂ and dry air. Based on the understanding that the temperature of the melt entering the die cavity is critical for both distortion and stress generation, the following HPDC parameters were varied: A-first phase injection speed, B-the temperature difference between the two die halves through variation of the temperature of fixed half of the die, C-cooling time and D-intensification pressure. Other process parameters were constant. The rationale for omitting the second stage speed as a variable was that the temperature loss in the shot sleeve during the first stage is of greater importance than that during the second stage filling. This is a specific effect for the Mg-alloys as the heat

Table 2. Chemical Composition of the AZ91D Alloy (wt%) Established Through OES

Mg	Al	Zn	Mn	Fe	Ni	Cu	Si
Balance	8.5 ± 0.2	0.67 ± 0.3	0.25 ± 0.1	0.0023 ± 0.01	0.0017 ± 0.005	0.021 ± 0.03	0.017 ± 0.1

Figure 2. Illustration of the crankcase. The left side picture is the surface of the crankcase facing the fixed side of the die, and the right-side picture is the surface facing the moving side. The points for distortion measurements are indicated as D1, D2, D3, D4, and D5. The locations for residual stress measurements are indicated as R1, R2.

content of Mg-alloys due to its low density. An experimental design was created by DesignExpert™ software (Stat-Ease) using a response surface method the D-optimal design, including lack of fit and replication points, collated in Table 1. It should be mentioned that after setting the HPDC parameters, the first ten shots were rejected to allow a new steady state to develop after which samples were taken. Moreover, it was assured that acceptable parts were made under all the test conditions.

Clean Blasting

Clean blasting was performed by Husqvarna AB Company, using the standard recommended procedure for improvement of the surface integrity and paint adhesion of the components. Cut aluminum wire (shapes as small cylinders) were used as-clean blasting media.

Paint Bake Cycle

In the present study, the actual paint was not applied, but the components were subjected to the paint bake cycle in the production oven. The paint application cycle involved a series of three-step processes. The first step was cleaning the components with water at a temperature of 40 °C for 8 min. During the second step, the components were dried at 100 °C for 20 min and subsequently cooled in the air. The third step was the paint curing cycle at 200 °C for 30 min.

Component Distortion Measurements

Distortion was measured using the standard in-house quality assurance tool as shown in Figure 3. The distortion values were obtained by the comparison of dimensional measurement as the difference between the actual HPDC part, and the ideal design at 5 critical reference points D1, D2, D3, D4, and D5, see Figure 2. The measured deviation

Figure 3. The standard in-house quality assurance tool applied for measuring the distortion value. A negative value implied a movement away from the zero-plane in the direction toward the moving side and away from the fixed side.

was along the normal vector of the surface, and the value measured was the positive or negative deviation away from the zero-plane. A negative value implied movement away from the zero-plane in the direction toward the moving side and away from the fix side.

Distortion values of the components cast under 21 different conditions, Table 3, in the as-clean blasted, as-clean blasted and painted, and only as-painted states, e.g., no clean blasting before the pain cycle, were measured. The distortion value at each specific condition was determined as an average value of minimum 5 replications for adequate accuracy.

Table 3. Experimental Results as Distortion Responses at Different Reference Points for (1) As-Cast from ⁹, (2) As-Clean blasted, (3) As-Clean Blasted, and Painted and (4) As-Painted Components

