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WINNING BACK THE CUSTOMER'S CONFIDENCE: A CASE STUDY ON THE APPLICATION OF DESIGN OF EXPERIMENTS TO AN INJECTION-MOLDING PROCESS

U. H. Acharya and C. Mahesh
Statistical Quality Control and Operations Research Unit
Indian Statistical Institute
8th Mile, Mysore Road
Bangalore 560 059, India

Key Words

Warpage; Root causes; Factorial experiment; Local control; ANOVA; Average response.

Background of the Study

A large injection-molding company was manufacturing plastic molded components used in washing machines, automobiles, and television sets. Customers were not happy with the quality of these molded parts. Customer complaints concerned warpage primarily (as shown in Fig 1).

Warpage refers to the nonflatness property in the product. It may occur at the edge or within the product. Warpage not only affects the aesthetic aspect but also the usability of the product. A warped product cannot be assembled easily.

The company was eager to solve this problem and win back its customers' confidence. Samples collected from the existing process indicated very high levels of warpage (see Table 1).

Process of Injection Molding

The injection-molding machine was an "in-line reciprocating-screw-type" machine. The manufacturing practice required that the mold be loaded first on the machine (incidentally, it was a customer-supplied mold). The operator then sets the various process parameters at predetermined levels. With these settings, a few samples will be processed and checked. If he finds the samples are not good enough, he would change the setting of some process parameters, depending on his experience/intuition. With the new setting, he again collects a few samples and checks them. He repeats the above steps until good components are obtained. The process then is left undisturbed and production is continued until the order is completed.

After the component is ejected from the mold, the operator loads it onto a jig, where external stress is applied for a few minutes in a direction opposite to that of the warpage, so as to reduce it to some extent. It was decided exclusively by the company to reduce the warpage. After removing the component from the jig, it was checked, packed, and sent to the customer.

Each operator had his own setting values for the process parameters and there was no standard maintained. Hence, it was of prime importance to standardize the process parameter settings.

Cause-and-Effect Diagram

Brainstorming was conducted on the "how and why" of warpage with the factory personnel to generate a substan-

NO.	CAUSE	FREQ.	CUM %
1	WARPAGE	1987	31.4
2	DAMAGE	1039	47.8
3	PIN MARK	834	61.0
4	SCRATCHES	442	68.0
5	BLACK SPOT	413	74.6
6	SILVER STREAK	413	81.1
7	SINK MARK	371	87.0
8	SPRAY MARK	292	91.6
9	SHOT MOLD	275	95.9
10	JETTING	258	100.0

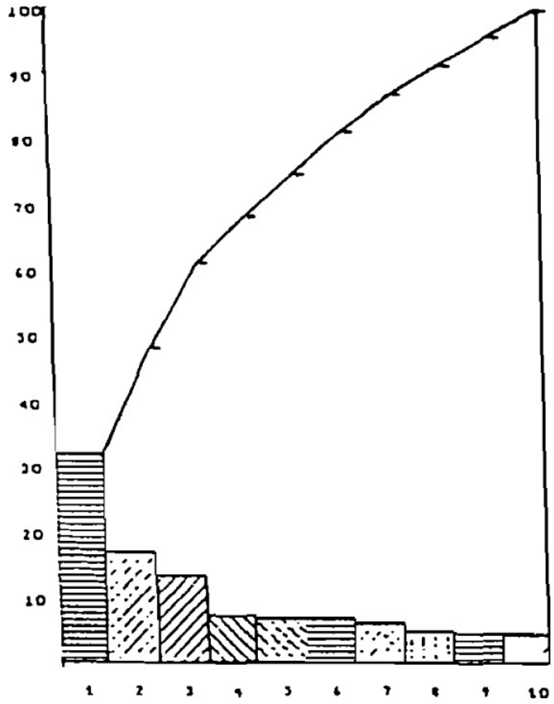

Figure 1. Pareto diagram. Data corresponded to all the computer keyboards produced during a 3-month period.

tial list of potential causative factors. A cause-and-effect diagram was drawn (Fig. 2).

