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by Thomas T. Bales, Charles R. Manning, Jr., and W. Barry Lisagor

Langley Research Center
Langley Station, Hampton, Va.

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SUMMARY

Glass-bead peening equipment which utilizes programed motions has been developed and used to peen uniformly the inner surface of 26 titanium alloy spacecraft tanks for the alleviation of stress corrosion resulting from exposure to nitrogen tetroxide. The tanks which were peened varied from 20 inches to 14 feet (0.5 to 4.3 m) in length and from 12.5 to 51 inches (0.3 to 1.3 m) in diameter. The function of each component of the developed equipment and the procedures used for peening are described herein. Glass-bead peening parameters have been investigated and parameters were established which produced a compressive stress of approximately 100 ksi on the peened surface of titanium test strips. The effect of glass-bead peening on the mechanical properties of the titanium Ti-6Al-4V alloy was determined from tests conducted by using peened and unpeened standard tensile and V-notch specimens as well as from results of a burst test of a peened tank. A slight reduction in the yield and notch properties of the material was noted after peening; the ultimate tensile strength, elongation, and modulus of the material, however, were found to be unaffected.

INTRODUCTION

Many of the NASA launch vehicles currently utilize solution-treated and aged Ti-6Al-4V titanium alloy fuel and oxidizer tanks. Recently, several of the titanium tanks were found to be incompatible with the oxidizer nitrogen tetroxide (N_2O_4) and failure from stress corrosion occurred during exposure testing (ref. 1). Ten tanks were subjected to simulated flight conditions and failure occurred after exposure times of approximately 1 day to 3 days. As a result of such failures, the scheduled launch dates for several of the space programs were threatened. Since it was not considered feasible to use an alternate tankage material because of the resulting weight penalty, schedule slippage, and cost involved, it was imperative that a method for preventing stress corrosion failures of the titanium tanks be found.

In order to define the environmental factors associated with the N_2O_4 stress corrosion problem and to determine methods for protecting the tanks against stress corrosion, an investigation was undertaken at the Langley Research Center with small stressed specimens. The results of this study (ref. 2) showed that stress corrosion of Ti-6Al-4V alloy in an N_2O_4 environment could be prevented by inducing compressive stresses into the surface by glass-bead peening. Unpeened specimens stressed at the tank operating stress (approximately 100 ksi) failed in a few hours at 165° F (347° K) whereas no stress corrosion occurred in peened specimens after 1 week exposure at the same temperature. As a result of these encouraging results, a small titanium alloy spacecraft tank was glass-bead peened to determine the feasibility of peening the inner surface of the tanks. Although the equipment and procedures utilized to peen the tank with glass beads were considered inadequate for reliably treating flight tanks, the peened tank successfully completed a 30-day test when exposed to simulated flight conditions.

As glass-bead peening showed every indication of being capable of preventing stress corrosion of Ti-6Al-4V titanium alloy tanks, equipment capable of reliably peening the inner surface of titanium tanks was developed. This paper describes this equipment and its operation, the results obtained on studies of peening parameters, and the effect of peening on the mechanical properties of Ti-6Al-4V titanium alloy.

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI) (ref. 3). Factors relating the two systems are given in appendix A. The mathematical relationships given in appendix B and used for programing the glass-bead peening motions were developed by Stephen K. Park of the Langley Research Center.

DESCRIPTION OF GLASS-BEAD PEENING EQUIPMENT

The precision glass-bead peening equipment developed for reliably treating the inner surfaces of spacecraft tanks consisted of five major units. (See figs. 1 and 2.) These five units are:

(1) The bead-propelling equipment for accelerating, sorting, and retrieving the glass-beads

(2) The cradle for supporting and rotating the titanium tanks

(3) The lance and carriage for advancing the peening nozzle along the length of the tank

(4) The lance arm on which the peening nozzle or nozzles are mounted

(5) The programing and control equipment for operating the systems. These units are described in this section.