EXP. no	As-cast					As-clean blasted					As-clean blasted and painted					As-painted				
	Point D1	Point D2	Point D3	Point D4	Point D5	Point D1	Point D2	Point D3	Point D4	Point D5	Point D1	Point D2	Point D3	Point D4	Point D5	Point D1	Point D2	Point D3	Point D4	Point D5
	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)	(10 ⁻² mm)
1	4.70	- 3.75	- 17.6	2.31	6.32	12.2	- 3.5	- 21.0	1.25	5.37	14.6	- 3.00	- 22.8	2.60	9.40	12.2	- 4.40	- 20.8	1.60	12.4
2	10.4	- 2.56	- 20.1	7.25	- 4.15	16.6	- 3.12	- 21.1	4.12	2.25	16.6	- 2.8	- 23.2	2.40	- 0.40	17.0	- 3.40	- 22.4	6.20	6.20
3	9.43	0.43	- 21.6	6.18	- 5.21	13.2	0.50	- 21.0	0.87	- 0.62	15.2	- 1.00	- 24.0	- 0.20	- 12.6	13.0	- 2.00	- 24.6	3.00	1.80
4	7.62	- 2.93	- 20.5	2.50	3.32	11.8	- 2.12	- 20.3	- 3.37	- 5.12	13.0	- 2.40	- 22.6	- 3.40	- 0.60	12.0	- 3.60	- 22.4	- 1.20	6.40
5	7.60	- 2.30	- 19.6	4.70	4.20	12.4	- 2.40	- 19.6	1.20	6.20	15.4	- 4.20	- 21.4	- 3.20	10.4	12.6	- 3.00	- 19.8	4.00	15.8
6	9.50	- 3.30	- 21.4	2.90	9.33	14.8	- 2.60	- 21.2	0.80	0.60	17.0	- 3.80	- 21.8	1.00	- 0.20	14.0	- 4.00	- 22.0	3.00	8.80
7	8.50	- 3.60	- 20.5	5.70	- 3.79	14.6	- 2.20	- 22.6	4.60	- 6.20	15.2	- 2.80	- 24.0	5.00	- 6.40	14.0	- 3.60	- 24.2	6.20	0.80
8	8.70	- 3.60	- 20.6	5.70	- 3.50	14.2	- 2.20	- 23.2	3.80	- 5.40	15.4	- 3.00	- 24.4	5.20	- 6.80	14.6	- 3.60	- 22.6	6.40	1.40
9	10.3	- 2.60	- 22.5	7.60	0.40	13.8	- 2.80	- 22.6	2.60	- 6.80	13.2	- 2.80	- 25.4	5.40	- 3.80	14.2	- 2.20	- 24.2	3.60	3.60
10	7.50	- 4.90	- 20.0	3.84	13.3	14.2	- 4.60	- 19.0	4.60	9.80	13.6	- 4.40	- 21.0	3.40	10.8	13.0	- 5.00	- 20.2	3.00	19.4
11	7.00	- 5.20	- 19.7	3.80	12.8	14.4	- 3.80	- 19.8	5.20	12.4	14.6	- 4.00	- 21.0	5.80	13.0	13.6	- 5.00	- 20.8	3.40	19.6
12	8.80	0.10	- 20.3	7.35	13.8	12.0	- 1.80	- 20.4	3.20	14.6	13.4	- 1.40	- 21.6	2.20	14.2	12.8	- 3.00	- 21.0	- 5.00	19.2
13	9.20	- 1.40	- 21.9	6.54	14.8	14.6	- 1.80	- 22.2	2.60	18.2	14.8	- 2.40	- 23.4	4.60	18.8	14.4	- 1.80	- 21.2	3.60	19.6
14	7.00	- 2.40	- 20.0	6.93	14.9	14.6	- 3.20	- 23.2	4.60	19.2	14.6	- 1.00	- 21.4	9.20	20.2	13.2	- 2.80	- 21.4	6.80	21.4
15	6.43	- 4.06	- 19.25	4.62	9.90	12.7	- 4.12	- 20.0	2.00	10.87	12.8	- 3.80	- 19.6	3.80	12.2	16.8	- 3.00	- 19.8	5.00	19.0
16	8.50	- 2.00	- 22.4	4.57	- 4.04	14.8	- 1.80	- 21.0	1.40	- 12.8	20.8	- 2.40	- 24.2	2.40	- 9.00	29.6	- 4.20	- 25.0	4.00	- 2.6
17	11.6	- 3.20	- 20.8	6.06	- 3.33	16.0	- 3.40	- 21.8	2.40	- 1.00	16.0	- 3.60	- 23.2	5.40	3.40	22.0	- 5.20	- 23.0	4.60	7.00
18	7.43	- 4.00	- 18.8	3.75	8.26	12.3	- 4.62	- 19.5	0.75	- 11.5	14.0	- 3.40	- 22.4	6.00	8.00	11.6	- 4.60	- 19.8	4.80	21.2
19	10.06	- 2.18	- 22.1	2.25	- 3.67	13.5	- 2.75	- 21.0	- 0.75	- 9.50	13.8	- 1.80	- 23.0	- 0.20	- 9.00	18.2	- 2.60	- 22.2	5.20	- 4.40
20	7.25	- 3.68	- 21.5	1.00	8.70	12.6	- 3.50	- 19.5	0.12	1.75	12.2	- 2.60	- 20.6	0.40	1.40	12.4	- 3.40	- 20.6	0.80	9.20
21	8.80	- 2.80	- 19.3	0.90	8.73	11.4	- 2.20	- 20.2	- 3.00	1.40	12.0	- 2.20	- 20.4	- 2.20	4.60	11.6	- 2.60	- 20.2	0.40	9.60

