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Simulation of Wax Injection Process in Investment Casting

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Abstract: ***The investment casting process is gaining prominence, especially in the production of complex, high-quality components with near-net shapes, due to its exceptional versatility and adaptability. A major challenge in this process, however, is the shrinkage of wax patterns, which substantially affects the quality of the final product. This shrinkage is influenced by multiple variables, including the wax composition, mold and injection temperatures, pressure, and duration of injection. In this study, the Mold flow simulation software was utilized to evaluate volumetric shrinkage. This simulation presents a promising approach to significantly enhance the dimensional accuracy of wax patterns in investment casting.***

Keywords: Investment casting, volumetric shrinkage, wax pattern, simulation

1. Introduction

Investment casting is a specialized manufacturing technique used for producing high quality, net-shape complex parts. It is considered as the most ancient of metal casting arts. Technological advances have also made it the most modern and versatile of all metal casting processes [1]. Difficult to machine metals are best shaped by this process. Excellent surface finish is a major advantage of this process [16]. The steps involved in the investment casting process are as follows: wax injection process, pattern assembly, ceramic shell building, dewaxing, Pre-heating, metal casting, knocking out of the ceramic shell and cutting off the components, and minor finishing operations.

W. Bonilla et al. [17] found that not only the composition of wax blend is affecting the quality of wax patterns, but also there are some other factors such as geometry of the cast part and injection process parameters like injection temperature, injection pressure, die temperature, cycle time etc., which are also plays a significant role in making a good wax pattern. It is necessary to identify the important control factors and then, the optimal combination of selected control factors should be analyzed for improving the quality of the wax patterns. Rahmati et al. [13] presented a rapid wax injection tool of a gearbox shift fork was designed, simulated, and manufactured using rapid prototyping and rapid tooling technology to save time and cost of producing wax models used for the investment casting process. The model of the gearbox shift fork part was analyzed using CAE simulation software such as Mold Flow to investigate the ideal and optimum conditions of tool operation during wax injection molding process. Parameters investigated include filling patterns, temperature profiles, residual stresses, and tool clamping force, the pressure at different time intervals, air trap spots locations, wax model weld lines and freeze time. The results from analysis were compared with conventional wax model production methods and it has not only confirmed the success of such application, but also proves valuable benefits with respect to the common tooling techniques.

S. Pattnaik et al [11] presented the wax blend, to be used in the investment casting process, is prepared by mixing different waxes and starch as filler material to reduce the shrinkage of wax patterns. The effect of the injection process parameters on the dimensional stability of the wax patterns made using silicon rubber mould has been studied and the optimum injection process parameters to reduce the shrinkage of wax patterns have been suggested.

This investigation focuses on four crucial process parameters: mold temperature, injection temperature, injection pressure, and injection time. The researchers evaluate the quality of wax patterns by measuring their volumetric shrinkage as a performance indicator. To validate the efficacy of the proposed methodology, a confirmation analysis is conducted using mold flow simulation software.

2. Materials and Methods

This section addresses the selection of process parameters and their levels, the choice of wax material for pattern fabrication, and the identification of a suitable orthogonal array for experiment design.

2.1 Wax pattern material choice

The wax pattern's accuracy directly affects the final casting's precision. Ideal wax pattern qualities include: high dimensional accuracy, significant hardness, superior surface finish, excellent flowability, easy mold release, and bubble-free injection molding [8]. Cerita wax F30-75 was selected based on Rahmati et al. [16]. This lightly filled pattern wax demonstrates exceptional flow properties and dimensional stability. Criteria F30-75 wax characteristics include:

- Low ash yield upon combustion
- Facile injectability
- Smooth interaction with ceramic cores
- Exceptional surface appearance

2.2 Wax injection process parameter selection

The selection of wax injection process parameters for investment casting is based on research by Pattnaik et al.

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[14] and Bonilla et al. [20]. Factors potentially affecting wax pattern dimensional stability include:

1) Wax injection process variables: injection temperature, pressure, and duration.
2) Wax blend characteristics: composition (various waxes and additives), viscosity, and thermal conductivity.
3) Mold-related factors: mold temperature, cooling time, and air venting.

Mold temperature, injection temperature, pressure, and time were chosen to examine their impact on wax pattern dimensional accuracy in investment casting. Other factors, such as wax composition, ambient temperature, and pattern cooling (in-mold and post-ejection), remained constant throughout the study.