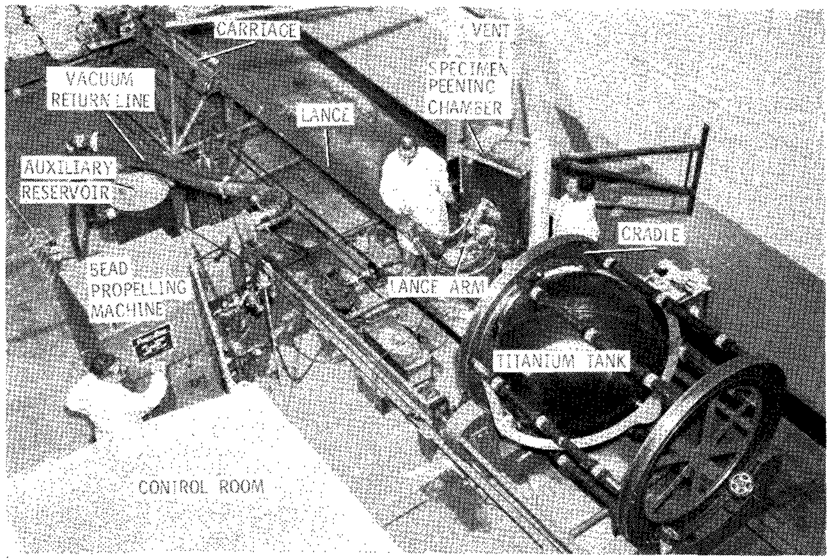


Figure 1.- Glass-bead peening equipment and 51-inch (1.3 m) diameter tank. L-66-377.1

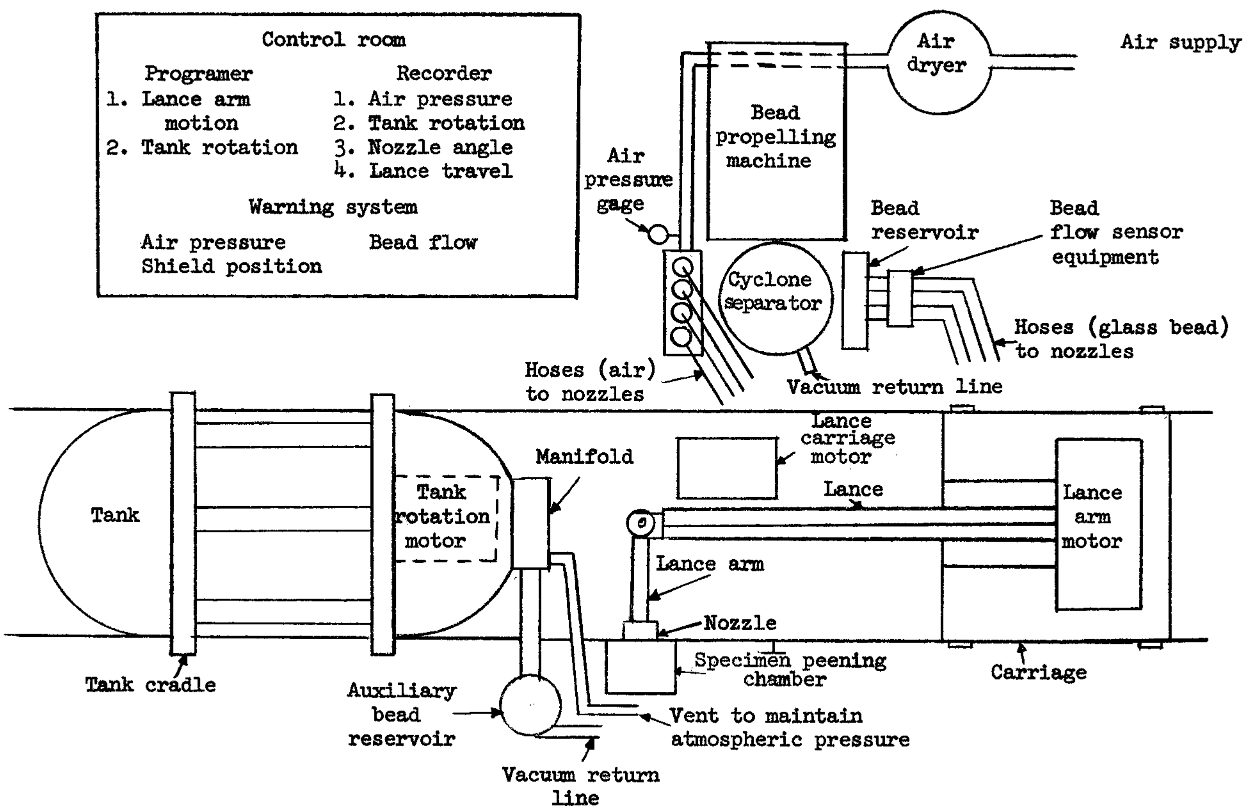


Figure 2.- Schematic of glass-bead peening system.

Glass-Bead Peening Equipment

The equipment for propelling the glass beads was available commercially. In this equipment the air and glass beads are introduced into the nozzle by separate hoses and the glass beads are drawn into the nozzle by aspiration. The equipment was designed to permit use of from one to four peening nozzles simultaneously.

One of the design features of the bead-propelling equipment consisted of a vacuum line through which the used beads were returned to the basic unit. A cyclone separator was used to separate the broken beads from the unbroken (see fig. 2), and the unbroken beads were returned to the hopper for reuse.

