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Final Report

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THE BENDIX CORPORATION

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ABSTRACT

Manufacturing techniques for filling paper honeycomb with a polyethylene wax to form a composite structure are discussed. Processing parameters for a filler material which proved to be satisfactory, and test data on filled honeycomb blocks, are provided.

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SUMMARY

This project was initiated to develop manufacturing techniques for filling paper honeycomb with materials to form a structure for a specific use. Studies were initially made of processing parameters of the fillers and support materials applicable to the fabrication of composite structures.

The primary application for filled honeycomb was the Forward Support, 223937. Other applications were anticipated; since none materialized, this endeavor was directed solely toward the problems of filling the Forward Support with Epolene C-10 polyethylene wax.

Work on this project resulted in the following conclusions:

- Epolene C-10 polyethylene wax is an adequate filler material for the 223937 paper honeycomb Forward Support, even though this material has poor shrink and tensile strength properties.
- A study of diametric shrinkage of the filled parts showed an average change of 0.022 inch on a diameter. It is assumed that this loss in diameter is caused by stresses from plug pressures on the chevron V's and side walls of the honeycomb cells.
- The strength of paper honeycomb is adversely affected by high temperatures. Therefore, it is impractical to reduce the viscosity of Epolene C-10 by heating it above 350°F because of the subsequent deterioration in the structural strength of the paper honeycomb and degradation of the polyethylene.
- The compressive strength of paper honeycomb decreases by 1.78 psi per each degree Fahrenheit as the honeycomb is conditioned in a nitrogen environment between 250°F and 400°F.
- X-ray inspection of polyethylene-filled paper honeycomb supports is feasible.
- Centrifugal casting is an acceptable process for filling the 223937 paper honeycomb Forward Support with polyethylene.

No additional work on this project is planned at this time.

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DISCUSSION

SCOPE AND PURPOSE

In June, 1968 funds were appropriated for process development of filled paper honeycomb. The purpose was to investigate materials and manufacturing techniques for filling paper honeycomb to form a structure for a specific use. The project evolved into the development of processes for filling the paper honeycomb Forward Support, 223937, with Epolene C-10 polyethylene wax.

PRIOR WORK

An investigation was initially made into processing parameters of the filler and support material applicable to the fabrication of composite structures. From these studies, filling, machining, and inspection techniques were developed.

Sandia Livermore, under the direction of R. W. Weaver, proved it feasible to fill the Forward Support with polyethylene wax. Several prototype parts were produced at Livermore prior to assigning the development task to Bendix. To the knowledge of the writer, a formal report was not issued on the Sandia Livermore work.

ACTIVITY

Evaluation of Materials

The purpose of the early investigations on this project was to establish the physical properties of polyethylene filler materials which had desirable processing characteristics and could fulfill the original requirements of the support. Epolene C-10, the material originally specified, had relatively poor shrink and tear strength properties. It was believed that these characteristics would produce an undesirable amount of voids in the finished parts. Therefore, an effort was made to find a polyethylene with more desirable properties and at the same time to determine the parameters of interest in Epolene C-10.

By investigating the physical properties of other materials, it was hoped that a filler that could be easily processed might be proposed to the design engineer. However, processing techniques developed on this project and described below served to increase the quality of the honeycomb part filled with Epolene C-10 to the point that a new and better material was considered unnecessary. In a meeting with J. T. Carrell at Sandia Livermore on September 20, 1968, it was pointed out that Epolene C-10 was considered

adequate as a filler, and that it would be unnecessary to eliminate all the cracks and voids then contained in the composite structure.

Flow Characteristics of Polyethylene Wax

To fill each honeycomb cell, the polyethylene material must be melted and forced into the carrier structure. As the material becomes viscous, it becomes increasingly difficult to fill each cell without voids. To determine the best temperature range in which to operate, a relationship between the temperature and viscosity of Epolene C-10 was established. Measurements were made between 225°F and 425°F, using a Brookfield viscometer with a Number 7 spindle at 20 rpm. From the graph in Figure 1 it may be concluded that a substantial decrease in viscosity can be obtained by heating the polyethylene from its melting point of 215°F to about 300°F. However, a temperature increase above 350°F does not induce a comparable decrease in viscosity. In addition, when the polyethylene is heated slightly above 350°F it will rapidly oxidize, will eventually degrade because of breaking of the molecular links, and will become brittle upon solidification. Considering the decrease in the strength of the honeycomb carrier, and degradation of the polyethylene, with an increase in conditioning temperatures, processing the polyethylene above 300°F does not seem advisable.

Paper Honeycomb Temperature Limits

To determine the influence of high temperatures on paper honeycomb structures, groups of honeycomb test blocks were conditioned in a nitrogen atmosphere at the temperatures, and for the periods, listed in Table 1.