Residual Stress Measurements

The near-surface residual stress profile in components was determined using a hole drilling technique. The measurements were performed using a Stresstech Group PRISM hole driller, where the residual stresses were evaluated from the surface displacement that develops as a result of the progressive drilling hole. PRISM system measures surface distortion using electronic speckle pattern interferometry (ESPI). Images from before drilling are compared to those after each incremental drilling cycle using an end mill bit. Every condition is described by a set of four images, each taken with the reference beam phase-shifted a different amount: 0° , 90° , 180° , and 270° . The numerical model developed for the PRISM system supports drilling with depth, h , and with a drill diameter, d , with ratios in the range $0.1 < h/d < 0.6$. In the current study, an end mill with 0.8 mm diameter was used, and the drilling rig was programmed to reach the final depth of 0.5 mm in 14 equidistant steps. The drilling feed rate was 0.05 mm/s, and after every drilling step, the drilling was stopped for about 60 s before taking the first set of images; a second image set was taken about 30 s after that. Stresses were calculated using a Poisson's ratio of 0.3 and a Young's modulus of 45,000 MPa.

Points R1 and R2 shown in Figure 2 are the locations where residual stress was measured. Residual stress was measured for components cast under seven different conditions, see Table 4, at three different states; as-clean blasted, as-clean blasted and painted and as-painted. Each run was repeated three times for adequate accuracy.

The signed von Mises stress (SVM) was used to quantify the residual stress, see Eqn. (1). The SVM represents the sign (positive or negative) of the von Mises stress based on the first stress invariant I_1 and its sign.

$$\sigma_{svm} = \text{sign}(I_1) \cdot \sigma_{vm} \quad \text{Eqn. 1}$$

where σ_{vm} is the von Mises stress and $I_1 = \sigma_x + \sigma_y + \sigma_z$

Result and Discussion

The “Results and Discussion” section is divided into two parts. The first treats the distortion after each tempo and the effect of the process routes. Subsequently, the same is made for residual stress measurements.

Analysis of Distortion

The average distortion responses at the points shown in Figure 2 are collated in for (1) as-clean blasted, (2) as-clean blasted and painted, and (3) as-painted states. The distortion direction was also taken into consideration. Figure 4 shows the distortion values for each point after the

post-treatments. Here, the distortion values at as-cast state, from Ref.⁹ are given as a reference.

