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Optimization of Injection Molding Operational Conditions

by

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ABSTRACT:

A major goal of the injection molding process is to produce complex parts to a relatively high degree of accuracy. To do this, one must be able to control the warpage the often occurs in injection molded products. We have developed a methodology to minimize product deformation. Pressure and temperature distributions obtained from flow simulation software are used as an indirect measure of the quality of the molded product. Optimization theory is then used to determine the optimal molding conditions to minimize product deformation. Molding conditions include melt temperature, mold temperature and fill time. Software was developed using an artificial intelligence language for the top level program which performs decision making and administrative duties. Subroutines for the iterative optimization tasks were written in FORTRAN. Experimental verification was performed to validate the results of the research.

INTRODUCTION:

Injection molding is known as one of the fastest and most efficient means of producing a large variety of thermoplastic products. Unfortunately there are part defects often associated with the process. These defects may include warpage, sink marks, voids, weld lines, excess shrinkage, discoloration and others. A major cause of defects such as warpage and excess shrinkage is the existence of residual stresses. Residual stresses are predominantly induced by differential shrinkage and anisotropic orientation caused by a large gradient in the temperature distribution or a non-uniform gradient in the pressure distribution [1]. The variables that affect the temperature and pressure distributions can be categorized into geometrical or operational considerations. Geometrical considerations such as wall thickness variation and gate location will affect the temperature and pressure distributions, but the optimization process must be taken into consideration during the physical design of the mold. On the other hand, operational considerations such as melt temperature,mold temperature and fill time can be controlled on-line for molds already in use. The operational considerations are said to make up the injection molding conditions. Our goal in this paper is to minimize part distortion by determining the optimal values for the molding conditions.

Molding conditions that reduce orientation tend to reduce distortion [2]. For example, rapid fill is important so that the material first entering the mold will not have much more time for heat transfer than the material last entering the mold. Higher injection pressure and longer injection forward time tend to minimize warpage [3]. However if the melt is too cold, it will not be possible to pack the mold. On the other hand, overheating the polymer causes burning and material degradation, leading to deformation. The mold temperature is also important because it controls the rate at which the plastic cools once it contacts the mold surface. If the mold is too cold, the plastic will have a large internal temperature gradient or the plastic may cool below its flow temperature before the mold is filled. If the mold is too hot, the part will take longer to cool and cycle time will be increased. Therefore the working range for the polymer is between these extremes. The exact selection of the molding conditions will depend on the properties expected from the end product. This will be the basis of our optimization.

At this point it should be apparent that the focus of our research has been to develop a methodology to aid in the *design* concerns of injection molding. Our goal is to help designers find the optimal conditions by integrating *available* analysis tools and optimization theory to make the process as automated as possible.

OPTIMIZATION THEORY:

There is a frequent misconception that a methodology developed as an aid to the design process is labeled as an optimization methodology. True optimization occurs only when the process is iterative and self-contained. It should require no interaction with the user except to input the necessary data at the beginning.

Nonlinear constrained optimization is implemented to determine the maximum or minimum value of a set of criteria which are pertinent to a given system. The requirements of the system are that it can be accurately represented by a system of equations and feasible regions of operation can be described. After accurately defining the system and the constraints to describe the region of the system in which the optimization process must take place, several different mathematical methods can be used to determine the optimal values for the pertinent system variables [4].

In order to apply optimization theory to the design process, quantitative measures of the part quality need to first be developed. The mathematical formulation of a general optimization problem may be stated as follows:

Determine the vector of design variables x such so as to minimize the function $f(x)$ subject to the constraint that the design vector x belongs in a feasible space Ω. Equivalently we can state the problem:

$$\min_{\underline{x}} f(\underline{x})$$

subject to the constraint that $\underline{x}$ is contained in Ω

where

$\underline{x}$ is the design vector

Ω defines the feasible space.