Table 1. Temperature Conditioning of Paper Honeycomb Blocks

Number of Blocks	Conditioning Temperature (°F)	Conditioning Time (Hours)
4	250	4.0
4	300	4.0
4	350	4.0
4	400	4.0
4	450	4.0

Figure 1. Viscosity Versus Temperature of Epolene C-10 Polyethylene Wax

The blocks were 5/8-inch chevron honeycomb made from 100-lb basic-weight 0.62-g/cc-density, cotton linter paper impregnated with ERL 0510 epoxy resin and skinned on one side only. After heat conditioning at temperatures ranging from 250°F to 450°F the 20 blocks were compression tested. The results in Table 2 show that the strength of a paper honeycomb structure decreases as its conditioning temperature increases.

Figure 2 illustrates graphically the relationship of the average compressive stress of the blocks to the temperature at which they were conditioned. Between 250°F and 400°F the blocks decreased 1.78 psi in compressive strength per each degree Fahrenheit increase. The temperature should be as low as possible if compression strength is a factor. Since viscosity or flow considerations make operation below 250°F impractical the best range of operations is between 250°F and 300°F.

Compressive Strength of Filled-Honeycomb Blocks

Eight 5/8-inch chevron honeycomb test blocks (Figure 3) were filled with Epolene C-10 and allowed to cool by two different methods. Four cooled naturally in the atmosphere, and four cooled from bottom to top with a heat source at the top to facilitate directional heat transfer. To eliminate voids and cracks due to shrinkage, control of the cooling cycle was attempted. X-ray techniques were used on one block from each process to determine the effectiveness of process variations. After the blocks were cooled, they were milled to a height of 2.900 inches, 1/10 inch below their original height. Six of the blocks were then compression tested. The other two blocks were compression tested after radiographic inspection. Test data are given in Table 3.

X-Ray Inspection of Polyethylene-Filled Paper Honeycomb

Two polyethylene-filled blocks made for the compression study were radiographed, using standard radiographic techniques. The principal objective was to determine the effect of controlled cooling on the void content in the polyethylene filler. The different cooling methods are discussed in the next topic. Figures 4 and 5 illustrate the voids that are present in these blocks. In addition to the blocks, one polyethylene-filled Forward Support was radiographed. This phase of the project was only exploratory to show that the shape and size of voids in filled honeycomb could be detected by radiography. Further investigations would be necessary to develop an optimum technique.

Table 2. Compressive Strength of Chevron Honeycomb Conditioned for Four Hours at Various Temperatures

Block Number	Conditioning Temperature (°F)	Block Weight (G)	Ultimate Stress (Psi)
17	250	170.9	536.7
18	250	168.0	556.3
19	250	175.1	477.2
20	250	176.2	512.0
Average		172.5	520.5
1	300	171.3	418.8
2	300	175.8	517.2
3	300	172.9	378.1
4	300	175.5	487.5
Average		173.8	432.9
5	350	172.0	346.3
6	350	173.9	321.0
7	350	173.2	315.1
8	350	176.0	355.2
Average		173.8	334.4
9	400	Damaged Spec	
10	400	173.0	202.1
11	400	174.5	300.2
12	400	176.2	257.9
Average		174.6	253.4
13	450	171.5	217.0
14	450	169.0	267.0
15	450	169.1	246.7
16	450	170.0	249.0
Average		169.9	245.1

Figure 2. Average Ultimate Compressive Stress of Twenty 5/8-Inch Chevron Honeycomb Test Blocks Conditioned in Groups

Figure 3. Polyethylene-Filled Paper Honeycomb Block

Table 3. Compressive Strength of Filled Blocks

Block Number	Resin Ratio (Percent)	Weight (G)	Ultimate Compressive Strength (Psi)
41	48.87	1244.3	1111
42	49.41	1246.4	1112
43	50.84	1329.9	901
44	50.38	1100.0	1073
45	49.51	1230.0	1047
46	49.22	1070.6	1090
47	49.66	1248.0	949
48	49.23	1198.8	1261
Average	49.64		1068

Figure 4. Photoprint of an X-ray of a 5/8-Inch Chevron Paper Honeycomb Test Block Filled With Epolene C-10 Polyethylene and Cooled Naturally

Figure 5. Photoprint of an X-ray of a 5/8-Inch Chevron Paper Honeycomb Test Block Filled With Epolene C-10 Polyethylene and Cooled Under Controlled Conditions

A Filling Process For Production

The early development units of the 223937 filled-honeycomb Forward Support were made by centrifugal casting. A horizontal-axis, variable-speed spin fixture was used to rotate the unfilled honeycomb cylinder about its axis of symmetry at about 200 rpm while molten Epolene was poured into the structure, forced into the cells by centrifugal force, and cooled during rotation. For various reasons, this process produced parts with many cracks and voids. Therefore, the techniques of injection and transfer molding were analyzed to determine their feasibility. Concurrently, efforts were made to improve the process of centrifugal casting. It was clear that the positive pressure attainable in this process was 300 to 400 times less than that available in the injection or transfer molding operations, and for that reason the centrifugal casting process was believed to be incapable of producing parts of comparable quality.