From Figure 4a, it can be observed that the distortion value at point D1 for every run after all post-treatment states increased from the as-cast condition toward the moving side. However, the level of this increment does not follow any significant pattern, which could be related to differences in run conditions or post-treatments. The distortion values at point D2, Figure 4b, were in the range of 1×10^{-2} mm to -6×10^{-2} mm, which was a small distortion value compare to the other points. Point D2 has a central location in the parts near to a large through feature around which the part will bend, but the possibility to distort away from the zero-plane is small. Hence, only small distortions were noticed. Distortion at point D3 was always negative and showed larger values in the range of -18×10^{-2} mm to -26×10^{-2} mm, see Figure 4c. The large values of distortion, indicating that it bends toward the fix side and that D3 was adjacent to an ejector pin, suggest that the component may have deformed during ejection. The fact that the distortion had the same high value of distortion with the same direction for all process conditions, as well as has no statistically significant correlation to the as-cast state, also supports this fact. Deformation on ejection may also cause additional residual stress that in subsequent processing would be released, and therefore, the distortion in point D3 tended to larger distortion toward the fix side at the end of post-processing after the exposure to heat during the paint cycle with a likely release of residual stresses. The distortion values at point D4 were in the range of -4×10^{-2} mm to 8×10^{-2} mm, see Figure 4d. A weak tendency toward distortion reduction, moving point D4 toward the fix-side direction following clean blasting, can be visually observed, Figure 4d. It was, however, not possible to confirm this statistically. No statistically significant apparent effect from post-treatments was found for distortion at points D2, D3, and D4. Similar to point D1, the effect of different casting run conditions on distortion values at points D2, D3, and D4 after post-treatments was not clear.

The distortion values of the as-painted components at point D5 were higher than as-cast, as-clean blasted, and as-clean blasted and painted components, see Figure 4e. Moreover, the distortion increments at point D5 after painting were always toward the positive direction, moving the point toward the moving side. However, no clear correlation to the run conditions from casting after post-treatments was found. The effects of the post-treatments were thus not directly coupled to the casting process, but issues related to part design and factors hindering die release may indirectly influence the distortion outcome and depend on the casting conditions.

Figure 4. The distortion responses for as-cast, as-clean blasted, as-clean blasted and painted and as-painted components at (a) point D1, (b) point D2, (c) point D3, (d) point D4, and (e) point D5. The as-cast distortion data are from⁹.

Figure 4. continued

Analysis of Residual Stress Measurements

Figures 5 and 6 show the SVM stresses profiles for all conditions evaluated at points R1 and R2. The residual stress data at an as-cast state were provided from previous work⁹ as a baseline for the changes incurred by the subsequent post-processing. To quantitatively describe residual stresses, different characteristic measures of the residual stress were reported: σ_s^{rs} , the residual stress at the surface (MPa.); $\sigma_{\text{max}}^{\text{crs}}$ the maximum value of the compressive residual stress (MPa.). The resulting values of σ_s^{rs} and $\sigma_{\text{max}}^{\text{crs}}$ for all test conditions are collated in Table 4.

Analysis of Residual Stress at the As-Clean Blasted State

The residual stress distributions for the clean blasted state for the different casting conditions were measured. The SVM stress profiles for the different casting conditions

after clean blasting are shown in Figures 5b and 6b for point R1 and R2, respectively. For all components, the residual stresses at the surface were compressive except run 3 and run 19 at point R1. Moreover, the profiles and type of the residual stresses were similar: the compressive residual stress value increased with depth to the peak value and then decreased. From Figures 5 and 6, the values of σ_s^{rs} , $\sigma_{\text{max}}^{\text{crs}}$ for all of the clean blasted components had been determined, as collated in Table 4.

Comparison of σ_s^{rs} at as-cast to the as-clean blasted condition showed that clean blasting changed the tensile residual stress at the surface in the as-cast state to the compressive residual stress in the as-clean blasted state with exceptions of run 3 and run 19 at point R1. However, clean blasting resulted in decreasing the magnitude of tensile residual stress for run 3 and run 19 at point R1. It can be concluded that clean blasting makes stresses to a more compressive nature in the surface, but as the residual stresses from the HPDC casting process are high, it may

Figure 5. Trends of residual stress profiles of the SVM stress at point R1 for (a) as-cast (from⁹), (b) as-clean blasted, (c) as-clean blasted and painted, and (d) as-painted components. The run conditions are given in Table 1.

Figure 6. Trends of residual stress profiles of the SVM stress at point R2 for (a) as-cast (from⁹), (b) as-clean blasted, (c) as-clean blasted and painted, and (d) as-painted components. The run conditions are given in Table 1.

not be sufficient to remove the tensile element of the residual stress altogether. The outcome parameters controlling σ_s^{rs} in the as-cast state should thus also influence the as-clean blasted state.

