ANALYSIS OF INJECTION MOLDING PROCESS OF PLASTIC PROPELLER FAN BASED ON THE ROBUST DESIGN METHOD

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Abstract. *Despite the wide use of polymers in the production of industrial components, it is observed that the natural dimensional variability of this type of material is difficult to control. In a large number of applications, this characteristic can compromise the final performance of the product. For this reason, different techniques are employed to minimize the negative effects of the dimensional variability, among them, the Robust Design, also known as Taguchi Method, stands out. The Robust Design method assists in the development of products and processes capable of reducing the undesired effect of noise. These noises are usually present in the operating conditions of the product or process and the variability of its components. In this work, the Robust Design method will be used to reduce the variability of an injection molding process of plastic propeller fan. Based on a preliminary investigations of the rejection rates, it was observed that 94.0% of the problems were associated with propeller unbalance. Thus, the Robust Design method was employed to identify the factors of the injection molding process responsible for this problem and to determine their effects on the process. During the experimental work, 4 parameters of the injection molding process were investigated. The melt temperature ranging between 250 ºC and 280 ºC, injection time ranging between 3 s and 4 s, cooling time ranging between 17 s and 19 s and hold pressure ranging between 91 and 93 bar. A vibration meter equipment was used to measure the vibration of the fans with the collected propellers, where the maximum acceptable value of vibration displacement was assumed to be 0.30 mm. Different combinations of the factors were investigated in three production batches, with thirty samples in each batch. Based on the experimental results, the signal-to-noise ratio was evaluated to identify the factors levels that reduced the process variability by 88% and the rejection rate by 100%.*

Keywords: Robust Design, Taguchi method, plastic injection molding, process variability, propeller fan.

1. INTRODUCTION

Although the industrial use of plastic can be considered recent, it is difficult to imagine our daily lives without the presence of this material. Plastic contributes to technological advances and enables several innovations, which permeate from the food industry to the automotive and household appliances. Zamora et al. (2020) estimate that 9.2 billion tons of plastics have been produced since the mid-twentieth century, when plastics manufacturing began on an industrial scale, and it is estimated that in 2025 the production will reach about 600 million tons of the material per annum.

In the plastics industry, one of the most important processing operations is injection molding. Approximately one third of all plastics are transformed through this process (ABIPLAST, 2018). When compared to other production processes, injection molding has greater efficiency, yield and dimensional accuracy, in addition to resulting in an excellent surface finish of the injected parts. Chen et al. (2013) state that injection molding is one of the most important techniques for processing polymers due to its high molding speed and ability to manufacture complex geometric shapes. In addition, this process is capable of mass production, which is why it is widely used in many products, especially in small appliances.

1.1 Ventilation and Robust Design

In order to a fan meet the project's performance requirements, all of its components must be produced according to its specifications. Deviating from these specifications results in reduced performance or disposal of the product during the production process. The propeller is one of the components of the fan, and its unbalance is a common problem in the manufacture of fans. An unbalanced propeller will create forces in its bearings and structure, consequently, will cause vibrations in the fan (Cory, 2005; Rao, 2009). Excessive vibration levels can lead to premature fan failure, high noise levels and transmission of unwanted forces to the support structure. Although fan vibration can never be completely eliminated, acceptable levels can be achieved through adaptation to product design, manufacturing and application (ASRHAE, 2020). Eisenmann (1997) shows that unbalance is one of the most common sources of vibration in machines and equipment, and it happens due to a change in the balance of radial forces acting on the machine axis. The most

common cause is material buildup on different mobile components, such as buildup or lack of mass in one of the propeller blades.

Due to the complex production process of plastic components, plastic parts end up showing variability in their dimensional and performance characteristics. This variability is undesirable, as it can lead to dissatisfaction among users of the final product. For this reason, different techniques are used to minimize the effect of these variability, and among them, the Robust Design stands out.