OPTIMIZATION SCHEME:

In order to use optimization theory to determine the optimal molding conditions, we must first decide what are the pertinent variables and which are quantifiable. Generally when using flow simulation software we have the following information available to us after analysis:

-Shear rate
-Shear stress
-Fill time
-Temperature distribution
-Pressure distribution

We have used the pressure and temperature distributions as a measure of the quality of the flow characteristics for the given set of molding conditions. Pressure affects the density and the orientation of the polymer melt which in turn affects the amount of residual stress. The ideal pressure distribution will have a constant gradient ending with zero pressure at the last element to fill [4]. This is illustrated in Figure 1. The temperature distribution has direct influence on the amount of differential shrinkage a part undergoes. In general the ideal temperature distribution will have zero gradient as shown in Figure 1. Constant elemental end of fill temperatures would eliminate differential shrinkage due to temperature concerns [5]. To quantify these two measures we simply use the difference between the actual and ideal values at each node as seen in Figure 2. The mathematical representation for the total pressure error is:

$$\Delta_{pres} = \sum_{i=1}^{N} \left| P_{actual_i} - P_{ideal_i} \right|$$

where

P_{actual} is the nodal end-of-fill pressure from a flow analysis

P_{ideal} is the nodal pressure resulting from a constant pressure gradient

The mathematical representation for the total temperature error is:

$$\Delta_{temp} = \sum_{i=1}^{N} \left| T_{actual_i} - T_{ideal_i} \right|$$

where

T_{actual} is the nodal end of fill temperature from flow analysis

T_{ideal} is a constant nodal temperature

OBJECTIVE FUNCTION:

Now that the significant parameters have been determined, an objective function and its constraints must be formulated for the optimization process. Based on information that can be gained from the flow simulation software we may set the following inequality constraints:

$$T_{mold}^{min} < T_{mold} < T_{mold}^{max}$$
$$T_{melt}^{min} < T_{melt} < T_{melt}^{max}$$
$$t_{fill}^{min} < t_{fill} < t_{fill}^{max}$$

where

T_{mold} is the mold cavity temperature

T_{melt} is the plastic melt temperature

t_{fill} is the time required for the fill stage

Now that we have determined the system constraints we can present the equations of the optimization process:

$$\min_{\underline{p}} f(\underline{p}, \underline{g})$$

where

$\underline{p}$ is the set of molding conditions to be obtained

$\underline{g}$ is the given mold cavity geometry and gate location

$f = w_1(\Delta_{pres}) + w_2(\Delta_{temp})$

The weighting coefficients w_1, w_2 are used to set the importance of each of the factors in the objective function. Their values may differ depending on the application and the material used. The weighting coefficients can be altered to reflect the significance of a given factor to the product quality for the given conditions.

MOLDOPT SOFTWARE:

The program we have developed incorporates several different utility programs to accomplish the entire optimization process. Flow simulation software is used for obtaining the end-of-fill pressures and temperatures. It must be noted here that this software only evaluates the flow during the fill stage. It does not give results for the packing and cooling stages.

Inputs

To properly represent the problem the program must be given accurate inputs. These include a $2\frac{1}{2}$ dimension geometric description, an initial set of molding conditions to begin the optimization process with and the pertinent static constraints. The initial molding conditions include mold temperature, melt temperature and fill time. The required constraints include upper and lower bounds for melt temperature, mold temperature and fill time.

Outputs

After the optimization is completed the program will output the conditions it has determined. These are values for melt temperature, mold temperature and fill time. The optimal values are determined by using the Sequential Quadratic Programming (SQP) subroutine to evaluate the given objective function. This is a FORTRAN program based on the method developed by M.J.D. Powell [6].

Example

An example is presented to illustrate the improvement of the factors in the objective function. Table 1 shows the initial molding conditions and the given constraints. Table 2 gives the values before and after optimization. Figure 3 shows the pressure distribution before and after optimization. Figure 4 displays the temperature distribution before and after optimization.