The previous study on residual stress in the as-cast state showed that increased intensification pressure strongly increased σ_s^{rs} at points R1 and R2 making the stress more tensile in nature. Moreover, it was also shown that an increased die temperature (fixed half) reduced σ_s^{rs} at points, R1 and R2 and cooling time in the die had a similar influence at point R2.⁹

To analyze which of the process parameters effects that translates through to the as-clean blasted state regression fitting and analysis of variance (ANOVA) were made for the as-cast state for σ_s^{rs} at points R1 and R2,

The outcome of the ANOVA analysis is shown in Table 5. Intensification pressure (D) is a statistically significant model term for σ_s^{rs} responses at point R1. Cooling time

(C) was kept keeping model hierarchy intact because of that the interaction between the cooling time (C) and intensification parameter (D) also was statistically significant. The fact that both intensification pressure (D) and the interactions between cooling time (C) and intensification pressure (D) stresses the fact that in-die cooling conditions play an essential role for part residual stress build-up. The relationship between distortion and intensification pressure (D) and cooling time (C) was not possible to establish, which suggests that that residual stress build-up depends primarily on the local properties, but distortion is heavily impacted by part geometry as well, and the relations to HPDC processing parameters are weaker (Table 6).

Figure 7a shows the impact of the cooling time (C) on σ_s^{rs} responses at points R1. The physical significance of cooling time (C) is small, which also is the reason for its difficulty in reaching statistical significance. The impact of the intensification pressure (D) on σ_s^{rs} is shown in Figure 7b. A decreased intensification pressure strongly increased compressive σ_s^{rs} at point R1. The interaction

Table 4. Experimental Layout for Residual Stresses Measurements Together with the Obtained Values of σ_s^{rs} , σ_{max}^{crs} for Point R1 and R2 Under (1) As-Clean Blasted, (2) As-Clean Blasted and Painted, and (3) As-Painted Components Conditions

EXP. number	Rep. number	As-clean blasted				As-clean blasted and painted				As-painted			
		σ_s^{rs} (MPa)		σ_{max}^{crs} (MPa)		σ_s^{rs} (MPa)		σ_{max}^{crs} (MPa)		σ_s^{rs} (MPa)		σ_{max}^{crs} (MPa)	
		Point R1	Point R2	Point R1	Point R2	Point R1	Point R2	Point R1	Point R2	Point R1	Point R2	Point R1	Point R2
1	1	- 56	- 85	- 24 (0)	- 24 (0)	18	27	- 36	- 34	35	19	- 11	- 8.1
	2	- 94	- 79	- 21 (0)	- 23 (0)	13	22	- 35	- 32	30	17	- 19	- 9.3
	3	- 65	- 81	- 10 (0)	- 20 (0)	15	24	- 33	- 32	36	18	- 17	- 8.5
2	1	- 30	- 79	- 17 (0)	- 15 (0)	18	29	- 35	- 29	27	18	- 11	- 1.2
	2	- 33	- 65	- 17 (0)	- 14 (0)	18	24	- 36	- 24	28	18	- 13	- 1.1
	3	- 35	- 62	- 14 (0)	- 14 (0)	21	25	- 34	- 24	26	19	- 17	- 1.2
3	1	28	- 79	- 21 (0)	- 14 (0)	24	37	- 49	- 21	42	25	- 22	- 6.4
	2	25	- 68	- 22 (0)	- 14 (0)	24	35	- 31	- 21	41	24	- 23	- 9.1
	3	34	- 72	- 20 (0)	- 14 (0)	26	32	- 27	- 22	46	23	- 17	- 7.2
4	1	- 12 (0)	- 12 (0)	- 21 (0)	- 21 (0)	13	15	- 71	- 26	19	15	- 21	- 7.4
	2	- 13 (0)	- 12 (0)	- 19 (0)	- 13 (0)	13	17	- 75	- 31	20	13	- 12	- 7.6
	3	- 99	- 12 (0)	- 20 (0)	- 20 (0)	13	19	- 62	- 27	18	15	- 17	- 8.1
15	1	- 11 (0)	- 11 (0)	- 20 (0)	- 18 (0)	13	21	- 22	- 21	20	17	- 21	- 1.1
	2	- 89	- 11 (0)	- 21 (0)	- 18 (0)	13	21	- 24	- 37	20	18	- 19	- 1.2
	3	- 78	- 11 (0)	- 20 (0)	- 19 (0)	12	19	- 23	- 33	16	16	- 21	- 1.1
19	1	24	- 56	- 21 (0)	- 82	21	31	- 22	- 19	44	24	- 14	- 1.4
	2	26	- 53	- 24 (0)	- 82	22	29	- 19	- 19	42	21	- 33	- 1.6
	3	23	- 58	- 21 (0)	- 77	21	31	- 19	- 21	46	21	- 11	- 1.4
20	1	- 62	- 92	- 12 (0)	- 17 (0)	11	29	- 54	- 23	26	17	- 31	- 4.7
	2	- 70	- 94	- 12 (0)	- 12 (0)	11	23	- 57	- 23	24	16	- 12	- 6.3
	3	- 74	- 91	- 12 (0)	- 11 (0)	12	27	- 34	- 22	27	19	- 14	- 5.3