The Robust Design method helps in the design of a product or process so that it works properly under various conditions of use, being able to maintain its performance characteristics even when subjected to different sources of variability, known as noise (Taguchi et al., 2005). There are many factors that contribute to the occurrence of defects that affect the quality of injection molded parts, and the definition of process parameters for plastic products has a notable influence on their quality (Chen et al., 2013). Noise variables bring variability to the system, distancing the response from its specified value. The Robust Design method identifies the levels of control factors that optimize the defined quality characteristic, so that the process is robust or insensitive to the variation caused by noise (Robinson et al., 2004).

Ginghtong et al. (2018) used the Robust Design to optimize the plastic injection molding process parameters. Through experiments using the L9 orthogonal matrix, they studied the effect of three main factors on the compressive strength of injected polypropylene plastic containers, namely: injection speed, injection pressure and melting temperature. Furthermore, the authors were able to identify that the injection speed is the most significant factor to achieve the desired result, having a contribution of 71 %. Mehat and Kamaruddin (2012) also used the Robust Design to optimize the plastic injection parameters using recycled material, evaluating the mechanical behavior of the injected parts.

Based on these facts, the objective of this work is to use the Robust Design method to identify the parameters of the injection molding process that reduce the vibration in fans caused by unbalanced plastic propellers and control its variability inside acceptable levels.

2. METHODOLOGY

The Robust Design method will be used in the planning and analysis of the results to be obtained for the plastic propeller injection process in an appliance company. The study will be carried out on a 400 mm diameter plastic propeller with 6 blades, as shown in Figure 1. The material used to manufacture the propellers is a polypropylene, whose density is 0.9 g/cm³ and melting temperature is 152 ℃. The injection machine used has a clamping force of 3200 kN, power 60 kW, injection rate 350 g/s and injection pressure 180 MPa. The mold studied has two cavities, in which they were measured separately.

Figure 1. Propeller used on the experiments.

Figure 2 shows the P-diagram of the plastic propeller production process, indicating the main inputs and outputs. Although there are several inputs and outputs related to the process, in this study the response chosen for the analysis was the vibration. The choice of this response variable was based on a survey of data regarding the production process of plastic propellers. This study showed that approximately 4.5% of the total propeller production was rejected due to vibration problems during the investigated period. On the other hand, the selected control parameters were the injection time, cooling time, hold pressure and melt temperature. This decision was take based on the previous experience of the engineering team responsible for the production process under analysis.
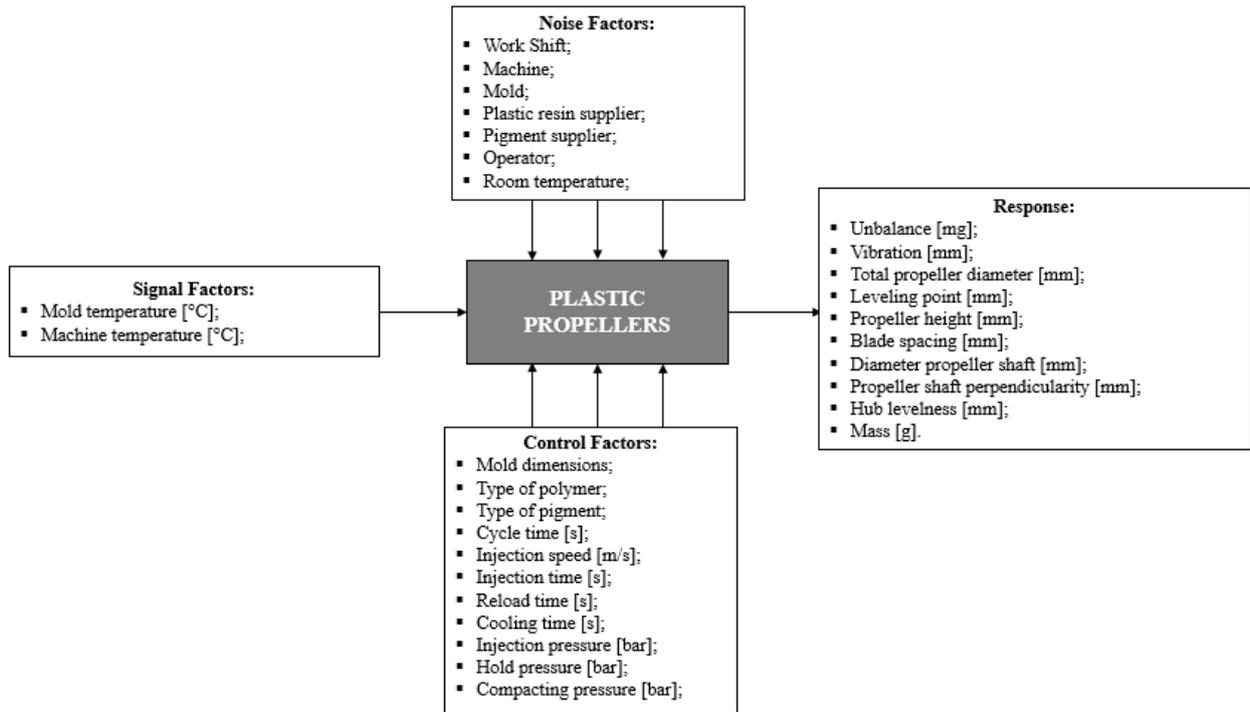
Figure 2. P-diagram of the plastic propeller injection process.

