FDM® TECHNOLOGY PROCESS IMPROVEMENTS

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ABSTRACT

Since the introduction of rapid prototyping technology as a tool for time compression and concurrent engineering in the design and manufacturing process, many enhancements and refinements have been made based on the experience of users and manufacturers of rapid prototyping equipment. These improvements contribute significantly to faster production of quality output from rapid prototyping systems.

There are diverse control and material selection parameters that affect prototype models built using the Fused Deposition Modeling (FDM®) process. This paper reviews the role of several of these parameters in the process. Data will be presented to help the user choose the appropriate material for specific applications including density, tensile modulus, flexural modulus, tensile strength, flexural strength, impact strength, and hardness.

The integration of material, hardware, and software in the FDM technology begins with the understanding of the basic requirements of the machine and ends with an operating procedure to choose the parameters for optimal model output and efficiency. Some of the variables include: part geometry, deposition geometry, deposition speed, liquefier temperature, material, flow control parameters, etc. Designed experiments are used in material formulation through modeling parameter definition activities.

INTRODUCTION

The fused deposition modeling process for rapid prototyping integrates three key components of the system: software, hardware, and materials. Each component can be analyzed independently for very simple model systems, but for real systems and broad operating conditions, the system complexity and interactions grow. The challenge to develop user-friendly FDM rapid prototyping systems is to define the relationship between the key input variables and the key modeling characteristics, or responses. Designed experiments can begin to identify the key variables and lead to strategies for optimizing the modeling process in a very efficient manner.

PROCESS

The FDM process forms three-dimensional objects from CAD generated solid, wire frame or surface model data through the consistent dispensing of individual layers or thermoplastics materials through a controlled temperature head. The model is built layer upon layer, from the bottom up. The designed object emerges as a solid three-dimensional part without the need for tooling.

The process involved in the development of a three-dimensional model begins with the creation of a conceptual geometric model on a CAD workstation. The model is imported into the ProtoSliceä software program which mathematically slices the conceptual model into horizontal layers and deposition paths are created. The path data is then downloaded to the modeler. The modeler operates in the X, Y, and Z axes, basically drawing the model one layer at a time. Once the build cycle begins, no operator attendance is required.

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A spool of thermoplastic modeling material, .070 inches (.18 cm) in diameter, feeds into the temperature controlled FDM extruding head, heating the material to a semi-liquid state. The semi-liquid is extruded and deposited into ultra-thin layers onto a fixture-less base. Once the material is directed into place by the X-Y controlled FDM head, the material solidifies, creating a precision laminate.

MATERIALS

Users of rapid prototyping technology tend to request models with materials whose properties are similar to materials they might use in their end-use applications, e.g. injection molding. In reality, each rapid prototyping technology rarely brings all the properties of an end-use material to the designer, and FDM is not an exception to this. Materials used in Fused Deposition Modeling must satisfy the requirements of the designer, their subsequent application, and their integration into the FDM process.

As a subset of the universe of thermoplastic materials, FDM materials form strong interlayer bonds at or near their melting points and have appropriate composition and morphology to provide a relatively stress-free, low distortion part once the material has reached room temperature.

An FDM material must also have an adequate flexural modulus and strength to be formed into a filament, spooled, and used as a piston to pump the material through the head, liquefier, and tip. In addition, it must have sufficiently low viscosity to be pumped through the same hardware and also produce well-defined road widths over a broad range of geometries and deposition rates.

These requirements specify the materials which will effectively produce quality models using the FDM process. Some familiar candidate polymer chemistries include polyolefins, polyamides, and polyesters. The four materials currently available from Stratasys have the mechanical properties shown in Table 1. MW01 and ICW04 are wax formulations for use in the investment casting process; and P200 and P300 are plastic formulations (polyolefin and polyamide, respectively) that are stronger and have higher melt points.

Thermal and rheological analysis has been performed on all of the current materials. These data have been important in designing the mechanical components of the FDM head which melt and pump the material. Figures 1-3 show this data for ICW04, the Stratasys investment casting wax. Melt viscosity is measured using a vibratory rheometer. Thermal analysis was performed using differential scanning calorimetry (DSC) and volumetric expansion by thermal mechanical analysis (TMA). ICW04 has the lowest volumetric expansion of the current materials. Table 2 lists the ash content, specific gravity, softening point (R&B), and penetration.