Identification of Potential Causes and Process Parameters

Based on the discussion of potential causes of warpage in the cause-and-effect diagram, the following three factors were identified for in-depth study:

1. Melt temperature
2. Injection speed
3. Injection pressure

As the plastic material passes from the hopper to the nozzle, it encounters three zones: the feed zone, a compression zone, and a metering zone (see Fig. 3). In the metering zone, the molten plastic is conveyed through an anti-flow-back valve to the nozzle. When the chamber in back of the nozzle becomes full, the resulting pressure forces the rotating screw back to a point where a switch is tripped, causing the screw to be forced forward by hydraulic pressure. This forward thrust of the screw injects plastic into the closed mold. A nozzle shutoff valve is incorporated to prevent plastic from seeping out of the nozzle when the mold is open.

Table 1. Status of Warpage

STATUS	AVERAGE WARPAGE (mm)	STANDARD DEVIATION	SPEC. (mm)	EXPECTED % NONCONFORMANCE
Before using jig	2.08	0.092	1.2 max.	100
After using jig	1.27	0.438	1.2 max.	56.36

Note: "Before using jig" means immediately after unloading from the machine. "After using jig" means after the jig has been placed on the component for 3–5 min and before packing it in a plastic sheet.

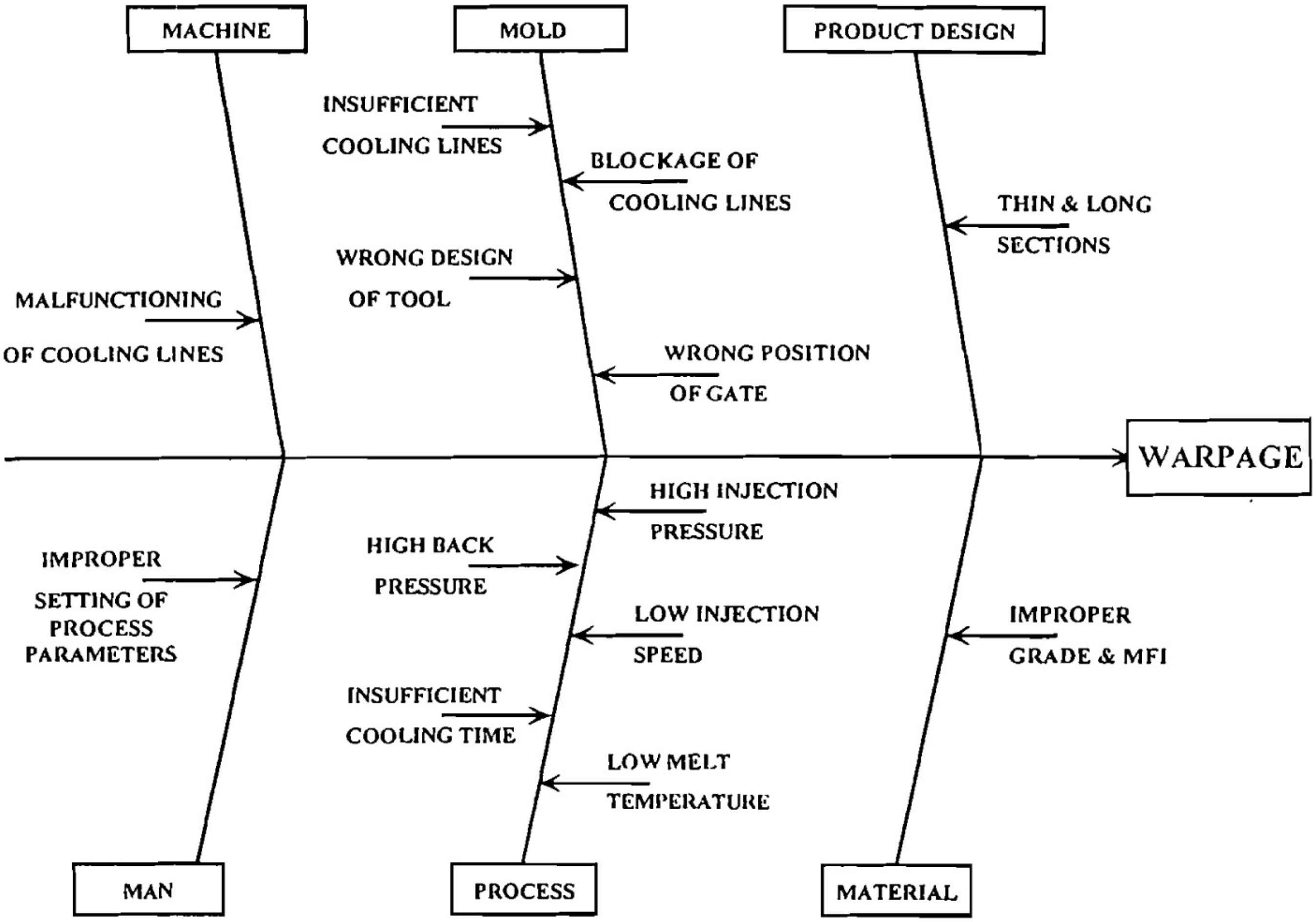

Figure 2. Cause-and-effect diagram.

Melt temperature refers to the temperature of the molten material in the barrel. Five heaters are provided along the length of the barrel and each one is set at some particular temperature level. The set of temperatures 200, 203, 203, 195, 180 means that the temperature at the nozzle end is 200°C and at the hopper end is 180°C, with other temperatures in between.

Injection speed refers to the speed at which the material is fed into the mold. The set of speeds 5, 45, 25 means that material is fed at 5% of the maximum speed* in the feed zone, at 45% in the compression zone, and at 25% in the metering zone.

Injection pressure refers to pressure at which the material is fed into the mold. The set of pressures 99, 80, 80 means that the material is fed at a rate of 99% of maximum pressure* in the feed zone and at 80% in the compression and metering zones.

Higher melt temperature, higher injection speed, and lower injection pressure were chosen for the study, as it was felt that they would lower the warpage in the parts molded.

Investigative Study

A full-factorial experiment was planned with the three factors. Each factor was studied at two levels. Throughout the experiment, a high degree of local control was exercised by maintaining nonexperimental factors at fixed levels, which were the usual production levels. The factors along

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*The maximum speed and maximum pressure that can be set vary by product and are documented. This maximum value (speed/pressure) is taken as 100%.