Modifications.- Several modifications of the basic bead-propelling equipment were made to obtain the desired performance. The equipment originally provided for a 40-lbm (18 kg) bead supply in the system with no provision for adding new beads to the system while the machine was in operation. An auxiliary bead reservoir having a capacity of 200 lb (91 kg) was installed in the vacuum return line between the tank and the bead-propelling equipment as indicated in figure 2. The auxiliary bead reservoir was necessary because of the large bead inventory required for the peening of tanks and to allow for the replacement of beads lost or broken during operation.

To facilitate bead recovery from the tank being peened and to prevent the glass-bead dust from escaping into the immediate area, a manifold was designed which was connected to the open end of the tank being peened. This manifold was connected to the vacuum return line of the bead-propelling equipment.

Air dryer.- It was necessary to keep the glass beads dry to obtain uniform bead flow. This requirement was achieved by providing a large desiccant-type air dryer capable of drying 400 ft^3 (11 m^3) of air per minute. This air dryer provided the dry air for the incoming airline to the bead-propelling equipment and also served to dry the glass beads.

Bead flow.- To establish reliable peening parameters, it was necessary to maintain a uniform rate of bead flow during the peening process. The bead flow to the peening nozzles was monitored by a direct current micro-volt-ammeter and recorded on a strip chart recorder. This equipment was devised to give an indication of bead flow in a synthetic nonconductive hose by picking up a very small current from the static charge on the glass beads flowing in the hose.

Tank Cradle

The tank cradle was designed and constructed to facilitate rotation of tanks up to 51 inches (1.3 m) in diameter and 14 feet (4.3 m) in length during peening. The cradle consisted primarily of two structural support rings held together by spacer bars. This assembly was supported by four 14-inch-diameter (36 cm) wheels. Three of the wheels were idler wheels that rotated freely while the fourth was chain-driven by a variable-speed motor. The variable-speed motor rotated the cradle in the range from 0.8 to 14 revolutions per minute.

Movement of the cradle assembly along the longitudinal axis was prevented by two wheels mounted at each end of the assembly on a rigid support with their axes at right angles to the cradle rotation and positioned so that contact was made with the support ring at all times (see fig. 1). The entire cradle assembly was inclined at approximately $2\frac{1}{2}^{\circ}$ to facilitate removal of glass beads at the open end of the tank.

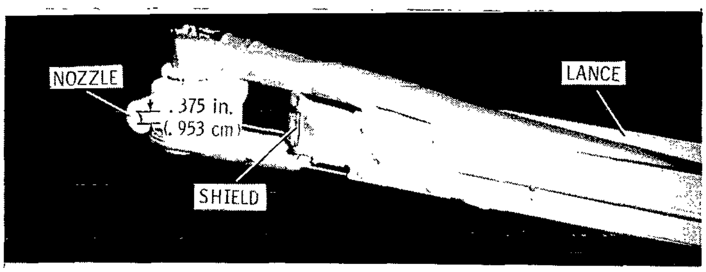
Lance and Carriage

The lance and carriage were designed to advance the peening nozzles along the longitudinal axis of the tank during peening.

Carriage.- The carriage which supported the lance was mounted on four small grooved wheels and driven by a variable-speed motor. The rate of carriage advance could be varied from 0.8 inch to 4.8 inches per minute (0.3 to 2 mm/s). The carriage could be moved or positioned by a manual control which was usable only when the motor drive was disengaged.

Lance.- In order to peen various sizes of titanium tanks in a reasonable time, it was necessary for the lance to support a multiple-nozzle peening configuration for large tanks and a single-nozzle configuration for use on the smaller tanks. A large lance used with the multiple-nozzle arrangement is shown in figure 1. The hoses leading from the peening machine to the nozzles were mounted within the lance.

A smaller lance designed for use with a single peening nozzle was constructed of steel plate 3 inches (7.6 cm) wide and 13 feet (4.0 m) long and welded in the form of an H-section. (See fig. 3.) The bead and air hoses leading to the nozzle were supported in the upper portion of the lance. The single nozzle was mounted on the lance in such a manner that it was capable of sweeping an angle of 165° in a horizontal plane. The shield shown in figure 3 was used to prevent the beads from impinging on the tank surface until equilibrium flow conditions were reached.



L-67-6666

Figure 3.- Single-nozzle assembly for glass-bead peening.

Lance Arm

The lance arm used with the multiple-nozzle arrangement is shown in figure 4. The arm was machined from aluminum alloy and connected to a gear box housed in the lance arm which was capable of advancing the peening nozzles through an angle of 165° in a horizontal plane at a rate varying from 0.06° to 0.86° per second. The forward portion of the lance arm supporting the four nozzles was made so that the distance of the nozzles to the workpiece could be varied. The L-shaped device shown above the nozzles in figure 4 is the shield used with the multiple-nozzle configuration.