EXPERIMENTAL PROCEDURE:

Molding experiments were carried out to determine the validity of the results of our numerical optimization. The work was performed on a Cincinnati Milicron 100 ton, four ounce, reciprocating screw injection molding machine. The machine was equipped with three heating zones in the barrel and a Variac at the nozzle tip to control melt temperature before entering the cavity. A mold temperature controller was used to accurately control the temperature of the mold surface. The injection, holding and back pressure could also be controlled along with the rotational speed of the screw. Timers control the injection, holding and cooling times.

The material used was Cosden 525P1 general purpose polystyrene. This is a widely used polymer among researchers because there is a large quantity of data available with regard to its fundamental properties and molding characteristics.

The following procedural sequence was employed during the experiment to insure repeatability:

1.) Each set of experiments was begun by setting the barrel temperature on the individual heating bands and allowing 45 minutes for thermal stabilization of the injection unit.

2.) At the same time, water at the desired temperature and flow rate was circulated in the mold cooling channels so as to achieve a uniform mold temperature.
3.) The screw's rotational speed control valve, injection pressure, shot size, holding pressure, holding times were set after four initial runs. These settings were then maintained throughout the experiment.
4.) When all components of the system were ready the barrel was purged using the manual mode of the machine.
5.) All systems were switched over to the fully automatic mode for part production.
6.) The first four shots were considered to be transient conditions. The next eight samples were taken for analysis of the system response for the given set of molding conditions.
7.) For each set of molding conditions to be tested, steps 1.) through 6.) were repeated.

EXPERIMENTAL RESULTS:

Several methods were used to analyze the test specimens. Some of the specimens underwent an annealing process to relax the frozen-in residual stresses and the subsequent deformation was measured. Specimens in their original and annealed state underwent photoelasticity analysis. All of the specimens were weighed to determine the effects of the changing conditions on their specific volume.

Annealing

A free convection oven at $210^\circ F$ was used to anneal the parts for four hours. The specimens were then allowed to cool slowly inside the oven. The resulting deformation in the X, Y and Z directions was measured and is presented in Table 3.

The results clearly show that the parts molded under the optimized conditions exhibited much less deformation after the annealing process. Specimens molded under non-optimal conditions were rendered virtually useless after annealing. Overall shrinkage was also decreased in the optimal specimens. This displays the decrease in residual stresses and the tighter tolerances that can be realized by optimizing the molding conditions.

Photoelasticity

Photoelasticity relies on molecular polarization phenomena to indicate equal shear stress planes. By covering the polystyrene specimens with a birefringent coating and viewing them through a circular polariscope, a fringe pattern can be photographed. This fringe pattern may be considered analogous to a topographic map of stress levels in the given cross section of the part. If the fringe pattern is closely spaced and irregularly shaped, there are high levels of residual stresses [7]. A widely spaced fringe pattern with smooth curves is indicative of low residual stress levels. An illustrative example is shown in Figure 5.

The fringe patterns indicate a much lower level of residual stresses in the parts molded under optimized molding conditions. Reducing the residual stresses increases the dimensional stability and raises the allowable service temperature of the part. Cracking and other long term effects are also avoided.

Weight measurement

The specimens were all weighed to determine the effects of optimization on specific volume. The results are tabulated in Table 4.

Significant weight reduction has been achieved among the other benefits of our optimization. Besides the obvious advantages of a lighter weight part, the cost per part will be reduced with the amount of material required.

SUMMARY:

The increasing demands and competition in the injection molding industry require that a more thorough analysis be made of the process so the system can be more rigidly controlled. With the advent of increasingly effective control systems, the ability to determine the optimal control settings must be raised from an art to a science. Our work can be considered as a step in this direction. By implementing flow simulation software and optimization theory, we have developed software to find optimal values for the most influential control settings. The results of the research were verified experimentally and showed definite reduction in warpage, overall shrinkage and product weight. This proves the effectiveness of our methodology as a design tool.

