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PLANT**

THE F-111 WINDSCREEN MACHINING

H. L. Gerth
R. J. Brown

September 1980

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UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

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Fabrication Systems Department
Y-12 Development Division

Final Report for United States Air Force
(Military Interdepartmental Purchase Request FY14567900010)

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ABSTRACT

Studies were conducted to determine the feasibility of improving the optical image transmitted through a military aircraft windscreen by using single-point diamond turning. Reduced warpage (waviness) of the windscreen surfaces ensures that a more accurate optical image is presented to the aircraft pilot. Machining the acrylic surface was accomplished with slightly impaired image transmissibility. The use of this technique as a potential production process is discussed.

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SUMMARY

Recent experience has shown a need to improve the optical image transmitted by the F-111 military aircraft to the pilot during the normal operation of the aircraft. Distortion of the image was shown to result from surface warpage (waviness) of the two surfaces of the aircraft windscreen.

The warpage was reduced by machining the inner and outer surfaces of the windscreen. A single-point natural-diamond tool was used with a machine highly modified to reduce vibration. The resulting surface was nearly optically clear, requiring only a brief surface polish. Machine improvements that have been made since the earlier machining was done should show even more significant improvement, possibly eliminating the need to polish.

Machines and fixturing needed to machine windscreens in a production mode are discussed.

INTRODUCTION

A new method for manufacturing and refurbishing windscreens for high-performance military aircraft is being investigated at the Oak Ridge Y-12 Plant.^(a) The method involves the machining of the inner and outer surfaces of the windscreen to remove excessive waviness, thereby reducing optical distortion and improving the production acceptance rate. A new method is needed, and this report describes work recently completed that will be useful in assessing the potential for manufacturing windscreens by using machining processes.

"Greatest problem faced by F-111 crews during peacetime training missions is the threat of bird strikes in the windshield area. Bird strikes have caused more F-111 accidents than all other causes combined.

"Most F-111s at Upper Heyford have been modified with a new, thicker polycarbonate windshield, sufficiently strong to resist any bird that is not large enough to break the windshield frames."¹

"Because windscreens need to be slanted, curved, and multi-layered in order to provide good aerodynamic performance and bird strike protection, they often produce optical problems adversely affecting the capabilities of the pilot.... The ultimate aim is to develop more precise and demanding specifications for the fabrication of the windscreen."²

(a) Operated by the Union Carbide Corporation, Nuclear Division, for the Department of Energy.

WINDSCREEN MACHINING

PRESENTATION OF WORK

The new windscreen for use on the F-111 aircraft is a multilayer composite of polycarbonates and acrylics. Figure 1 shows a cross section of a typical windscreen with its material thicknesses. The outer layer is acrylic which gives the windscreen resistance to damage from abrasion—from ground-crew cleaning and other surface damage more easily done on the soft polycarbonates.

Figure 1. CROSS SECTION OF IMPROVED WINDSCREEN FOR F-111 AIRCRAFT.

Present fabrication processes introduce a waviness in the surface of the windscreen which, in turn, presents optical distortion to the pilot. Part of the waviness takes the form of a sag in the surface; that is, if one would tautly draw a string between the front and rear edges of the windscreen, one would observe as much as a 3-mm (1/8-in.) sag between the string and the surface. Some of this sag is caused by the slump method of making glass masters; much of the remainder of the sag is created during the laminating process. The excessive amount of sag is a major contributor to the rejection of up to four of every five windscreens manufactured. Windscreen machining should reduce waviness, thereby reducing distortion and improving the acceptance ratio.³

Single-point turning under near vibration-free conditions with a single-crystal diamond tool has produced optical-quality surfaces in recent years.⁴ New improvements to the diamond-machining process have improved contour accuracies to such a degree that the elimination of waviness in the windscreens is feasible with only an inexpensive, brief polishing of the machined surfaces to remove residual tooling marks and haze.