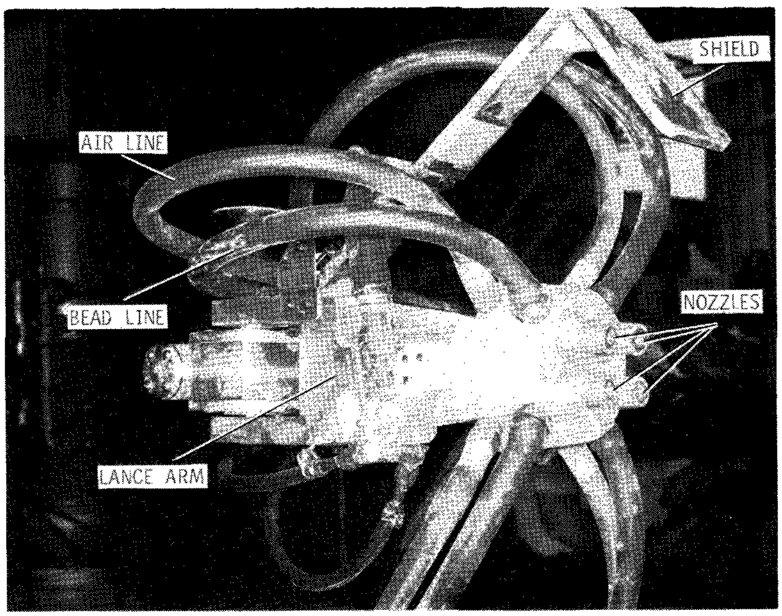


Figure 4.- Multiple-nozzle assembly for glass-bead peening. L-67-6667

Specimen Peening Chamber

A specimen peening chamber (fig. 1) was installed to permit glass-bead peening of small metal strips to establish peening parameters and to permit frequent checks on the peening. The chamber could be moved in or out of position as needed.

Programers and Controls

A control room was used for housing the programers and controls for operation of the equipment. The drum-type programers utilized to program the rate of tank rotation and lance-arm movement (nozzle angle) are shown in figure 5. One programer was used to regulate the tank rotation and the two programers controlled the nozzle angle in the tank domes. The relationships that were used to establish the plots on the programing drums for controlling the peening equipment are shown in appendix B.

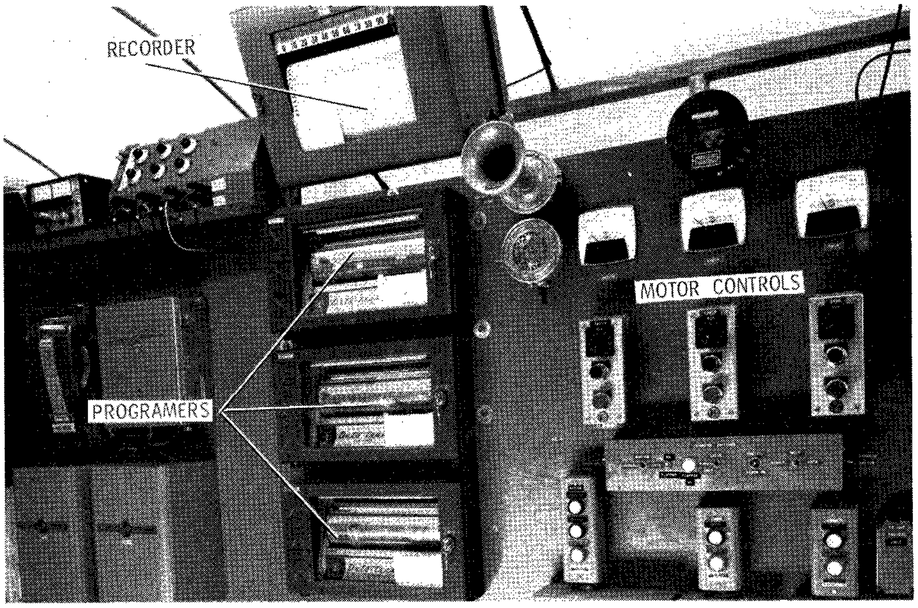


Figure 5.- Equipment for programing, controlling, and recording glass-bead peening process. L-67-6668

The movement of the lance along the longitudinal axis of the tank was programed into the peening operation and lance travel was controlled by means of two limit switches. At the completion of the peening program for the open-dome portion of the tank (see fig. 6), the motor driving the lance arm was stopped and the motor driving the carriage and lance assembly was started. The lance was then advanced along the longitudinal axis of the tank to permit peening of the cylindrical section of the tank. When this movement was completed, the lance and carriage assembly were stopped and the lance-arm movement for the peening of the closed-dome end of the tanks was controlled by the programer.

Recorder.- The strip chart recorder shown in figure 5 was used to monitor the air pressure used for peening, the rate of tank rotation, the angular rate of change of the nozzles, and the lance motion. The strip chart provided a permanent record of the critical motions necessary for treating the titanium-alloy tanks reliably.