TABLE 1:
Optimization Constraints for Cosden 525P1 Polystyrene

	Lower	**Upper**
Mold Temperature:(F)	60.8	96.8
Melt Temperature:(F)	374.0	428.0
Fill Time:(sec)	2.0	3.5

TABLE 2:
Molding Conditions Before and After Optimization

	Original	**Optimized**
Mold Temperature:(F)	35.0	51.4
Melt Temperature:(F)	220.0	193.6
Fill Time:(sec)	9.0	2.0

TABLE 3:
Specimen Deformation After Annealing

AXIS	Original	Optimized
X	0.500	0.268
Y	0.825	0.395
Z	0.588	0.528

TABLE 4:
Specimen Weight

SAMPLE	Original	Optimized
1	8.9571	8.9531
2	8.9593	8.9173
3	8.9564	8.9164
4	8.9644	8.9177
5	8.9693	8.9125
6	8.9610	8.9126

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3.) Jensen,M. and Whisson,R.R.,p.193.

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5.) Dym, J.B., *Injection Molds and Molding*, Van Nostrand Reinhold Company, New York, 1979, 76.

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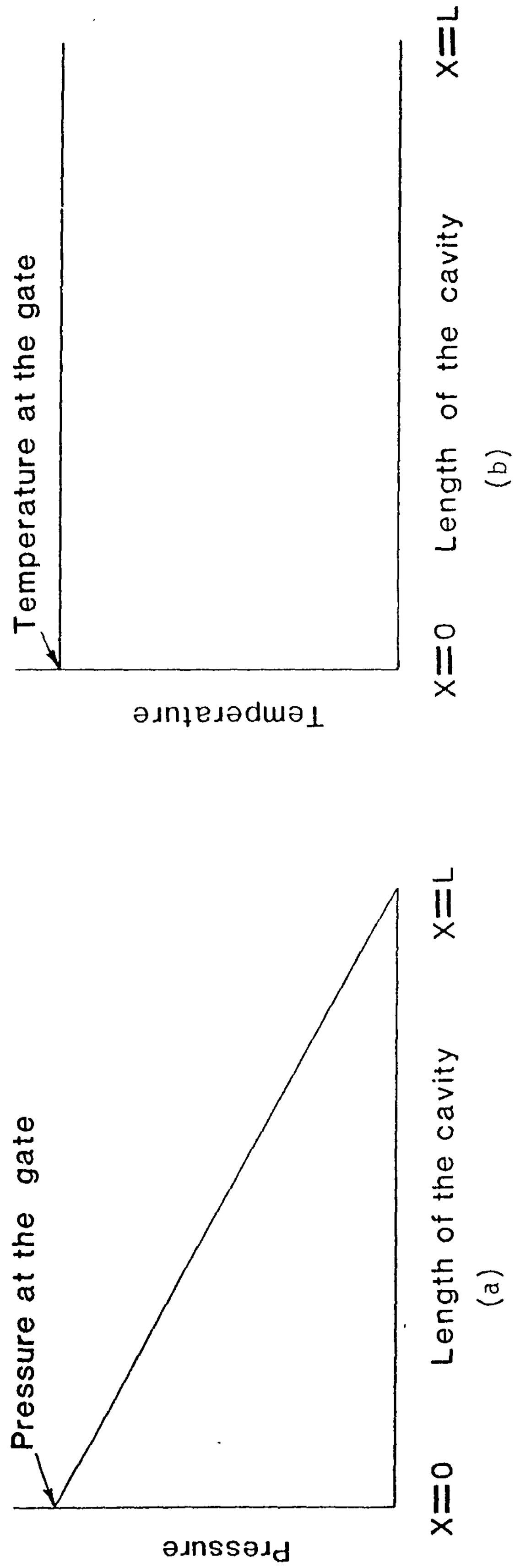
7.) Powell,M.J.D., "A Fast Algorithm for Nonlinearly Constrained Optimization Calculations," *Proceedings of the 1977 Dundee Conference on Numerical Analysis, Lecture Notes in Mathematics*, Vol.630, Spriger-Verlog, Berlin, 1978, 144-157.