HARDWARE

Figure 4 depicts the mechanical design of the FDM head. The function of this assembly is to heat and pump the modeling material through the tip and onto the modeling surface to produce precise parts. It is a lightweight assembly designed to move at modeling speeds without affecting positioning accuracy.

A small D.C. motor drives a set of feed wheels to provide up to 10 lbs force to push the filament through the liquefier and tip. The feed wheels, which are 1/2" in diameter and covered with an elastomer, are driven in a counter-rotating direction to provide the torque to feed the filament, which acts as a piston. The material must have sufficient column strength to accomplish this task; column strength is a function of the filament diameter, flexural modulus and strength. This provides a positive feed allowing no slippage of the filament.

In the FDM process, material is deposited in layers with rectangular cross-section known as roads, and these have a width (W) and a height (Z). Coupled with the speed of the deposition (S), a volumetric flow rate which the system must provide is defined. The feed mechanism must be able to meet or exceed this flow rate over the full range of viscosities and pressure drops. The design considerations involve the material properties described earlier. The pressure (P) which develops in the liquefier and tip is dependent upon the length and diameter of the liquefier (d_L,L_L) and tip (d_T ,L_T) as well as the material viscosity (h) at temperature (T), and volumetric flow rate ($\dot{V}$). The

tip diameter has a very large impact on the pressure drop because it is much smaller than the liquefier diameter. For Newtonian fluids, the pressure drop can be expressed as[1]

$$P = \frac{128\eta\dot{V}}{\pi}\left[\frac{L_T}{d_T^4} + \frac{L_L}{d_L^4}\right]$$

Because pressure is force divided by area and the area is the cross-sectional area of the filament in FDM, the force is proportional to pressure as well. A force vs. volumetric flow rate curve is shown in Figure 5 for various tip sizes and liquefier combinations. This data was taken using the P200 material with tips of .010", .016", and .052", and liquefier temperatures of 102 and 107^{0}C. As the theoretical equation implies, extrusion force is heavily dependent on tip size. This force is also significantly influenced by liquefier temperature, though to a lesser extent, as material viscosity decreases at higher temperatures. For a given set of operating conditions, the maximum flow rate can be determined by comparing that extrusion force with the column strength of the incoming filament.

A key characteristic of a finished model is the surface finish which is a function of the liquefier viscosity, envelope temperature, deposition speed of the material, and the geometry of the part. The liquefier and tip must heat the material to setpoint and the feed mechanism must pump the material out of the tip at the full range of tip diameters and material viscosities. The required heat transfer is a function of the thermal properties of the liquefier, tip, and modeling materials as well as the diameter of the filament and volumetric flow rate. Whereas it is advantageous to increase the filament diameter to increase the column strength for pumping, the reverse is true for melting the modeling material. The envelope temperature can affect the surface finish (see Figure 6) of the model by softening the material and reducing its flexural modulus. As a new layer is deposited, the previous layer may deflect downward causing preferential flow, due to a lower pressure drop and a poorly defined road width.

SOFTWARE/FIRMWARE

This discussion is limited to the pumping and motion control rather than the slice routines. The software/firmware control the motion of the head assembly on the carriage and also the motion of the feed wheels. The major tasks of feed wheel control can be broken down into two major categories: steady-state and transient behavior; i.e., start/acceleration and stop/deceleration activities. Steady-state pumping requires very accurate carriage and feed wheel control to assure precise geometry and road width. At the start or stop of the road, material flow is inherently different and requires different motor control to accommodate visco-elastic material behavior to precisely begin or end a road.

Before the carriage moves to start a new road, the feed wheels meter a small amount of material in anticipation of the carriage accelerating to the steady-state. When the carriage moves, the flow is slowly turned on based on constant acceleration to the full pumping rate. Likewise, near the end of the road, the pumping rate decelerates prior to the actual end point which creates a "starving" condition at the end point. The deceleration, acceleration, and pre-start metering control values are dependent on the material visco-elastic properties at the application temperature. Each material has its own characteristics which must be programmed into the software/firmware.

SYSTEM INTEGRATION

The integration of material, hardware, and software in the FDM technology begins with the understanding of the basic requirements of the machine and ends with an operating procedure to choose the parameters for optimal model output and efficiency. Some of the variables include: part geometry, deposition geometry, deposition speed, liquefier temperature, envelope temperature, material, flow control parameters, etc. Designed experiments are used in material formulation through modeling parameter definition activities.