Warning system.- A warning system was employed to monitor selected equipment and performances affecting the peening operation. Warning lights were used to indicate whether the shield was in the proper position and whether an undesired change in the flow of glass beads had occurred. A warning buzzer was used to indicate a change in air pressure of more than 10 psi (70 kN/m^2) from the specified value of 50 psi (345 kN/m^2).

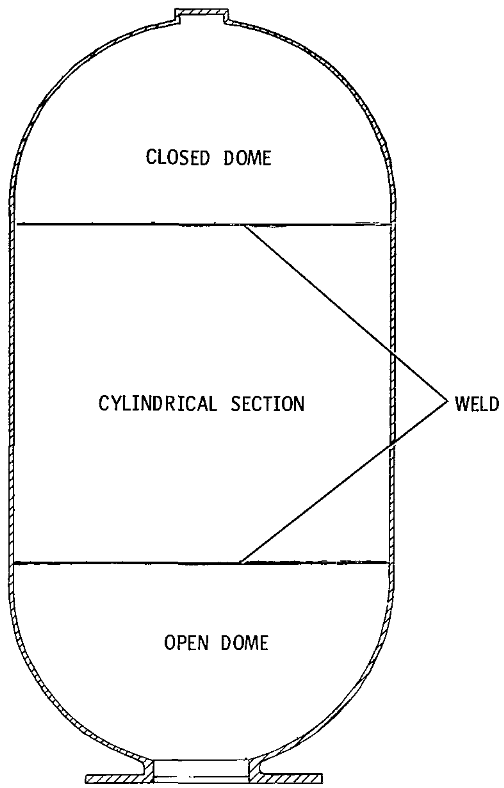


Figure 6.- Cross section of spacecraft tank.

INVESTIGATION OF GLASS-BEAD PEENING PARAMETERS

When the surface of a material is plastically deformed by glass-bead peening, a compressive stress is induced in the surface of the material. (See ref. 4.) The magnitude and depth of the residual stress induced is dependent on the extent of the plastic deformation, the restraint imposed by the underlying material, and the shape of the part being peened as well as other factors which are related to the mechanical properties of the material. The objective in glass-bead peening the titanium alloy tanks was to induce a compressive stress of approximately 100 ksi (700 MN/m^2) into the surface of the tanks to overcome the applied tensile stresses of 90 ksi (630 MN/m^2) resulting from the pressurization of the tanks. Therefore, to establish reliable peening parameters, it was necessary to investigate the factors associated with glass-bead peening and to determine the effect of each on the peening process. The various factors studied and the effect of each on the peening process are discussed in this section.

Peening Small Strips

The determination of the residual stresses induced into the surface of the titanium alloy tanks by glass-bead peening would be best determined from a study of the actual treated surface. Unfortunately, this procedure was not considered to be feasible for the titanium alloy tanks. The approach used in the study was to obtain stress measurements from test strips which were exposed to the same peening environment as the tank surface to be treated.

Procedure.- The specimens chosen for evaluating peening parameters were standard 3/4-inch by 3-inch (1.9 by 7.6 cm) Almen "N" test strips and solution treated and aged titanium alloy Ti-6Al-4V test strips of similar dimensions. The Almen "N" test strips (fig. 6), made of AlSl 1070 steel heat-treated to a Rockwell C hardness of 44 to 50 are 0.031 inch ± 0.001 inch (0.079 ± 0.002 cm) thick, and are described in reference 5. The 0.063-inch-thick (0.16 cm) Ti-6Al-4V strips were solution treated at 1725° F (1210° K) for 8 minutes, water quenched, and aged at 1050° F (840° K) for 2 hours. This heat treatment was similar to that experienced by the spacecraft tanks.

During peening, all the test strips were constrained and supported to remain flat and were peened uniformly on one side. After release of the strips, the induced residual stresses cause convex curvature of the strip on the peened side. Figure 7 schematically depicts a specimen before and after peening. The deflection of the Almen test strip was measured by using a standard No. 2 Almen intensity gage described in reference 5 and was estimated to the nearest ten-thousandths of an inch. This deflection is the Almen "N" intensity which is proportional to the magnitude and distribution of the residual stresses induced by peening. (See ref. 6.) An attempt also was made to use a titanium test strip in order to correlate directly the deflection of the test strip to the magnitude and distribution of stresses induced into the titanium alloy by glass-bead peening. However, reproducible deflection measurements could not be obtained with the titanium test strip. Therefore, the Almen "N" specimen which is a standard and accepted peening test strip