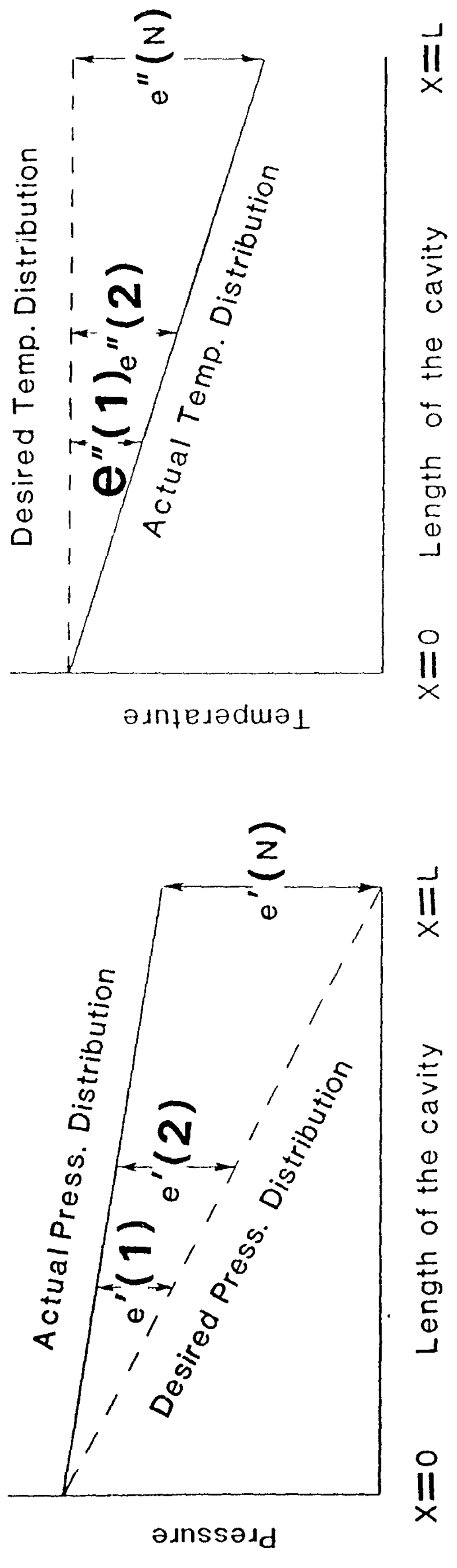
8.) Durelli,A.J. and Riley,W.F., *Introduction to Photomechanics*, Prentice-Hill Inc., New Jersey, 1965.

FIGURE 1:
Ideal Temperature and Pressure Distributions



Profiles for Optimum Pressure (a) and Temperature (b) Distribution in the cavity.

FIGURE 2:
Graphical Representation of Temperature and Pressure Error



Profiles for Optimum and Non-Optimum Distributions
superimposed for Pressure (a) and Temperature (b).