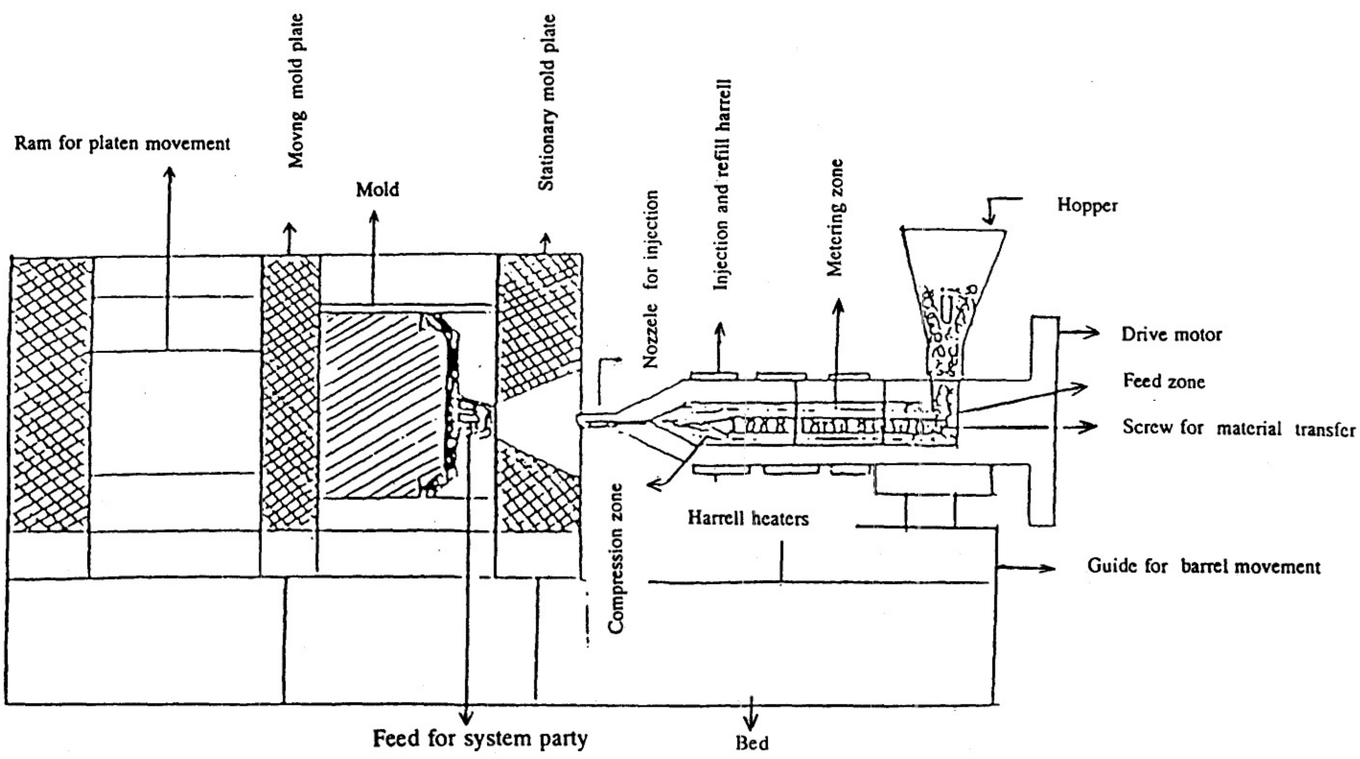

Figure 3. Sketch of injection-molding machine.

with the levels are given in Table 2. The physical layout of experimentation is given in Table 3.

Conduct of Experiment

The test order was randomized before commencement. At each of the eight conditions shown in Table 3, the process was run until stabilized and then five parts were molded. Measurements of all the control factor levels were taken at the start and at the end of each run to ensure that levels were maintained. The warpage in the parts were measured (to the nearest 0.05 mm) using slip gauges as shown in Figure 4. The data on warpage (response) is given in Table 4.

Analysis and Results

A factorial analysis of variance (ANOVA) was carried out on the data (see Table 5). It was found that all the three main effects were significant. Interaction between factors A and B and the interaction between factors B and C were also found to be significant. The average response values for various levels of the factors and their interactions are shown in Appendix 1. The best levels for these factors were deter-

Table 2. Factors and Levels of Experimentation

SI NO.	FACTOR	CODE	LEVEL	
			1	2
1	Melt temperature	A	200, 203, 203, 195, 180	190, 200, 200, 190, 175[a]
2	Injection speed	B	5, 45, 25	5, 30, 25[a]
3	Injection pressure	C	99, 80, 80[a]	99, 75, 75

[a]Usual production levels.

Table 3. Physical Layout of Experimentation

EXP. NO.	MELT TEMPERATURE	INJECTION SPEED	INJECTION PRESSURE
1	200, 203, 203, 195, 180	5, 45, 25	99, 80, 80
2	200, 203, 203, 195, 180	5, 45, 25	99, 75, 75
3	200, 203, 203, 195, 180	5, 30, 25	99, 80, 80
4	200, 203, 203, 195, 180	5, 30, 25	99, 75, 75
5	190, 200, 200, 190, 175	5, 45, 25	99, 80, 80
6	190, 200, 200, 190, 175	5, 45, 25	99, 75, 75
7	190, 200, 200, 190, 175	5, 30, 25	99, 80, 80
8	190, 200, 200, 190, 175	5, 30, 25	99, 75, 75