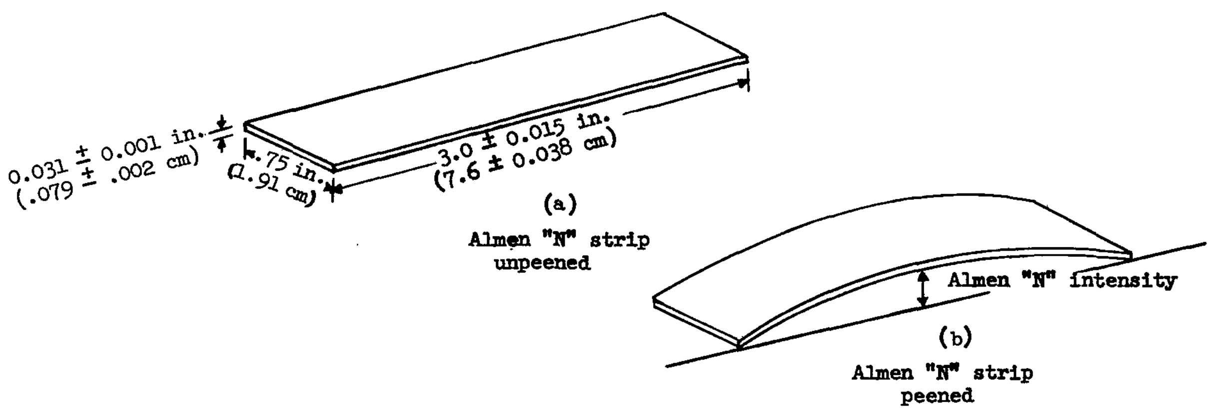


Figure 7.- Dimensions and schematic of Almen "N" AISI 1070 steel test strips.

was used to establish the effect of the various parameters on the peening process. The titanium test strips which were peened by using the parameters required to produce a specific deflection of the Almen "N" strip were examined by means of X-ray diffraction techniques to establish the magnitude and distribution of the stresses induced into the titanium alloy as a result of the glass-bead peening.

The residual compressive stresses in the titanium strips were determined by means of X-ray diffraction techniques using the 3-point parabola method described in references 7 and 8. The average stress factor utilized for stress determinations was determined experimentally by using a compression block and was found to be 71 ksi (490 MN/m^2). This value is lower than the value of 80 ksi (550 MN/m^2) determined in tension reported in reference 9. The distribution of the induced residual stresses beneath the surface of the titanium strips was determined by alternately measuring the surface stress and chemical milling a 0.0005-inch-thick (0.13 μm) layer from the specimens. The procedure was repeated until the determined residual stress approached zero. The titanium specimens examined were peened by using parameters which produced Almen "N" deflections of 0.018, 0.014, and 0.010 inch (0.46, 0.36, and 0.25 mm). Corrections were applied to the stress determinations to account for the effect of the removed layers in accordance with reference 10.

Effect of peening time and air pressure.- The effect of peening time on specimen deflection was determined by peening the Almen "N" test strips for times ranging from 2 to 40 seconds. Gage pressures of 45, 50, and 55 psi (310, 345, and 380 kN/m^2) were used for the multiple-nozzle configuration located at a distance of 5 inches (13 cm) from the strips. Gage pressures of 55, 60, 65, and 75 psi (380, 410, 450, and 520 kN/m^2) were used for the single nozzle located at a distance of 4 inches (10 cm) from the test strips. The effects of peening time and air pressure on the Almen "N" specimen deflection are shown in figure 8 for the multiple-nozzle configuration and in figure 9 for the single nozzle. Deflection is plotted against peening time for various air pressures. The data in both figures indicate that the deflection, which can be related to the compressive stress and depth of penetration, increases with increasing pressure. The specimen deflection increases rapidly during the first 5 to 7 seconds of peening time and then increases slowly as the exposure time is increased. The point on the curves where the deflection does not increase by more than 15 percent if the peening time is increased by 300 percent is defined herein as the saturation point.

Saturation is indicated in both figures after a peening time of approximately 8 seconds. Peening for a shorter period of time than that required to reach saturation results in inadequate coverage (ref. 6). Coverage as used herein refers to the amount of original surface area that has been indented by the glass beads after peening. When a specimen is peened to saturation, the coverage approaches 100 percent whereas peening for shorter times not only results in less coverage but also may leave areas having a residual stress