FIGURE 3:
Optimized and Non-Optimized Temperature Distributions

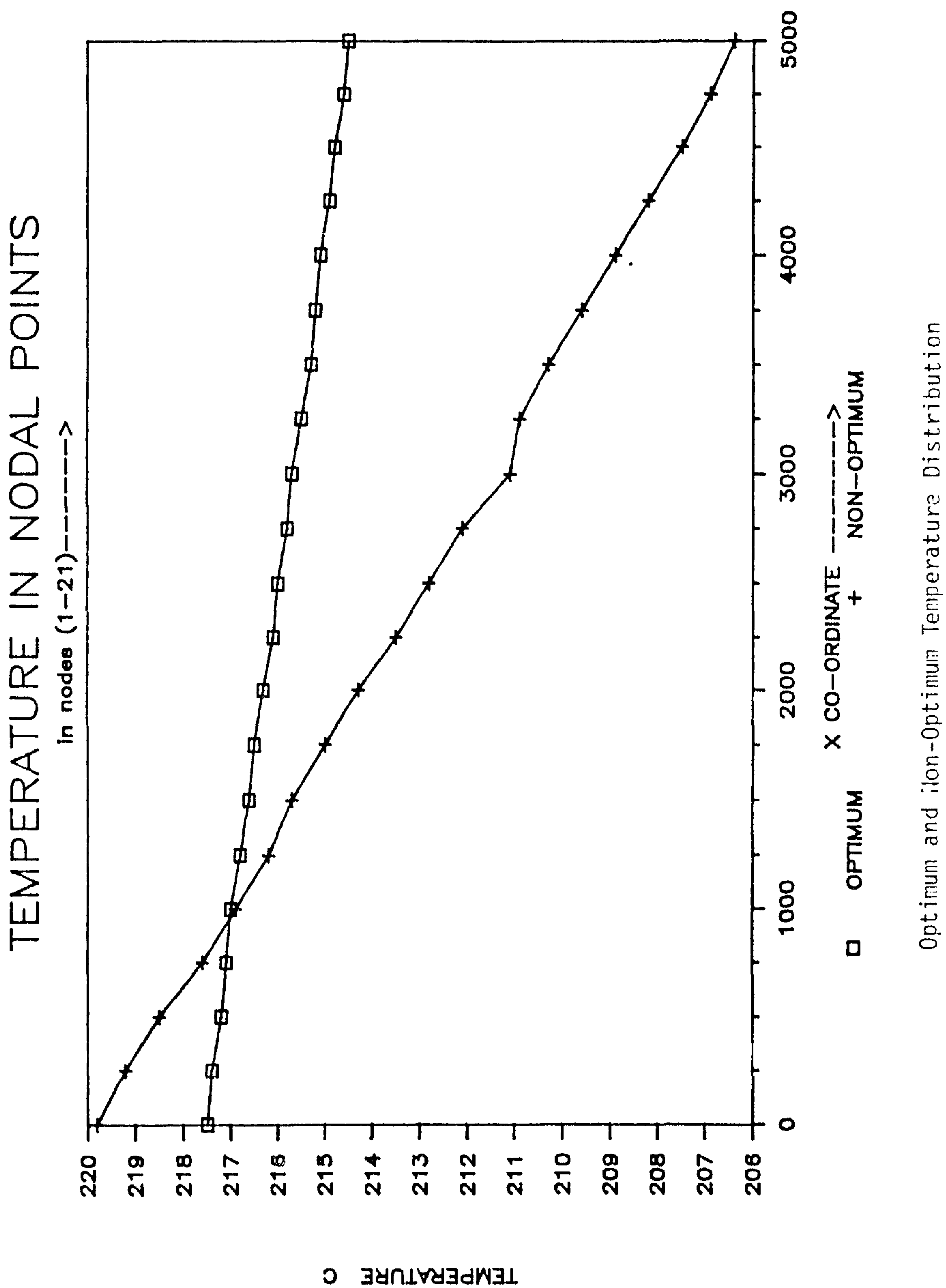