The effect of the injection process parameters on the fan vibration will be quantified based on the Robust Design parameter signal-to-noise ratio (S/N ratio), which takes into account the mean and variability of the response variable (Mehat and Kamaruddin, 2012). In the present study, the S/N ratio type smaller-the-better (STB) will be used, as it is intended to minimize the mean and variance of the response variable vibration. The S/N ratio of the small is the better is given by

$$S/N_{STB} = -10\,log[s^2 + \bar{y}^2] \tag{1}$$

where s is the sample standard deviation

$$s = \sqrt{\frac{\Sigma(y_i - \bar{y})^2}{n-1}} \tag{2}$$

and $\bar{y}$ is the sample average

$$\bar{y} = \frac{\Sigma y_i}{n} \tag{3}$$

The vibration of the fan propeller was measured by a Minipa vibration meter model MVA-400, shown in Figure 3. The equipment results of vibration can be measured as displacement, velocity or acceleration. In the present study, displacement was used as a response, which is measured in millimeters (mm). The maximum uncertainty of the displacement is 5.0%.
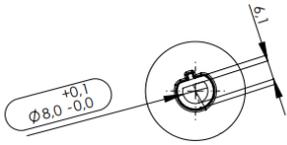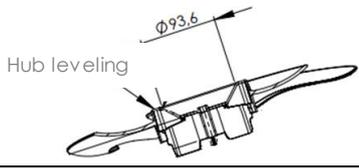

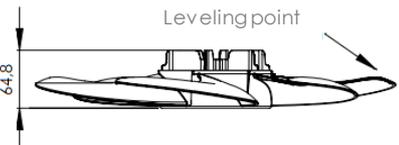Figure 3. Vibration meter used in the experiments.

To certify that the vibration problem is related to the injection process, an additional investigation of the propellers with vibration problems will be carried out. For this reason, 30 propellers with a vibration problem above the allowed tolerance, which is equivalent to 0.300 mm of displacement, will have the physical dimensions compared with

specifications presented in Tab. 1. From each sample, 4 measurements of each dimension will be performed, from which the average value will be obtained.

Subsequently, different combinations of propeller injection process parameters will be experimentally analyzed to evaluate their effects on the vibration problem. Three production batches will be investigated, with thirty samples in each batch.

Table 1. Plastic propeller specifications.