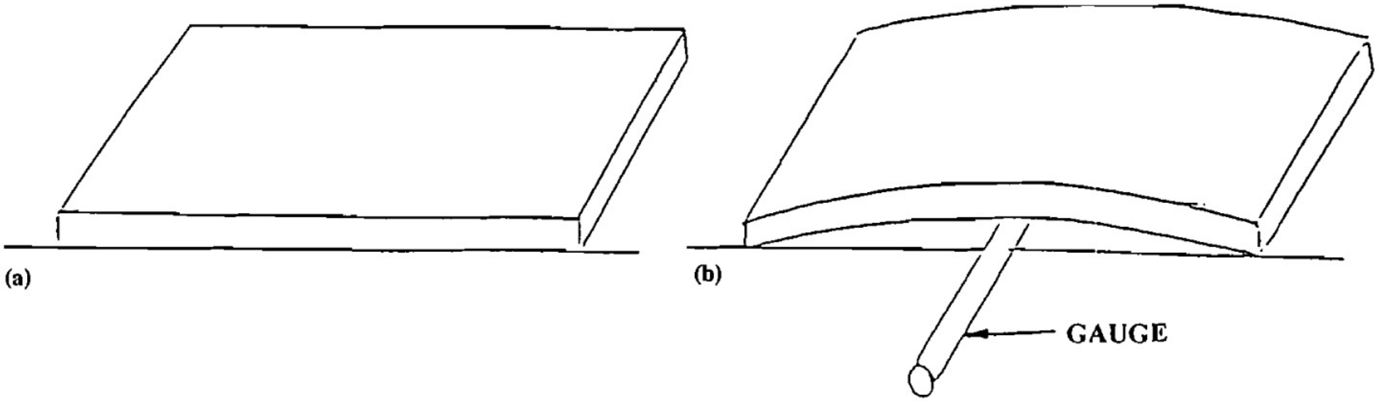

Figure 4. (a) Warpage absent in component; (b) warpage present and measured using a gauge.

mined from the average response values for the interactions. From the interaction table between factors A and B and the interaction table between factors B and C, the best levels were determined as shown in Table 6.

Table 4. Experimental Data

EXP.	RESPONSE (WARPAGE in mm)				
NO.	1	2	3	4	5
1	1.35	1.40	1.40	1.35	1.35
2	0.70	0.70	0.70	0.70	0.70
3	1.50	1.50	1.40	1.45	1.45
4	1.20	1.35	1.20	1.20	1.20
5	2.15	2.20	2.10	2.20	1.80
6	1.40	1.35	1.30	1.40	1.30
7	1.10	1.20	1.25	1.20	1.25
8	1.10	1.00	1.00	1.00	1.00

Trial Run and Recommendation

A confirmatory trial was carried out at the best levels of the experimental factors and with all other nonexperimental factors maintained constant. Data on 15 consecutive samples are given in Table 7. The average warpage was 0.64 mm with a standard deviation (S.D.) of 0.10 mm, a vast improvement in the performance which was previously 1.27 mm with a S.D. of 0.44 mm.

The best levels of experimental factors along with nonexperimental factors and their respective control ranges were recommended as given in Appendix 2.

Implementation

Management was very pleased with the results and, hence, the best levels of experimental factors along with

Table 5. ANOVA Table

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-RATIO	R^2 (%)
A	1	0.529	0.529	105.8[a]	8.9
B	1	0.210	0.210	42.0[a]	3.5
C	1	2.116	2.116	423.2[a]	36.0
AB	1	2.162	2.162	432.4[a]	36.8
AC	1	0.000	—	—	—
BC	1	0.650	0.650	130.0[a]	11.0
ABC	1	0.006	—	—	—
Error	32	0.181	—		
Total	39	5.855			
Pooled error	34	0.187	0.005		3.8

Notes: 1. F-ratios calculated against pooled error.

2. Sum of squares of AC [1 df (degree of freedom)] and ABC (1 df) are pooled with the sum of squares of error (32 df) to set pooled error (34 df).

3. Contribution ratio [R^2 (%)] explains percent contribution of each "source" in total sum of squares.

[a] Significant at the 5% level.