Even with the complete elimination of waviness, some visible distortion will still exist as a result of the change in the viewing angle that the pilot makes as he operates the aircraft.

Theoretical investigations by the Air Force Materials Laboratory (AFML) indicate this distortion can be minimized by machining the windscreen so that a controlled-variable windscreen thickness results.

Diamond turning is thought to offer improvements in windscreen fabrication in the following ways:

1. Machine windscreens which are otherwise acceptable except for the waviness of the surfaces. This would significantly improve the acceptance rate while providing much better windscreens than are presently being produced.
2. If windscreens cannot be directly machined in an acceptable way, the masters used to mold them could possibly be machined. The masters would then be straighter and would impart less sag to the windscreens. Furthermore, if it can be determined that the laminating process imparts reproducible errors, these errors might be compensated when machining the masters.
3. Decentering the windscreens prior to machining provides a method whereby the thickness can be varied in a controlled manner. This would allow a minimum distortion to be achieved as predicted by the theoretical calculations.

Windscreen material shown in Figure 2 is being diamond turned to assess the first potential improvement described above. The diamond-turning machine is a two-axis, horizontal-spindle, numerically controlled, single-point turning lathe that has been highly modified to reduce vibration and to improve contour accuracy.⁴ Several rectangular pieces of windscreen material were machined on the inner and outer surfaces. Figure 3 shows two pieces mounted on the machine just prior to machining. The samples were held in place with bolts to provide clamping forces on the sides as seen in Figure 4.

The samples were bowed—up to 3 mm (0.125 in.) along their length—which made proper fixturing difficult. Approximately 2 mm (0.075 in.) of the bow was removed by restraining the sample in the fixture with the clamp bolts. The remaining bow will result in a nonuniform thickness after machining and a bow of 2 mm (0.075 in.) when the sample is unrestrained. A single-crystal natural-diamond tool with a 3-mm (0.125-in.) radius was used to machine the samples. The rake angle was 6° positive, and the clearance angle was 6°. A vacuum line was placed near the cutting edge to collect chips before they were able to weld themselves onto the freshly machined surface. No coolant or lubricant was used. Spindle speed was set at 114 rpm. A 50- μ m (0.002-in.) depth-of-cut with a tool feed rate of 66 μ m (0.00263 in.) per revolution was used. The resulting surface seemed to be free of haze and tool feedlines; however, multiple images (ghosts) were observed when viewing an object through the material. This indicated the presence of a diffraction grating generated by the high tool feed rate. These samples were returned to AFML for optical evaluation, polishing, and impact testing. Impact tests are necessary to determine the effect of diamond turning on the impact resistance of the material.

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Figure 2. THE F-111 WINDSCREEN SEGMENT AND FLAT-IMPACT SAMPLE.

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Figure 3. MACHINING OF FLAT-IMPACT SAMPLES.

A second set of samples was machined, using various tool feed rates in an attempt to reduce the effect of the diffraction grating. Segments of the samples 76 mm (3 in.) long were machined at tool feed rates of 5.1, 7.6, 12.7, 19, 25.4, and 31.8 μm (0.0002, 0.0003, 0.0005, 0.00075, 0.001, and 0.00125 in.) per revolution. Optically, the 12.7- μm (0.0005-in.) feed per revolution seems to produce the least noticeable diffraction grating. These samples, along with experiment control (nonmachined) samples, were returned to AFML for evaluation.

The F-111 windscreen is shaped like a frustrum of a right-circular cone with a cone half angle of 4.97° . It is approximately 1.3 m (52 in.) high, and each piece subtends an arc of approximately 90° . The diameter of the midpoint of its height is approximately 1.4 m (56 in.).

Figure 4. FIXTURING TECHNIQUE FOR FLAT-IMPACT SAMPLES.