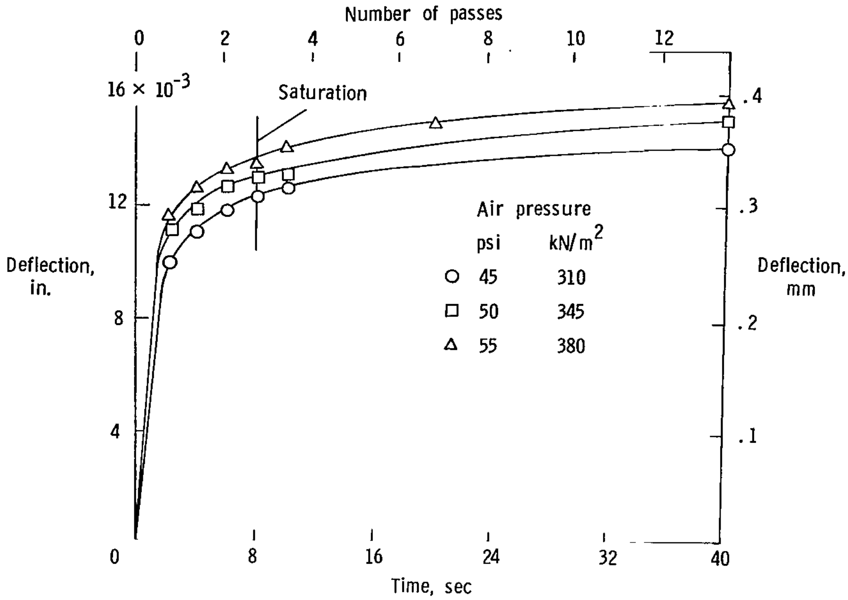


Figure 8.- Effect of peening time on deflection of AISI 1070 steel strip for the multiple-nozzle arrangement.

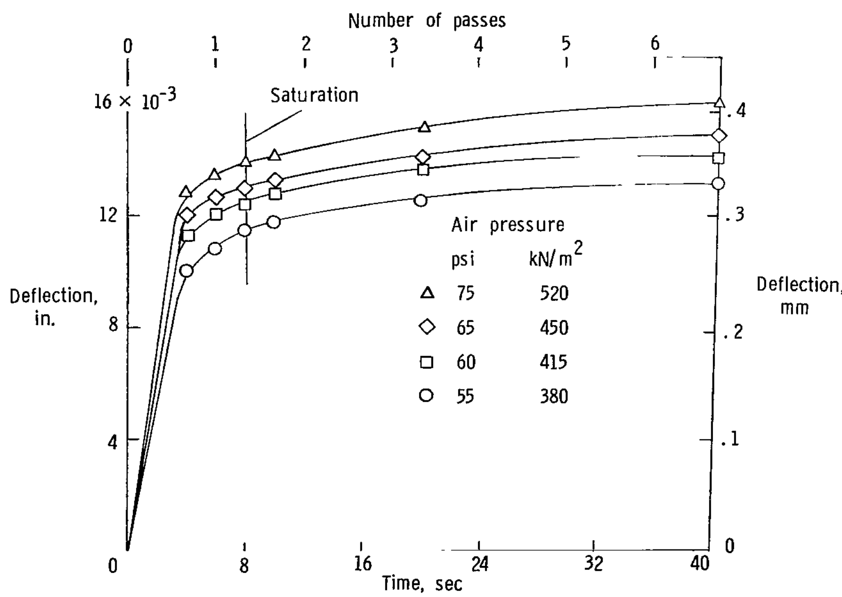


Figure 9.- Effect of peening time on deflection of AISI 1070 steel strip for the single-nozzle arrangement.

less than that desired. Therefore, saturation curves or intensity plotted against peening time data are required before the peening time is selected if uniform peening is required.

The parameters used to peen the titanium test strips were those which produced saturation on the Almen test strips. The residual compressive stress induced into the surface of the titanium strips was determined by X-ray diffraction techniques to be 120 ± 15 ksi (830 ± 100 MN/m^2). The magnitude of the residual compressive surface stress in the titanium strips was not found to vary with air pressure within the range of pressures of the investigation.

Effect of nozzle-specimen distance.- To establish the optimum distance from nozzle to workpiece, the distance was varied from 3 to 10 inches (8 to 25 cm) and the Almen "N" deflection was measured after peening for 9 seconds with an air pressure of 55 psi (380 kN/m^2). The results are shown in figure 10. Note that specimen deflection is insensitive to distance of the peening nozzles from the surface within the range of 3 to 6 inches (8 to 15 cm). Specimens peened at a distance of 10 inches (25 cm) exhibited a deflection of approximately 0.001 inch (25 μm) less than those peened at a distance of 3 to 6 inches (8 to 15 cm). From this result, it appears that within the range investigated, the effect of distance on Almen "N" deflection is minor.