As the polyethylene cools in a honeycomb cell, it begins to shrink drastically. If it cools from both ends of the cell, a reservoir of molten material remains in the center. As the solidification propagates to the center, the reduction in volume due to shrinkage creates a void in the center of every cell. These voids can be seen in Figure 4, discussed in the preceding topic on X-ray Inspection. However, if a heat source can be established at the top of a cell and a heat sink at the bottom, the solidification will propagate from the bottom to the top. As the material shrinks to the bottom, more molten material is supplied from the top by gravity, centrifugal force, or whatever pressure system might be employed. With the direction of heat transfer controlled, a minimum number of voids are created, and the pre-stresses introduced into the structure by solidification shrinkage are held to a minimum.

By placing a heat gun in the center of the rotating honeycomb cylinder, this kind of controlled heat transfer is established. The heat flows from the ID to the OD, and excess molten material is supplied from the warm ID area by centrifugal force. This process was employed on two test rings of honeycomb, and the cooled parts were cut into sections to be compared with those processed without controlled heat transfer. From visual inspection it was concluded that the crack and void content could be measurably decreased by employing this additional process. An X-ray of a block processed in this manner (Figure 5) illustrated the improvement in uniformity over that in Figure 4.

The Design Agency accepted the Epolene C-10 as an adequate filler material, and the process of centrifugal casting was approved as an acceptable method of filling the honeycomb carrier. The improvements in the casting technique developed during this project will be employed to enhance the quality of the part produced. Investigations of the injection and transfer molding methods were discontinued at this point.

Bonding Plastic Laminate Skins to a Filled Structure

The final operation in the process for the fabrication of the 223937 Forward Support was the wet lay-up of an epoxy-impregnated Fortisan cloth on the inner contour of the part. Because much of the shear strength of the part will depend on the soundness of this bond, an investigation of the process was initiated.

Inasmuch as the unskinned inner contour is flat, the resin fillet normally associated with a strong bond is markedly reduced. However, there exists approximately a 0.030-inch gap at the bottom, or OD, surface of each cell created by the natural shrinkage of the polyethylene filler. If each plug of filler material is pushed into the cell to fill this void, a space is available at the ID surface to form a resin fillet. On the other hand, this fillet may restrict the thermal expansion of the polyethylene in the cells as temperatures above room temperature (RT) are experienced in the environmental range required of the part. This structure may result in the delamination of the inner skin at high temperatures because of stress induced by expansion of the filler.

The relationship in strength of skins bonded to honeycomb with full fillet to those with limited fillet was not established. However, tests on the Forward Support showed that the limited fillet bond between honeycomb and inner skin was stronger than the skin material. All Supports that were axially tested to destruction failed by shearing of skin with no indication of honeycomb- to-skin bond failure.

Thermal Contraction of Polyethylene-Filled Paper Honeycomb Parts

There has been a need to determine the magnitude of shrinkage of a paper honeycomb structure after it has been filled with polyethylene. However, it has not been possible to determine the amount of diametrical shrinkage of a filled honeycomb structure on an average diameter gage because the part contracts in all directions. For example, a part with an OD contour, such as the 223937 conical honeycomb Forward Support, will shrink longitudinally as well as on a diameter. The exaggerated illustration in Figure 6 demonstrates that the measurement of an average diameter gage may not be a true reflection of diametrical contraction. While point A (Figure 6) actually shrinks bi-directionally to point B, the probe of the gage will locate from datum C and pick up the part at point A'. From this reading one might erroneously conclude that the radial contraction is the distance $(X + Y)$ in Figure 6. The true shrinkage on a radius is only Y.

The open setup technique illustrated in Figure 7 was used to determine shrinkage on the honeycomb structures. To eliminate the "X" error caused

Figure 6. Exaggerated Shrinkage of a Section of Filled Chevron Honeycomb Cone

Figure 7. Diagram of Open Setup Inspection Technique Used in a Diametrical Shrinkage Investigation

by longitudinal shrinkage, gaging stations were marked on the skin. As the part was rotated, measurements were taken at each marked station before and after filling with polyethylene. From these measurements, the average radial shrinkage at each station was calculated.

The results of the shrinkage investigation are tabulated in Table 4 according to part number, time of center heat source application, and average shrinkage. The average shrinkage values are the average change of height readings over 40 points on the surface of the part. The radial shrinkage is a cosine function of the average height differential. However, the cosine of $9^{\circ}5'25''$ is 0.984 inch, and the radial shrinkage is essentially the same as the change in height.