2.3 Process parameter level selection and orthogonal array

Process parameter ranges were obtained from industry sources. To design experiments and assess the effects of mold temperature, injection temperature, pressure, and time on wax pattern quality in investment casting, three levels were chosen for each parameter.

Table 1: The level of wax injection process parameters

Symbol	Process parameters	Range	L1	L2	L3
t_m	Mold temperature	13-17(ºC)	13	15	17
t_i	Injection temperature	60-70(ºC)	60	65	70
p_i	Injection pressure	1.0-1.5(MPa)	1.0	1.3	1.5
t_s	Injection time	5-10(S)	5	7	10

To select an appropriate orthogonal array for conducting the experiments, the degrees of freedom are to be computed. Hence, the total DOF required for three parameters, each at three levels is [4 x (3-1)], i.e. 8. Thus L9orthogonal array was selected to make the present analysis.

3. Validation of Software Data

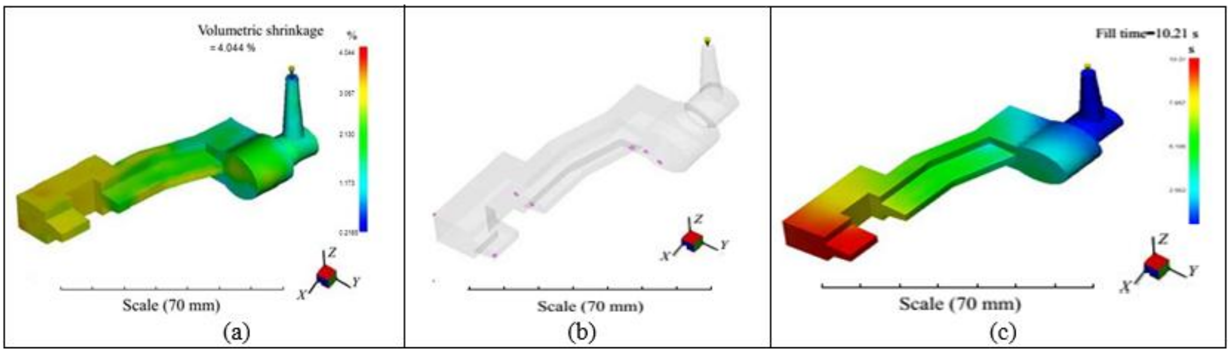
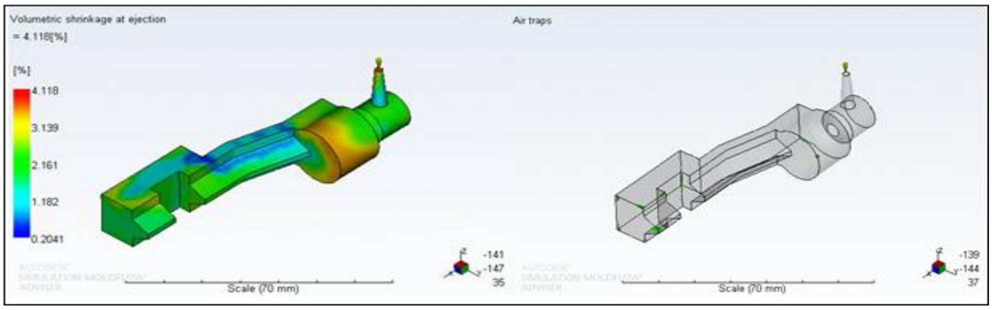
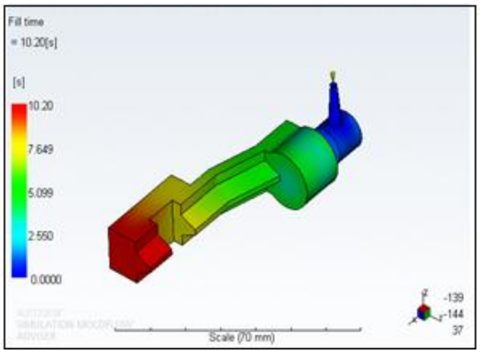


Figure 1: (a) Volumetric shrinkage, (b) air trap spots location and (c) Wax model filling time as given in reference literature [16]



(a) (b)



(c)

Figure 2: (a) Volumetric shrinkage, (b) air trap spots location and (c) Wax model filling time as per the present model

This study employs moldflow software to simulate the wax injection process, following the approach of Rahmati et al. (2009) referenced in [16]. A comparison is made between the current study's results, depicted in Figure 2, and those from the cited literature by Rahmati et al. (2009), shown in Figure 1. The analysis focuses on volumetric shrinkage, air trap spot locations, and fill time. The comparison reveals a strong correlation between the two models in terms of these three aspects, demonstrating the consistency of the findings.