between cooling time (C) and intensification pressure (D) is shown in Figure 7c. The response surface shows that for increased cooling time (C) the influence of the intensification pressure (D) on σ_s^{rs} at the point, R1 is reduced. In terms of physical influence, intensification pressure (D) had the largest influence on σ_s^{rs} .

Doing the same analysis for point R2, Table 6, reveals that both cooling time (C) and intensification pressure (D) were statistically significant for the influence on σ_s^{rs} at point R2. The main difference is that the interaction between cooling time (C) and intensification pressure (D) was not statistically significant. The main difference between point R1 and point R2 is that the cross section is thicker at point R2 than point R1. This means that the metal carries more heat locally, and the influence on the boundaries on its solidification and stress build-up will be less. Figure 8a shows the effect of cooling time (C) and intensification pressure (D) on σ_s^{rs} at point R2. Although cooling time (C) was statistically significant for point R1 the trend for point R2 is slightly different with a slight reduction in the compressive nature of σ_s^{rs} , with increasing cooling time (C). This supports the relaxation process previously discussed.⁹ Similar to the point R1 responses, a decrease in intensification pressure induced higher, more compressive σ_s^{rs} stress at point R2, see Figure 8b. Again, as point R1, the effect of

intensification pressure on residual stress was stronger compared to the effect of cooling time.

The results for maximum subsurface compressive stress σ_{max}^{crs} showed that the clean blasting introduced significant compressive stresses around 0.1 mm below the surface. No clear pattern nor statistically significant correlation could be established with the casting parameters, suggesting that the clean blasting process completely dominated the generation of compressive subsurface stresses σ_{max}^{crs} in the as-clean blasted conditions.

Analysis of Residual Stress at As-Clean Blasted and Painted State

Following the experimental plan illustrated in Figure 1, the samples were first cast, then clean blasted and subsequently subjected to the paint cycle, including baking in the curing oven. The as-clean blasted and painted state will thus show the changes following the clean blasting cycle by the paint pretreatment and curing cycle.

The experimentally assessed SVM stresses as a function of depth for the as-clean blasted and painted state for points R1 and R2 are shown in Figures 5c and 6c, respectively.

Table 5. ANOVA Response (with R-Squared of 0.97) for σ_s^{rs} Response at Point R1 After Clean Blasting

Source	Sum of squares	df	Mean Square	F value	p value Prob > F	
Model	50,657.39	6	8442.9	139	< 0.0001	Significant
C—cooling time	166.64	1	166.64	2.74	0.116	
D—intensification pressure	11,157.15	1	11,157.15	183.69	< 0.0001	
CD	1668.53	1	1668.53	27.47	< 0.0001	
Residual	1032.57	17	60.74			
Lack of fit	184.33	1	184.33	3.48	0.0807	Not significant
Pure error	848.24	16	53.01			
Cor total	51,689.96	23				

Table 6. ANOVA Response (with R-Squared of 0.90) for σ_s^{rs} Response at Point R2 After Clean Blasting