Because of the travel limitations of the diamond-turning machine, a 0.53-m (21-in.)-high section was cut from a full windscreen. This piece, shown in Figure 2, was diamond turned to demonstrate the applicability of this process for improving the windscreen performance. A single-axis cut was used by repositioning the spindle at an angle equal to the half angle of the conical section. Figure 5 shows an aluminum casting fabricated to support the windscreen segment on the diamond-turning machine. The large hole in the side of the fixture was originally intended to be filled with the windscreen; however, the segment shape was not as anticipated; and a new hole of different size and shape had to be cut in the opposite side. Figure 6 shows the windscreen segment mounted in the fixture which, in turn, was mounted on the diamond-turning machine. The tool is set up to machine the inside surface. Before beginning any material-removal processes, dimensional measurements were made to ensure that the entire surface (inside and outside) could be machined without hitting the fixture or cutting through the outer material and exposing the vulnerable, polycarbonate, inner layers. Figure 7 shows how the measurements were made. Dimension P shows the height above the inside of the fixture, and Dimension Q shows the height above the outside of the fixture. Measurements were taken at several points on the part as shown in Figure 8. The x- and y-coordinates of each point are listed.

The first measurements, made after bolting the windscreen into place on the fixture, showed insufficient clearance to clean the inside surface before cutting into the fixture or cutting through to the polycarbonate material. The windscreen was placed in a different position by placing shim stock on the supports and "stretching" the windscreen using the stretch bolts shown in Figure 7. This was necessary because the windscreen had a smaller radius of curvature than did the fixture. Set 1 of Table 1 shows the data after proper shimming and stretching. This data set indicates that a maximum of 1.32 mm (0.052 in.) of material would have to be removed before cleanup would be realized. The acrylic material thickness is 2.03 mm (0.080 in.).

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Figure 5. FIXTURE FOR HOLDING WINDSCREEN SEGMENT DURING MACHINING.

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Figure 6. MACHINING OF FULL WINDSCREEN SEGMENT.

Figure 7. TECHNIQUE FOR ATTACHING WINDSCREEN TO FIXTURE.

Machining was done with a tool feed of 12.7 mm per revolution (500 μ in. per revolution) with AFML approval. This feed rate gave the best results on the flat-impact samples mentioned earlier. A total of 1.75 mm (0.069 in.) of material was removed before cleanup occurred, which indicated that some part movement occurred during the cutting process as a result of centrifugal force (all measurements were made without centrifugal force). Unfortunately, the polycarbonate material was exposed after removing 1.68 mm (0.066 in.) of material which indicated a thin area in the acrylic, an error in the depth-of-cut assessment, or that the original high point was not properly located and measured. It is not possible with available information to determine the true reason. The exposed polycarbonate was covered, immediately after machining, with Dow Corning 3140 RTV coating to protect it from the atmosphere. Measurements were taken at depth-of-cuts of 0.00, 0.48, 0.86, 1.68, 1.75 mm (0.00, 0.019, 0.034, 0.066, 0.069 in.). These data are found in Sets 2, 3, 4, and 5 of Table 1.

The outside surface was cut in a similar manner requiring a total of 2.73 mm (0.017 in.) of material removal to reach a cleaned-up condition. Sets 6 through 12 of Table 1 contain the data gathered during the outside machining. Set 13 represents the data gathered after machining was completed. The windscreen segment was then removed from the fixture for shipment to AFML.

The second windscreen section was machined in a similar manner with one exception. After machining the inner contour, the windscreen was decentered so the outer surface would not be concentric with the inner surface. This was accomplished by shifting the fixture containing the windscreen on the spindle. The amount of decentering was 2 mm (0.080 in.) in a direction that would cause the windscreen to have its minimum thickness near the center.

Because of excessive warpage, the inside-surface acrylic was again removed; and some of the more sensitive polycarbonate material was exposed. The exposure was on the extreme edge, thereby leaving the center intact for testing purposes.

Both windscreen segments were returned to AFML for evaluation and polishing.