In the development process, the sheer number of variables to be considered is overwhelming, and therefore the use of small screening designs has great utility[2,3]. The following example illustrates a material formulation mixture design and shows how it is organized, executed and analyzed. The purpose of this design is to screen, or identify, the critical variables. It is a linear design which allows analysis of individual variables only, and as a four

component mixture, it contains nine unique trials. Table 3 shows the design and uses coded variables to illustrate the two levels (-1 and +1) and a center point (0).

Table 4 contains actual values for this example. Note that the sum of the components for each trial is one. The experiment is executed by preparing the trial mixtures and measuring the responses. Table 5 shows the response matrix of some of the properties that are important to an investment casting wax. These include softening point, density, ash, viscosity and volumetric expansion. Values for all the trials are listed in this table.

Next, regression analysis reveals the relationship between the variables and responses (Table 6), and the significance of each variable. The summary results figure indicates significance with stars - the more stars, the greater the significance. Finally, a graphical representation of the fit (Figure 7) can reveal meaningful trends. In this case, viscosity at 70^{0}C.

Another designed experiment we frequently use is the two variable, two level factorial with the center point (Table 7). An example for this type of experiment would be illustrated by Figure 6 where the liquefier temperature and air (envelope) temperature are variables, and surface finish, delamination and plugging are responses. A robust modeling zone is therefore identified. At this stage, some candidate materials may be eliminated due to lack of lamination, low flexural strength, and/or excessive viscosity.

The goal of the next stage is to expand the variables constrained in the first experiment. These would include tip diameter, deposition speed, deposition geometry, part geometry, liquefier temperature, and envelope temperature. Typically, this is done over a broad range of standard models and test parts. The hard barriers previously described are defined at this stage. Material formulations can be compared to determine which of the initial formulations offered the most desirable characteristics, and can lead to additional designed experiments if the product requirements are not met.

The final stage involves the definition of the flow control parameters in the software/firmware. This is accomplished by iteratively determining the values on test geometries within the modeling parameter envelope.

CONCLUSIONS

The integration of material, hardware, and software/firmware in FDM is accomplished in an efficient manner by understanding the basic independent functions of each system and using designed experiments to lead to optimal results.

REFERENCES

[1]Michaeli, W., 1984, "Extrusion Dies," Hanser, Munich.

[2]Box, G.E.P., Hunter, W.G., and Hunter, J.S., 1978, "Statistics for Experimenters," Wiley, New York.

[3]Wheeler, B., Betsch, R., and Donnelly, T., 1993, "ECHIP User's Guide and Reference Manual," ECHIP, Incorporated, Hockessin, Delaware.