Source	Sum of squares	df	Mean square	F value	p value Prob > F	
Model	9177.45	3	3059.15	45.36	< 0.0001	Significant
C—cooling time	439.72	1	439.72	6.52	0.0189	
D—intensification pressure	8659.13	1	8659.13	128.4	< 0.0001	
Residual	1348.83	20	67.44			
Lack of fit	13.62	3	4.54	0.57	0.6433	Not significant
Pure error	106.36	16	6.65			
Cor total	10,526.27	23

Figure 7. The effect of (a) parameter (C) = cooling time, (b) parameter (D) = intensification on σ_s^{rs} and (c) response surface for the interaction of parameters (C) and (D) on σ_s^{rs} at point R1 after clean blasting. The centerline is the actual trend. Dash lines are the 95% confidence intervals.

Figure 8. (a) The effect of cooling time parameter (C) and (b) the effect of intensification pressure parameter (D) on σ_s^{rs} responses at point R2 after clean blasting. The centerline is the actual trend. Dash lines are the 95% confidence intervals.

The values of σ_s^{rs} , σ_{max}^{crs} for the as-clean blasted and painted state are collated in Table 4 and sorted according to the casting conditions.

The σ_s^{rs} was found to be tensile for all components tested in the as-clean blasted and painted state. This showed that the compressive σ_s^{rs} stress in the as-clean blasted state change into tensile stresses after the paint curing cycle. Comparing to the as-cast state, the magnitude of σ_s^{rs} for the as-clean blasted and painted state was, in general, slightly lower. It should also be noted that compared to the as-clean basted

condition σ_{max}^{crs} was less compressive and tended toward zero.

Similar to as-clean blasted components, comparison of σ_s^{rs} at the as-cast state, the as-clean blasted and painted state showed that the component cast at conditions resulting in higher magnitudes of σ_s^{rs} still showed the higher magnitude of σ_s^{rs} after the paint cycle in the as-clean blasted and painted state. This was only observed for σ_s^{rs} and not seen for σ_{max}^{crs} .

Figure 9. Variation of σ_s^{rs} responses with (a) first phase injection speed, (b) temperature of fixed half of the die, (c) cooling time, and (d) intensification pressure at points R1 and R2 for as-clean blasted and painted components. Dash lines are trendlines.

Figure 10. Variation of σ_s^{rs} responses with (a) first phase injection speed, (b) temperature of fixed half of the die, (c) cooling time, and (d) intensification pressure at points R1 and R2 as-painted components. Dash lines are trendlines.

To understand the influence of the HPDC parameters on σ_s^{rs} responses efforts to use regression analysis and ANOVA was used, but no statistically significant models could be realized for σ_s^{rs} at points R1 and R2. Nevertheless, σ_s^{rs} responses at points R1 and R2 as a function of HPDC process parameters investigated are shown in Figure 9. As can be seen from Figure 9a–c, the σ_s^{rs} responses do not show a clear dependence on parameters first-stage injection speed, temperature of fixed half of the die, and cooling time. Subjectively, there is a slight increasing tensile stress trend with increasing first-stage injection speed and a weakly decreasing trend with cooling time, suggesting that there is an influence from the melt temperature entering the die and that relaxation during cooling influence to some extent. However, Figure 9d shows a more pronounced trend with an increase of σ_s^{rs} with an increased intensification pressure for both points R1 and R2. The earlier observation of the as-clean blasted state that intensification pressure dominated the residual stress state with an increased pressure driving toward increasingly tensile conditions also holds after clean blasting and paint curing. Clean blasting and paint curing will thus not wholly neutralize the residual stress conditions from the as-cast state

Analysis of Residual Stress at Painted Components

The tests made in the as-painted state, following the plan shown in Figure 1, were made to see the effects of omitting the clean blasting and the generation of strong compressive stresses as an intermediate step in the processing.

Figures 5d and 6d illustrate the residual stress in components cast with different run conditions and went through the painting cycle. The values of σ_s^{rs} , σ_{max}^{crs} are collated in Table 2.