CONCLUSIONS

The windscreen segments were quite different from the optical components that were previously diamond turned at this facility. The surfaces that were machined were large and nearly cylindrical. The materials were acrylics and polycarbonates. Most past experience had been on metallic, shallow, concave, optical components. As a result, many problems were encountered. Although the job was completed successfully, it is felt that significantly better results could be obtained by utilizing the experience gained in this first attempt.

The surface finish obtained by diamond turning did not compare well with an uncut surface. Bright objects that were viewed through the diamond-turned material produced multiple images and, sometimes, rainbows of light that would be distracting to the viewer. This results from the diffraction grating, which was produced by the rounded cutting edge of the diamond tool as the surface of the windscreen was machined. It is felt that the use of a very large radius tool and a slower tool feed rate would eliminate this problem. Large-radius tools were not available for this job, but they could be obtained by special order. The expected cloudiness in the diamond-turned surface did not appear even though no cutting fluid was used as a coolant. The surface did show a herringbone pattern of some prominence. This pattern had often been seen when machining metal optics. After the windscreens were machined, the cause of the herringbone was found and has since been eliminated. Typical surface finishes on metal optics improved from 75 to 175 nm (3 to 5 μ in.) peak-to-valley when the herringbone pattern was eliminated. Figures 9(a) and (b) show surface-finish interferograms with 317-nm (12.5- μ in.)-fringe spacing. They illustrate the surface-finish improvement gained.

It is felt that a surface finish much better than that demonstrated on these windscreens is now possible. Postmachining-polishing expenses would be minimal at most and may be eliminated if the large-radius tool reduces the diffraction-grating effect to the extent that it becomes insignificant. The main objective in machining the windscreens was to remove windscreen sag and its resulting distortion of the image viewed through the material. Images transmitted through nonmachined material did show significant amounts of distortion,

Figure 8. MEASUREMENT LOCATION FOR FIRST WINDSCREEN SECTION.

Table 1
DIMENSIONAL DATA OBTAINED DJRING MACHINING OF FIRST WINDSCREEN SECTION

Set	1	2	3	4	5	6	7	8	9	10	11	12	13
Date	3/20/79	3/21/79	3/22/79	3/23/79	3/27/79	3/28/79	3/28/79	3/29/79	3/29/79	3/30/79	3/30/79	4/3/79	Machining Completed
DOC(1)	-	0.48	0.86	1.68	1.75	-	0.54	1.08	1.64	2.20	2.65	2.73	-
P[Inside-Surface Height(2)] (mm)	A	2.03				1.40	1.37	1.37	1.40	1.42	1.45	1.45	1.45
	B	2.54				1.35	1.27	1.30	1.32	1.30	1.27	1.24	1.24
	C	1.90				1.35	1.40	1.40	1.45	1.45	1.45	1.42	1.42
	D	2.39				1.42	1.40	1.50	1.47	1.45	1.45	1.42	1.42
	E	2.29				1.35	1.27	1.35	1.29	1.30	1.14	1.14	1.14
	F	2.03				1.35	1.40	1.42	1.42	1.40	1.40	1.35	1.35
	G	2.54				1.40	1.40	1.42	1.37	1.35	1.37	1.37	1.37
	H	2.67				1.35	1.27	1.27	1.22	1.14	1.09	1.04	1.04
	I	1.90				1.35	1.37	1.24	1.19	1.14	1.12	1.07	1.07
	J	3.12				1.37	1.40	1.32	1.24	1.30	1.27	1.27	1.27
	Hi	3.12											
	Lo	1.80											
Q[Outside-Surface Height(2)] (mm)	A	5.76	5.76	5.71	5.71	5.71							3.89
	B	5.03	4.95	4.90	4.88	4.93	4.93						3.91
	C	5.21	5.23	5.21	5.08	5.18	5.18						3.91
	D	5.46	5.46	5.38	5.26	5.28	5.28						3.87
	E	5.33	5.33	5.38	5.23	5.21	5.21						3.91
	F	5.31	5.43	5.38	5.13	5.26	5.26						3.96
	G	5.64	5.64	5.61	5.74	5.76	5.76						3.87
	H	5.39	5.39	5.33	5.43	5.44	5.44						3.87
	I	5.84	5.99	5.97	5.97	6.10	6.10						3.91
	J	4.70	4.82	4.90	4.77	4.88	4.88						3.87
	Hi	5.84					6.53						
	Lo	4.70					4.09						
	ID				ID	OD							
	Base				Finish	Data							
	Data					Base							

(1) Accumulated depth-of-cut (mm).