Table 6. Factors and Their Prior and Best Levels

FACTOR	DESCRIPTION	PRIOR LEVEL	BEST LEVEL
A	Melt temperature	190, 200, 200, 190, 175	200, 203, 203, 195, 180
B	Injection speed	5, 30, 25	5, 45, 25
C	Injection pressure	99, 80, 80	99, 75, 75

Table 7. Confirmatory Trial Data

SERIAL NO.	WARPAGE (mm)
1–5	0.60, 0.60, 0.60, 0.53, 0.53
6–10	0.53, 0.60, 0.65, 0.60, 0.60
11–15	0.73, 0.65, 0.73, 0.85, 0.73

Note: Serial No. represents the order of production.

ionexperimental factors were incorporated into the ompany's process standard, as given in Appendix 2.

In subsequent batches produced, it was observed that the varpage level of the parts molded was almost the same as hose obtained during the confirmatory trial; the factory nanagement and the customers were very satisfied.

Conclusion

The company benefited on the following counts:

1. The values of the process parameters are now standardized.
2. There is no need for loading the components on the jigs after they are ejected from the mold. The components are directly packed.
3. The percentage rework which was 56.36% previously is now reduced to a negligible level.
4. The customer is now assured of good quality as shipped.
5. Company executives are now familiar with the methodology of design and conduct of experiments and are confident of adopting this methodology for other chronic quality problems as well.

Appendix 1: Average Response Values for Main Effects and Interactions

		LEVEL	
FACTOR	CODE	1	2
Melt temperature	A	1.19	1.42
Injection speed	B	1.37	1.23
Injection pressure	C	1.53	1.07

FACTOR B: Injection Speed

		Level 1	Level 2
FACTOR A	Level 1	1.03	1.35
Melt Temperature	Level 2	1.72	1.11

FACTOR C: Injection Pressure

		Level 1	Level 2
FACTOR A	Level 1	1.42	0.96
Melt Temperature	Level 2	1.65	1.19

FACTOR C: Injection Pressure

		Level 1	Level 2
FACTOR B	Level 1	1.73	1.02
Injection Speed	Level 2	1.33	1.13

Appendix 2: Recommendations and Background Factors

1. Hopper dryer temperature: 70°C
2. Screw recovery and back pressure (BP) set

	R (%)	BP (%)	POSITION
1	45	50	
2	45	55	25.0
3	45	50	50.0

3. Delay time: 1 sec
4. Shot size: 75 mm
5. Hold pressure (HP)

	HP (%)	HOLD TIME (sec)
1	70	
2	75	2.00
3	70	1.50

6. Injection hold time: 15 sec
7. Hold pressure transposition: 8.0 mm
8. Suck back
   (a) Mode: After recovery
   (b) Speed: 8%
   (c) Stroke: 3 mm
9. Injection clamp force: 325 tons
10. Injection

	INJECTION PRESSURE (%)	INJECTION SPEED (%)	POSITION
1	99	5	
2	75	45	65.0
3	75	25	15.0

11. Revolution: 36 rpm
12. Injection pressure: 109 kg/cm^2
13. Melt temperature: 200°C, 203°C, 203°C, 195°C, 180°C
14. Cooling medium: Chilled water circulation in core and ordinary water in cavity
15. Cooling water temperature: 11–14°C
16. Method of water circulation: Separate cooling lines to be used in the core

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About the Authors: U. H. Acharya is an associate professor in the Statistical Quality Control (SQC) and Operations Research (OR) Unit at the Indian Statistical Institute (ISI), Bangalore. He holds a master's degree in statistics from ISI, Calcutta. He is a consultant to the Indian industry in the field of TQM and ISO 9000.

C. Mahesh holds a bachelor of engineering degree in mechanical engineering and a master of technology degree in quality, reliability, and operations research from ISI, Calcutta. Currently, he is a Specialist in the SQC and OR Unit of ISI, Bangalore and is engaged in consultancy work in statistical quality control and operations research.