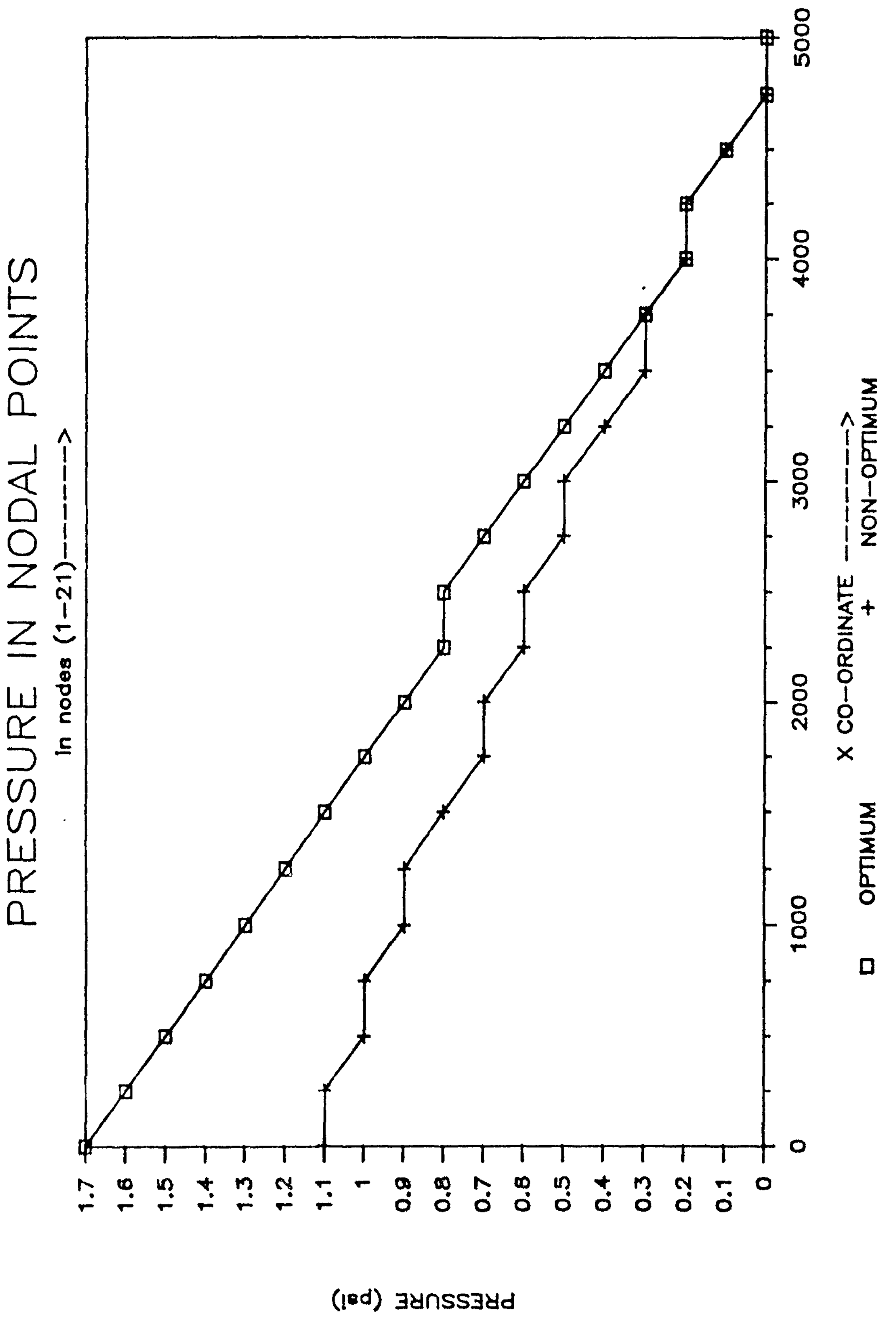
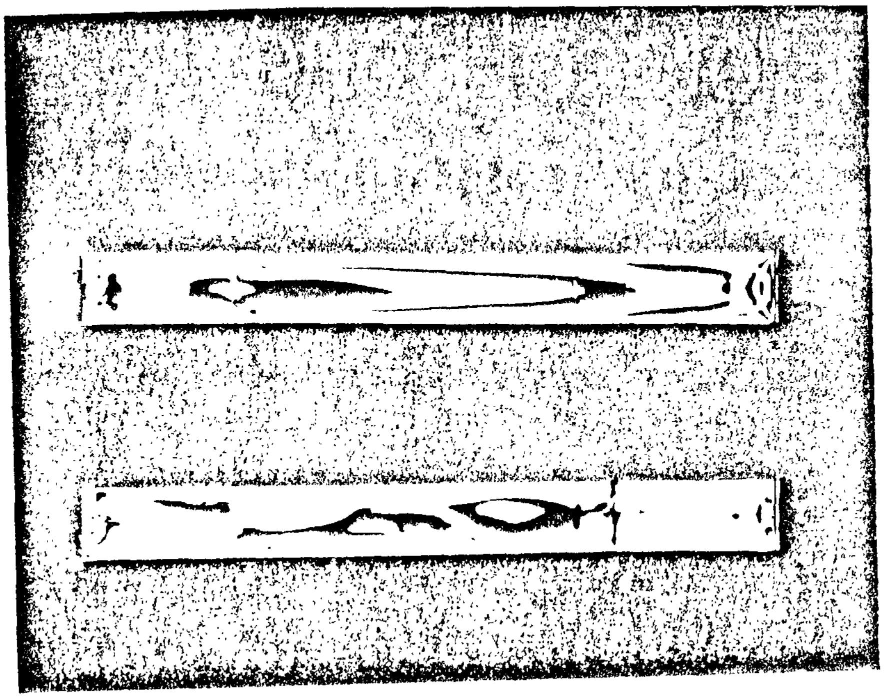