4. Wax Pattern

In this study, to analyze the wax injection molding a 3-D model of an industrial part hanger is created in part module of Creo 2.0 software shown in Fig 3.

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Figure 3: Wax pattern

5. Set of Process Parameters (orthogonal array)

The value of volumetric shrinkage at ejection is selected according to H. Oktem (2011) cited in [8] as a response of the analysis. Following are the combination of process parameter:

Table 2: Set of Process Parameters (orthogonal array)

Analysis No.	Process parameters			
	t_m(ºC)	t_i(ºC)	p_i(MPa)	t_s(s)
1	13	60	1.0	5
2	13	65	1.3	7
3	13	70	1.5	10
4	15	60	1.3	10
5	15	65	1.5	5
6	15	70	1.0	7
7	17	60	1.5	7
8	17	65	1.0	10
9	17	70	1.3	5

6. Simulation for Selected Orthogonal array

The simulation was conducted in moldflow simulation software with different set of process parameters shown in Table 2. Following were the Responses:

Table 3: Response table for selected orthogonal array L9

Analysis No.	Process parameters				Volumetric shrinkage, V_S (%)
	t_m(ºC)	t_i(ºC)	p_i(MPa)	t_s(s)	
1	13	60	1.0	5	4.76
2	13	65	1.3	7	5.118
3	13	70	1.5	10	5.467
4	15	60	1.3	10	4.761
5	15	65	1.5	5	5.191
6	15	70	1.0	7	5.511
7	17	60	1.5	7	4.756
8	17	65	1.0	10	5.157
9	17	70	1.3	5	5.578

For the first set of process parameter i.e. Mould temperature = 13 ºC, injection temperature = 60ºC, injection pressure = 1.0 MPa and the injection time = 10 sec., the volumetric shrinkage of the wax pattern was found to be 4.767%, which was shown in figure below.

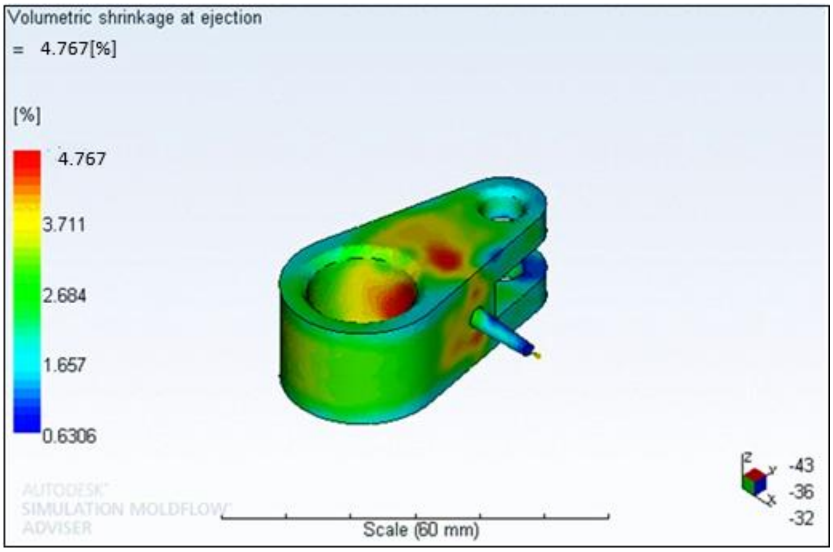

Figure 4: Volumetric shrinkage at Mould temperature at 13 ºC, injection temperature at 60ºC, injection pressure at 1.0 MPa and the injection time at 10 seconds

7. Conclusion

Moldflow package was applied to simulate and predict different scenarios and investigate the effect of injection parameters. The 3D model of the hanger part was imported and with the combinations of wax injection process parameters and analyses were performed as per different set of orthogonal array. The value of volumetric shrinkage at ejection is selected as a response of the analysis. As a result, it is seen that this study is sufficient to model the shrinkage under the process parameters.

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