Representation	Technical description	Engineering specifications	
		Minimum	Maximum
-	Mass	252.00 g	256.00 g
-	Mass Unbalance	0.00 mg	120.00 mg
	Largest shaft diameter	8.00 mm	8.10 mm
	Smallest shaft Diameter	6.10 mm	6.20 mm
	Hub leveling	0.00 mm	0.20 mm
	Hub diameter	93.50 mm	93.70 mm
	Propeller height	64.70 mm	64.90 mm
	Leveling point	0.00 mm	2.00 mm

3. RESULTS

3.1 Evaluation of the technical specifications

Figure 4 shows the results obtained from the measurements performed on samples that had a vibration problems. This analysis was carried out to identify whether the cause of the vibration problem was due to design or process. Propellers collected with problems presented vibrations ranging from 0.326 mm to 1.415 mm. The results show that the variables propeller height (Fig. 4g) and smallest shaft diameter (Fig. 4d) presented variations within the specification limits even with the vibration problem. Thus, these variables do not show significant variation to cause vibration. On the other hand, the variables mass (Fig. 4a), mass unbalance (Fig. 4b), hub leveling (Fig 4e), hub diameter (Fig 4f) and leveling point (Fig 4h), presented some samples outside specification limits, these being the variables that may be causing the vibration.

It is verified that 94% of the propellers with vibration problems had an unbalanced mass. Additionally, it is observed that 40% of the propellers had a hub leveling outside the specifications, 37% of the propellers had a height difference between the blades, 30% with the mass out of the specifications and, finally, 14% with a hub diameter outside the specifications.

The results show that most cases of fan vibration are caused by propellers with unbalanced mass, confirming the theory presented by Rao (2009), which states that mass unbalance is one of the main causes of vibration. Based on the results, it was also observed that all propellers with vibration problems had at least one value outside the design specifications. Such evidence shows that there is not a problem related to the design of the propellers, but rather to their injection process.
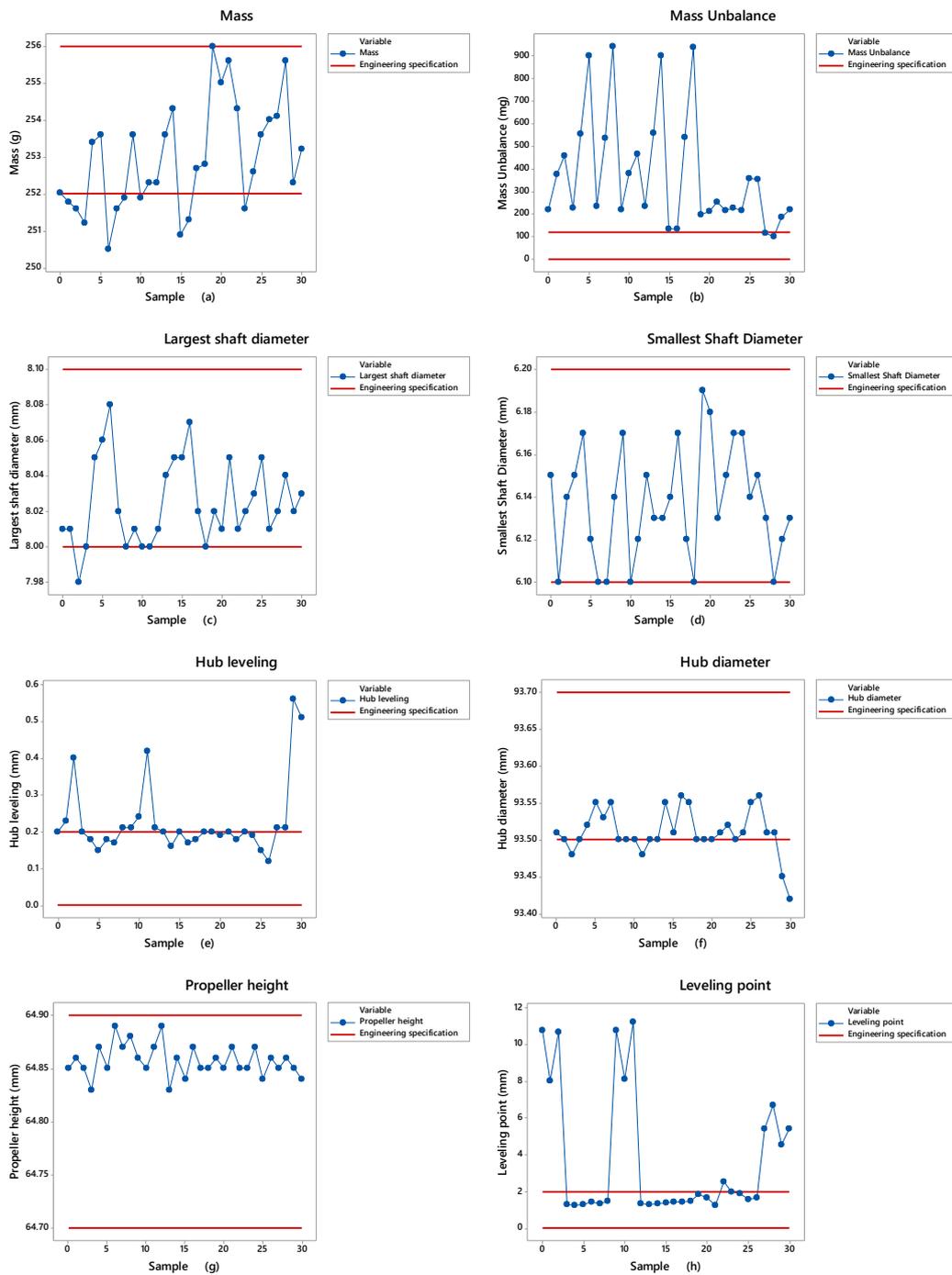
Figure 4. Comparison between physical and specified parameters.