FIGURE 4:
Optimized and Non-Optimized Pressure Distributions



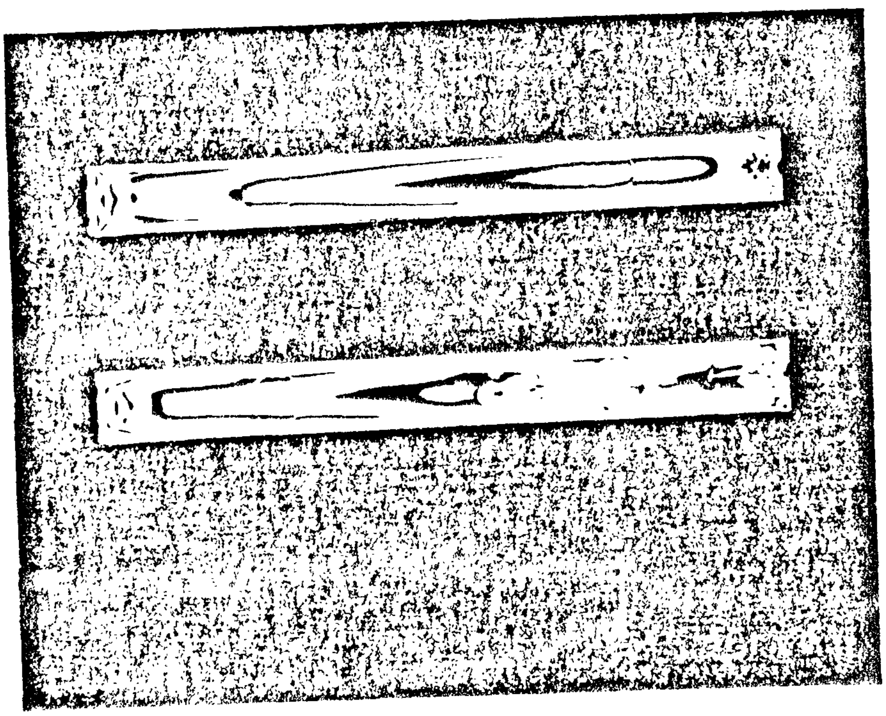
Optimum and Non-Optimum Pressure Distribution

FIGURE 5:
Photoelasticity Isochromatic Fringe Patterns for Non-Optimized (a) and Optimized (b) Molding Conditions



(b)

(a)



(b)

(a)

Isochromatic Fringe Pattern
Dark Field for (a) Optimum and (b) Non-Optimum Specimen.

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