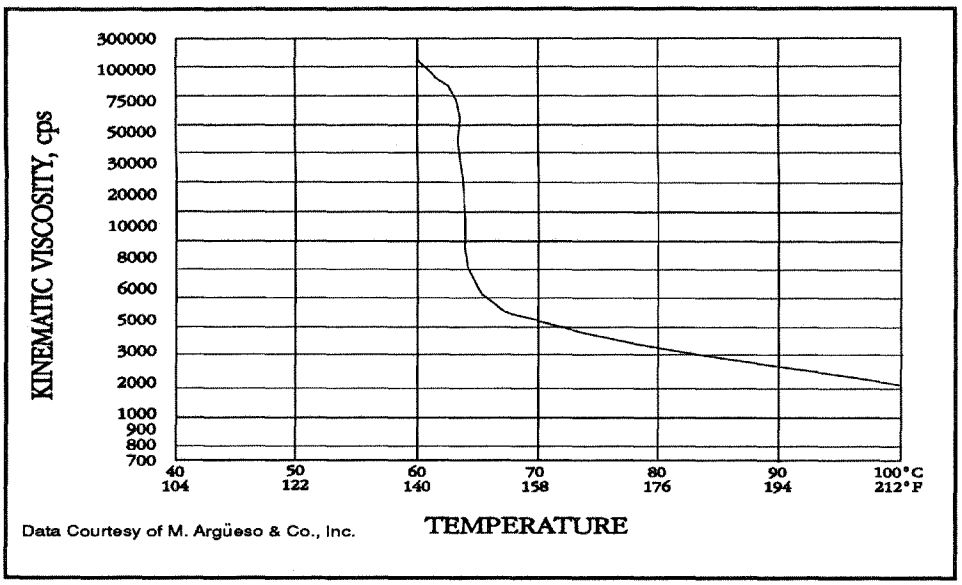

FIGURE 1. MELT VISCOSITY

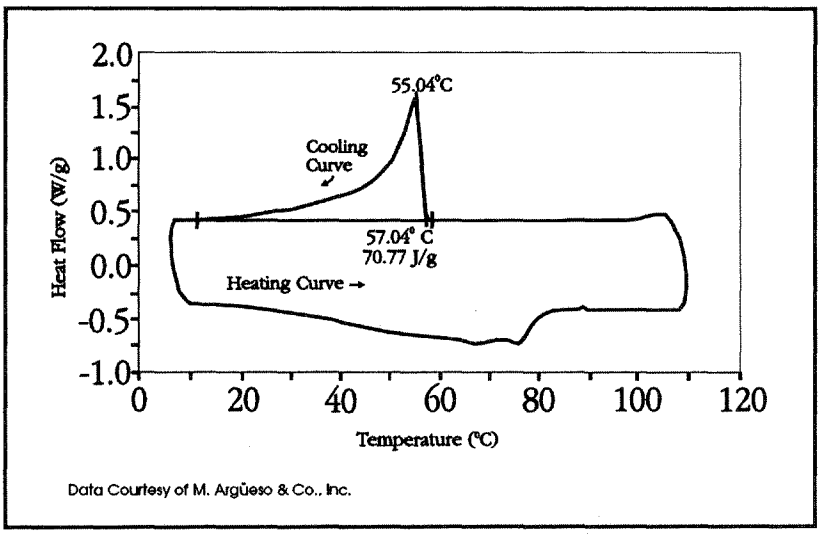

FIGURE 2. DSC THERMAL ANALYSIS

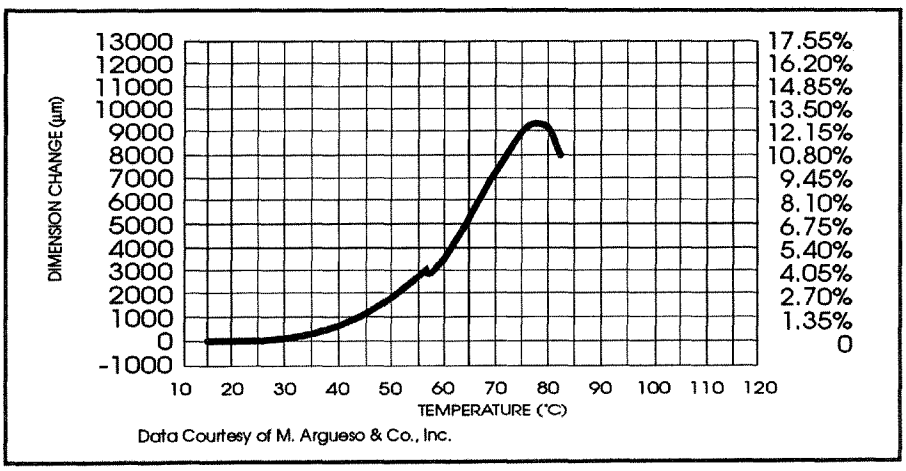

FIGURE 3. TMA VOLUMETRIC EXPANSION

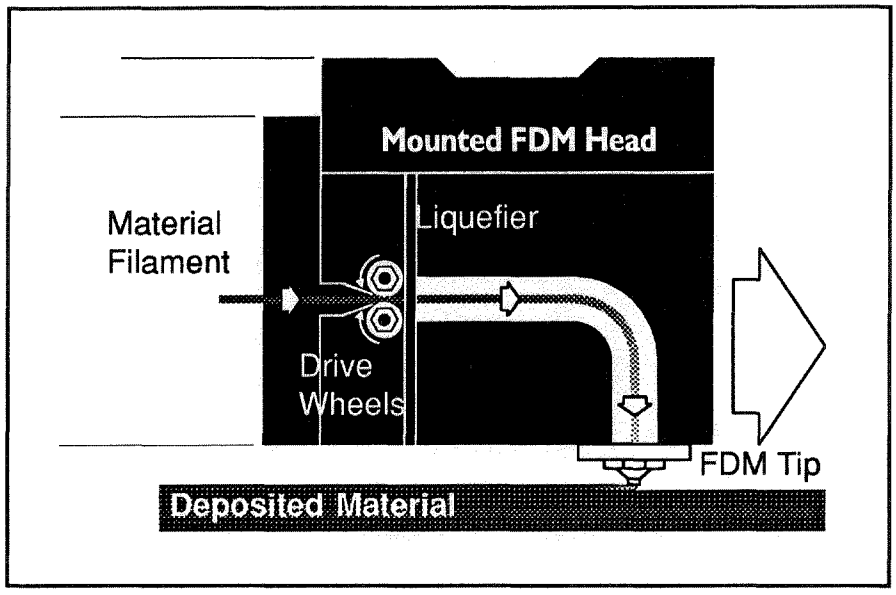

FIGURE 4. FDM HEAD

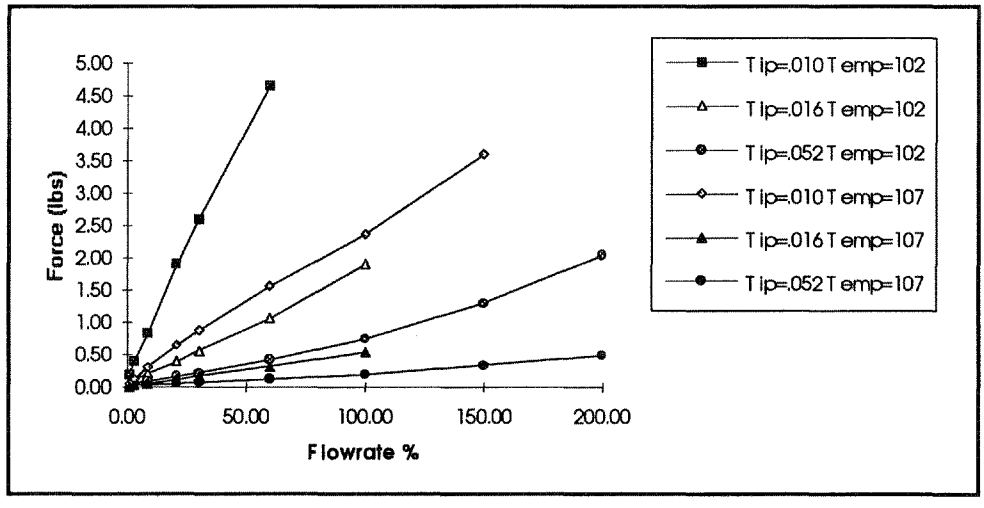

FIGURE 5. FORCE TO EXTRUDE P200 VS. TIP SIZE VS. LIQUEFIER TEMPERATURE

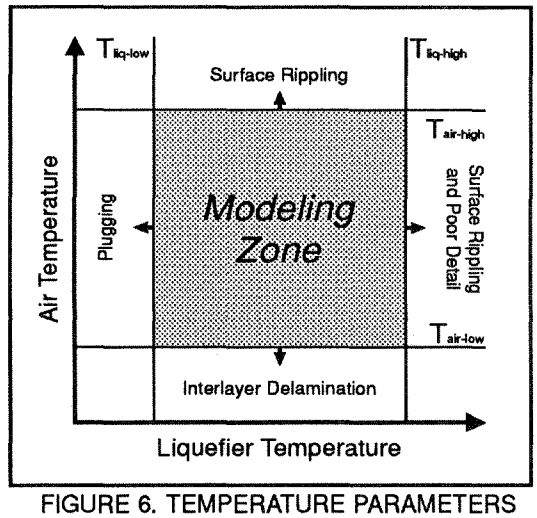

FIGURE 6. TEMPERATURE PARAMETERS

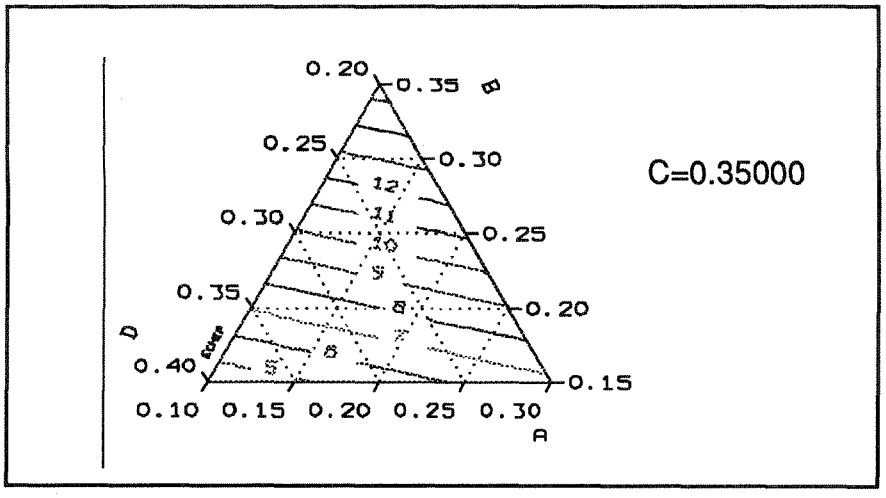

FIGURE 7. RESPONSE CONTOUR PLOT

PROPERTY	ICW04	MW01	P300	P200
Tensile Strength (psi)	509	1,114	1,765	1,324
Tensile Modulus (psi)	40,000	70,000	80,000	90,000
Elongation (%)	10.00+	6.65	3.48	4.68
Flexural Strength (psi)	619	1,293	2,113	1,537
Flexural Modulus (psi)	40,000	50,000	60,000	90,000
Notched Impact (ft*lb/in)	0.32	0.72	0.24	0.17