3.2 Evaluation of the injection process

Table 2 shows the value of the propeller injection process parameters for conditions A, B and C. These are the selected conditions used to investigate the effect of the injection parameters on the vibration of the plastic propellers. For each of the combinations, 30 samples of plastic propellers were collected to be measured. The average values of the vibration measurements of the propellers corresponding to each combination of parameters are presented in Table 3. The mold cavity was also identified during the experiments. With the data in Table 3, it is possible to calculate the mean vibration and the standard deviation for each combination of parameters and cavity, and also the S/N ratio. The results are shown in Table 4.

Table 2. Injection parameters.

PARAMETERS	COMBINATIONS		
	A	B	C
Injection time (s)	4.0	3.0	3.5
Cooling time (s)	19.0	17.0	17.0
Hold pressure (bar)	93.0	91,0	91,0
Melt temperature (°C)	280.0	275.0	250.0

Table 3. Vibration results of the plastic propellers for different combinations of parameters.

Combination A			Combination B			Combination C		
Sample	Mold cavity	Mean (mm)	Sample	Mold cavity	Mean (mm)	Sample	Mold cavity	Mean (mm)
1	1	0.22	1	1	0.30	1	1	0.02
2	1	0.22	2	1	0.32	2	1	0.03
3	1	0.24	3	1	0.36	3	1	0.20
4	1	0.25	4	1	0.16	4	1	0.18
5	1	0.27	5	1	0.34	5	1	0.28
6	1	0.26	6	1	0.13	6	1	0.17
7	1	0.24	7	1	0.13	7	1	0.44
8	1	0.21	8	1	0.24	8	1	0.39
9	1	0.22	9	1	0.29	9	1	0.04
10	1	0.20	10	1	0.15	10	1	0.51
11	1	0.20	11	1	0.13	11	1	0.16
12	1	0.20	12	1	0.12	12	1	0.41
13	1	0.22	13	1	0.19	13	1	0.03
14	1	0.21	14	1	0.24	14	1	0.41
15	1	0.23	15	1	0.25	15	1	0.02
16	2	0.21	16	2	0.21	16	2	0.29
17	2	0.23	17	2	0.27	17	2	0.25
18	2	0.21	18	2	0.07	18	2	0.01
19	2	0.23	19	2	0.25	19	2	0.18
20	2	0.23	20	2	0.20	20	2	0.23
21	2	0.27	21	2	0.34	21	2	0.02
22	2	0.21	22	2	0.32	22	2	0.51
23	2	0.20	23	2	0.21	23	2	0.32
24	2	0.22	24	2	0.10	24	2	0.30
25	2	0.27	25	2	0.40	25	2	0.02
26	2	0.20	26	2	0.11	26	2	0.40
27	2	0.22	27	2	0.11	27	2	0.08
28	2	0.21	28	2	0.43	28	2	0.39
29	2	0.27	29	2	0.22	29	2	0.32
30	2	0.21	30	2	0.21	30	2	0.38