(2) Height above fixture surface.

(a) Before improvement.

(b) After improvement.

Figure 9. TYPICAL SURFACE FINISH.

especially at high angles of incidence. Figure 10(a)(b) quantifies the image distortion produced by the windscreen segment before machining. Image distortions up to 38 mm (1.5 in.) are apparent. They are all relatively long in wavelength. Figure 10(b) shows long wavelength distortions reduced to 20 mm (0.8 in.). Some shorter wavelength distortions of up to 4 mm (0.16 in.) were introduced by the machining process. Although low in magnitude, they are very distracting and would render the windscreen unuseable for its intended purpose. Both the long and the short wavelength errors resulted when the tool does not travel a straight line during the machining process. Imperfections in the guide ways of the machine carriage caused this problem. The problem has been overcome on other jobs by mapping the nonstraightness and then compensating for the errors with a movement along another axis. The funding level and the scope of this contract did not include the mapping and correction for these errors. Hence, their presence is not unexpected. What was surprising was that their presence had such a profound effect on the quality of the transmitted image. It is obvious that this correction will have to be made to improve the image quality.

The method of fixturing the windscreens by support at two opposite edges caused considerable trouble and consternation. Because of internal stresses in the windscreen material, the free-state shape was not round enough to allow total machining of the inner surface without exposing interior polycarbonate material. Stretching and rotating the edge clamps to improve the roundness was not successful since polycarbonate material was exposed when machining both windscreens. Full windscreen components are more than twice the size of the segments machined which further enhances the risk of exposing polycarbonate material. Therefore, fixturing by this technique is not deemed feasible for use in a production machining process. Instead, a fixture technique shown in Figure 11 is thought to be promising in that it rounds the part, allows multiple parts to be simultaneously machined, and allows easy loading and unloading. With this fixture, four full windscreens could be simultaneously machined. Figure 11 is a cutaway view showing two windscreens in place. Each windscreen would be held in place by vacuum. Atmospheric pressure on the inner windscreen surface presses the windscreen against the fixture. Since the windscreen wall thickness is reasonably constant and the fixture is machined round, the inside surface of the windscreen can be machined all over with a minimum of material removal. It is estimated that $< 375 \mu\text{m}$ (0.015 in.) of material removal would be needed. This eliminates the possibility of exposing interior polycarbonate materials. Loading and unloading parts is greatly simplified since precise alignment is not needed.

Machining the outer surface would utilize a similar fixture shown in Figure 12. Again, four windscreens are held in place by vacuum. Decentering, if needed, would be achieved by decentering the fixture when the fixture surface-mating with the windscreen is machined.

(b) Courtesy Aero Medical Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio.

(a) Before machining.

(b) After machining and hand polishing (at correct position).

Figure 10. TRANSMITTED IMAGE DISTORTION.

Figure 11. FIXTURE FOR MACHINING INSIDE WINDSCREEN SURFACE (only two windscreens shown).

Figure 12. FIXTURE FOR MACHINING OUTSIDE WINDSCREEN SURFACE.

A diamond-turning machine large enough to machine full-size windscreens does not currently exist. However, a relatively inexpensive machine could be built by employing a vertical-spindle axis with an air-bearing spindle. Only one axis of travel during machining is needed; therefore, an expensive closed-loop numerical control system is not necessary. Normal-vibration isolation and elimination techniques now used for diamond turning would be required to maintain the best surface finish possible. Production machining times to machine both windscreen surfaces would not be expected to exceed 8 hours per windscreen.

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