Unnotched Impact (ft*lb/in)	0.92	12.9	1.46	1.37
Hardness (Shore D)	33	40	70	58
Softening Point (R&B)(F)	177	227	---	---
Melting Point (C)	---	---	100-110	72-108
Specific Gravity (gm/cm^3)	1	0.92	1.1	0.9

TABLE 1. MATERIAL PROPERTIES

Softening Point: (Ball and Ring)	177^{0}F
Hardness Penetration: (450 gms., 5 sec., 77^{0}F)	17.0 Dmm
Specific Gravity: (gm/cm3)	1
Ash Content:	0.0075%
Filler Content:	0.00%

TABLE 2. ICW04 ANALYSIS

Trial	A	B	C	D
1	+	-	-	-
2	-	+	-	-
3	-	-	+	-
4	-	-	-	+
5	0	-	-	0
6	-	0	-	0
7	-	0	0	-
8	-	-	0	0
9	0	-	-	0

TABLE 3. DESIGNED EXPERIMENT - FOUR COMPONENT MIXTURE

Trial	A	B	C	D
1	.40	.15	.25	.20
2	.10	.45	.25	.20
3	.10	.15	.55	.20
4	.10	.15	.25	.50
5	.25	.15	.25	.35
6	.10	.30	.25	.35
7	.10	.30	.40	.20
8	.10	.15	.40	.35
9	.25	.15	.25	.35

TABLE 4. SAMPLE MATRIX