Table 4. S/N ratio results for different combinations of parameters.

Combination	Mold cavity	Mean (mm)	σ (mm)	σ² (mm²)	S/N$_{MEM}$ (dB)
A	1	0.225	0.021	0.000	12.904
B	1	0.224	0.085	0.007	12.430
C	1	0.219	0.176	0.031	11.041
A	2	0.225	0.023	0.001	12.891
B	2	0.228	0.109	0.012	11.933
C	2	0.247	0.154	0.024	10.730

Figure 5 shows the comparison between the results of the signal-to-noise ratio. From the results, it can be seen that the set of parameters A presented the highest value in the S/N ratio, indicating that this is the most robust combination of parameters against the vibration problem.

Through the obtained results, it is possible to conclude that the parameters of the plastic propeller injection process can be used to reduce the variability of vibration in fans, and thus increase the robustness of the product. Using the signal-to-noise ratio proposed by the Robust Project method, it was possible to evaluate the levels of the injection process parameter sets that reduced the process variability by 88% and the rejection rate by 100%.
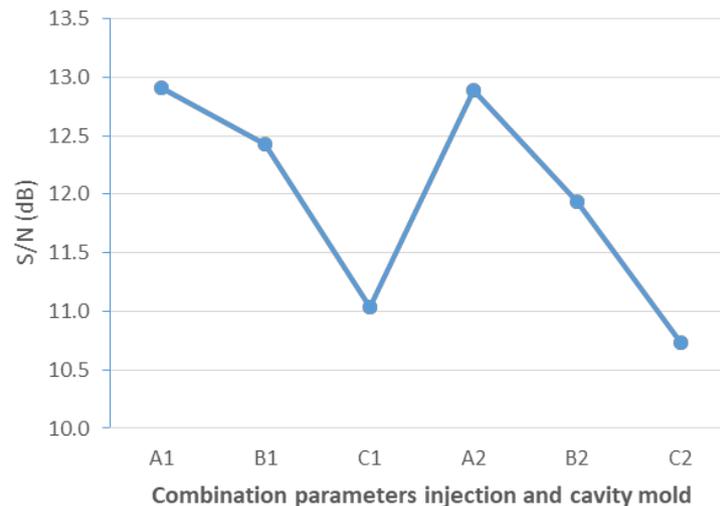

Figure 5. S/N ratio smaller-the-better results.

4. CONCLUSIONS

In this study, the Robust Design method was used to identify the parameters of the injection molding process that reduce the variability of vibration in fans caused by unbalanced plastic propellers. Initially, propellers with vibration problems were analyzed, where it was verified that 94% of the propellers with vibration problems had an unbalanced mass. This result showed that there is not a problem related to the product design, but to the manufacturing process. Next, an experimental work was done to analyze the effect of different combinations of process parameters on process variability.

During the experimental work, four parameters of the injection molding process were investigated in three production batches. The melt temperature ranging between 250 ℃ and 280 ℃, injection time ranging between 3 s and 4 s, cooling time ranging between 17 s and 19 s and hold pressure ranging between 91 and 93 bar. Based on the experimental results, the signal-to-noise ratio was evaluated to identify the factors levels that reduced the process variability. The combination of parameters that resulted in an 88% reduction in variability and the rejection rate by 100% was combination A, in which the melt temperature at 280 °C, injection time in 4 s, cooling time in 19 s and hold pressure in 93 bar.

5. ACKNOWLEDGEMENTS

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