In the as-painted state, it can be directly concluded that the maximum von Mises stress or [SVM] was at the very surface and of tensile nature for both points R1 and R2. The fact that σ_s^{rs} was tensile for all casting conditions in the as-painted state and that σ_s^{rs} tended toward zero at depths greater than 0.05–0.1 mm is different from the as-clean blasted and painted state. The as-clean blasted and painted state showed slightly higher compressive stresses at a slightly higher depth. In the as-painted state, σ_{max}^{crs} was lower than for any of the other post-processing conditions. The magnitude of σ_s^{rs} was in the as-painted state of the same level as that of the as-cast state. However, the level of σ_s^{rs} in the as-painted state was higher than for that in the as-clean blasted and painted state at point R1. This was likely due to the mode of solidification, being a thinner section, at the outer edge of the casting, away from the gate even though on the same side of the part as the gate. Clean blasting, as a second step, drives subsurface stresses toward slightly higher compressive stresses after the paint cycles than omitting it and directly going to the paint curing for

both points R1 and R2. This is due to that the subsurface compressive stresses generated by the clean blasting are not fully neutralized during the paint cycle and, therefore, must be balanced out by slightly higher surface stresses. This can be concluded as relaxation directly from the as-cast state in the paint cycle does not show the same high compressive stresses despite having the same as-cast original state. Therefore, it is likely that the most influential parameters on σ_s^{rs} for the as-cast condition should remain dominant also after the paint cycle.

No statistically significant correlation could be established for the influence of the HPDC process parameters on σ_s^{rs} responses in the as-painted state. Nevertheless, the effect of first phase injection speed, temperature of fixed half of the die, and cooling time on σ_s^{rs} responses of as-painted components are indistinct, see Figure 10a–c. Subjectively as for the as-clean blasted and painted state and there is for the as-painted state a slight increasing tensile stress trend with increasing first-stage injection speed with less temperature loss and a weakly decreasing trend with cooling time, suggesting that there is an influence from the melt temperature entering the die and that relaxation during cooling influence to some extent. However, a pronounced trend of increasing σ_s^{rs} responses with intensification pressure can be obtained, see Figure 10d. The trendlines are different for the as-painted state, Figure 10d compared to the as-clean blasted and painted state Figure 9d, suggesting that clean blasting to some extent neutralize the effect of section thickness

Conclusions

An empirical parametric study was carried out to investigate the influence of the HPDC process parameters on the distortion and residual stress formation in the AZ91D components after applying three different post-treatments: (1) as-clean blasted, (2) as-clean blasted and painted, and (3) as-painted. From the results of this study, the following conclusions can be drawn:

- Distortion responses after post-treatments for all different runs increased from the cast state at point D1.
- Distortion responses of as-painted components at point D5 were higher than as-cast, as-clean blasted, and as-clean blasted and painted components.
- A component cast by a combination of specific HPDC parameters that resulted in higher residual stress σ_s^{rs} , remained higher after any of the post-treatment applied to stress the importance of keeping the residual stress levels controlled in the as-cast state.
- Clean blasting shifted the residual stress σ_s^{rs} toward compressive stress, but with high tensile

stress from the as-cast state, tensile stress could remain after clean blasting, as shown by run 3 and 19. However, as-clean blasted and painted samples showed tensile σ_s^{rs} , while the magnitude of residual stresses was lower than the as-cast state.

- Components which went through the paint cycle without clean blasted showed tensile σ_s^{rs} with almost the same magnitude of as-cast state. For as-painted components, after a depth of 0.05–0.1 mm, the residual stress at these components showed the tendency toward zero.
- The study showed that intensification pressure was the most influential factor for the residual stress σ_s^{rs} for all post-processing treatments (1) as-clean blasted, (2) as-clean blasted and painted, and (3) as-painted components. An increased intensification pressure increased the tensile σ_s^{rs} .
- It should also be noted that the interaction between intensification pressure and cooling time was significant for point R1 in the clean blasted condition but not for the as-clean blasted and painted condition. This reaffirms intensification pressure as the dominant factor for the residual stress build-up as the dependence of the intensification pressure remained after clean blasting and painting.

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