Trial	Softening Point (°F)*	Penetration (Dmm)**	Density (gm/cm³)	Ash (%)	Visc. (cps, 70° C)	Volumetric Exp. (%)***
1	167.5	15	1.009	.0055	8250	16.8
2	178.0	19	0.980	.0170	19091	13.5
3	170.0	14	1.003	.0075	8500	16.4
4	179.0	14	0.999	.0135	3556	14.6
5	177.0	14	1.005	.0080	4643	18.1
6	180.5	18	0.992	.0115	13636	21.3
7	174.5	17	0.994	.0280	15909	15.4
8	178.0	16	0.994	.0080	6600	15.8
9	177.0	12	1.001	.0080	4286	14.2

* Ring & Ball method
** 450 gms., 5 sec., 77°F
*** TMA method (M. Argüeso)

TABLE 5. RESPONSE MATRIX

Variables	Softening Point (°F)	Penetration (Dmm)	Density (gm/cm³)	Ash (%)	Visc. (cps, 70° C)	Volumetric Exp. (%)
A	**	-	**	-	-	-
B	-	*	**	-	***	-
C	*	-	-	-	-	-
D	**	-	-	-	**	-

Significance Levels

*	5%
**	1%
***	.1%

TABLE 6. SUMMARY RESULTS

Trial	A	B
1	-	-
2	+	-
3	-	+
4	+	+
5	0	0

TABLE 7. DESIGNED EXPERIMENT -TWO VARIABLE, TWO LEVEL FACTORIAL (WITH CENTER POINTS)