Part Number 23 has a negative value for its shrinkage which is obviously impossible. The data on this part must be disregarded as a mistake in inspection setup.

As illustrated in Figure 8, nine of the 11 parts are in the range from 0.009 to 0.014 inch. The mean average shrinkage in the radial direction is approximately 0.011 inch.

Figure 8. Average Part Radial Shrinkage

Table 4. Average Radial Shrinkage of Twelve Polyethylene-Filled Paper Honeycomb Blocks

Part Number	Heat Source Cycle Time (Min)	Shrinkage (Inch)
29	0	0.005
30	0	<u>0.014*</u>
Average		0.010
25	12	0.013
20	12	0.019
27	12	0.012
31	12	<u>0.010</u>
Average		0.013
23	30	**
24	30	0.009***
28	30	<u>0.009</u>
Average		0.009
21	60	0.011
22	60	0.014
32	60	<u>0.012</u>
Average		0.012
*Warped in free state before and after filling **Data disregarded ***Warped in free state after filling		

Compressive Modulus of Epolene C-10 Polyethylene Wax

Tests were conducted to determine the compressive modulus of Epolene C-10 polyethylene in the operating temperature range predicted for the 223937 Forward Support. It was anticipated this data would be useful to:

1. Determine a relationship between modulus of the composite structure and component materials; and to
2. Enhance understanding of the structure and materials to enable the calculation of stresses that cause internal shrinkage in the filled honeycomb part.

Unfortunately, curtailment of the project prevented the full accomplishment of these intended purposes.

Twenty 1-inch cubes of Epolene C-10 polyethylene were compression tested in groups of five at 160°F, 90°F, 20°F, and -60°F. The ultimate strength and calculated modulus are reported in Table 5, and the relationship of modulus to temperature is plotted in Figure 9.

Since the polyethylene wax does not adhere to the honeycomb or skin, theoretical analysis to predict magnitude of shrinkage based upon thermal coefficients and induced strain would be complicated and based upon many assumptions which would require extensive testing for verification. However, one can theorize that shrinkage of the polyethylene plugs load the side walls and V's of the chevron cell structure in such a manner as to produce circumferential contraction of the honeycomb.

ACCOMPLISHMENTS

The following conclusions summarize knowledge acquired as a result of work on this project.

1. Although it has high shrink and low tensile strength properties, Epolene C-10 polyethylene wax is an adequate filler material for the 223937 paper honeycomb Forward Support.
2. The 223937 filled honeycomb part shrinks approximately 0.022 inch on a diameter after filling.
3. The compressive strength of paper honeycomb decreases by 1.78 psi per each degree Fahrenheit as it is conditioned in a nitrogen environment between 250°F and 400°F.

Table 5. Modulus and Ultimate Strength of Epolene C-10
Polyethylene Wax

Specimen Number	Test Temperature (°F)	Ultimate Compressive Strength (Psi)	Compressive Modulus (Psi)
1	90	1,320	15,600
2		1,340	17,900
3		1,350	15,600
4		1,380	14,700
5		1,380	<u>15,400</u>
Average			15,800
6	160	180	1,960
7		187	2,000
8		184	1,890
9		178	1,920
10		185	<u>2,000</u>
Average			1,950
11	20	*	40,000
12		*	43,100
13		*	43,100
14		*	38,500
15		*	<u>40,300</u>
Average			41,000
16	-60	*	250,000
17		*	278,000
18		*	263,000
19		*	250,000
20		*	<u>250,000</u>
Average			258,000
*Specimens did not reach an ultimate strength.

Figure 9. Average Modulus of Epolene C-10 Polyethylene Wax Versus the Temperature of the Material

4. High-temperature environments will reduce the strength of paper honeycomb. Therefore, it is impractical to reduce the viscosity of Epolene C-10 by heating it above 350°F because of the subsequent deterioration of structural strength of the honeycomb and possible degradation of the polyethylene.
5. X-ray inspection of polyethylene-filled paper honeycomb supports is feasible.
6. Centrifugal casting is an acceptable process for filling the 223937 paper honeycomb Forward Support with polyethylene.

FUTURE WORK

No additional work on this project is planned at this time. Should the project be reinstated, the following investigations are recommended.

1. Develop a more sophisticated technique for radiographic inspection of polyethylene-filled parts.
2. Investigate the expansion problems involved with a composite structure in a variable temperature environment.
3. Investigate the effect of resin fillets in bonding skins to filled parts.
4. Investigate techniques for machining the filled honeycomb structure and methods of retaining the filler in sectional cells during machining.
5. Investigate shrinkage causes and relationships to:
 - Establish empirical expressions for the dimensional changes caused by filler shrinkage;
 - Establish the effect that cell configuration has on part shrinkage; and
 - Determine the relationship that exists between filler quantity in the cell and shrinkage.

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