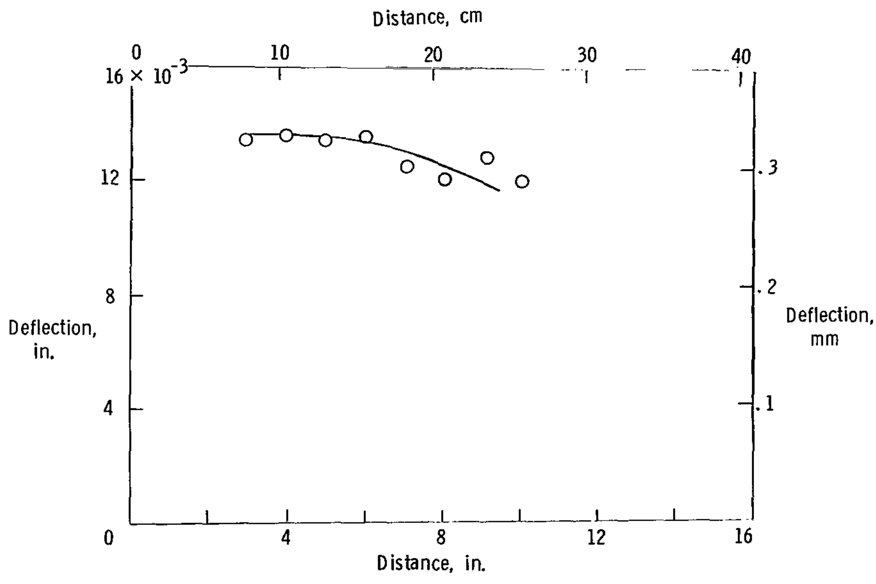


Figure 10.- Effect of distance from nozzle to specimen on the deflection of AISI 1070 steel strip.

Effect of peening angle.- The effect of the angle at which the glass beads strike the surface of the specimen was investigated by peening specimens mounted at angles of 15° to 90° to the blast stream. The peening time was that required to reach saturation for the specimen mounted at 90° (approximately 10 seconds).

The data obtained are shown in figure 11 where the deflection is plotted against the angle of impingement. The results in figure 11 indicate that the Almen "N" deflection is a maximum when the angle of impingement is 90° and as the angle of impingement deviates from 90°, the deflection decreases at an increasing rate. Therefore, to obtain the maximum Almen "N" deflection for a given air pressure, peening time, and nozzle-to-work distance, the angle of impingement of the glass beads striking the surface should be maintained as closely as possible to 90°.

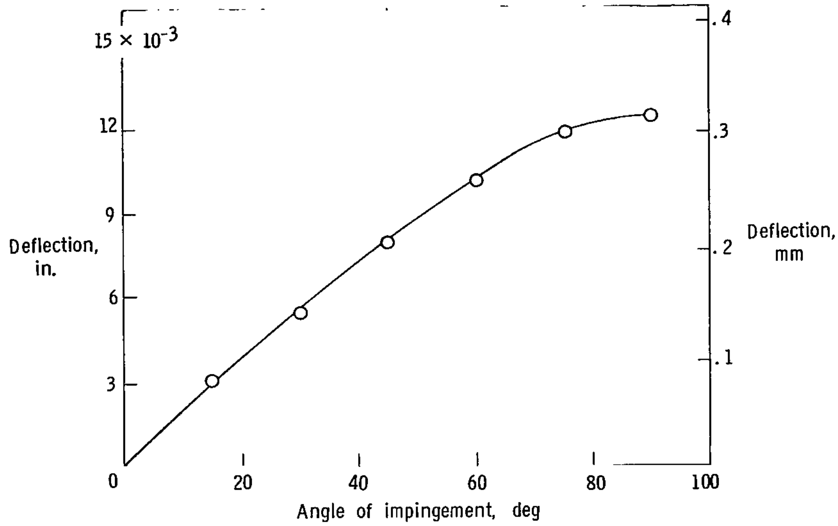


Figure 11.- Effect of angle of impingement on deflection of AISI 1070 steel strip.

Size of effective peening area.- Prior to calculating the time required to peen a given area, it was necessary to establish the area covered by the glass-bead blast by using a specific distance from nozzle to surface and a specific air pressure. The effective peened area must be known accurately to program the peening operation correctly.

The effective area of the blast was determined in this investigation by using several techniques. The first technique consisted of peening a 3- by 3-inch (7.5 by 7.5 cm) sheet of titanium that was coated with a dye. The specimen was peened for several seconds, and the region from which the dye was removed by the peening was determined. It was noted, however, that only the center portion of the area experienced a uniform intense peening whereas the outer region of the area appeared to have received only superficial peening. For this reason only the portion of the peened area which had received the more intense peening was taken to be the effective peening area. A second technique utilized was to peen a piece of template paper. The size of the ensuing hole was determined and taken to be the effective peening area. This process was then repeated with a sheet of stainless-steel foil. On the basis of these techniques which produced generally similar results, the effective peening area was determined to be a region measuring approximately 1.75 by 1.75 inches (4.5 by 4.5 cm) for the multiple-nozzle configuration and approximately 0.75 inch (1.9 cm) in diameter for the single nozzle. The distance from nozzle to specimen for both nozzle configurations was 4 inches (10 cm).

Residual stresses.- It was considered desirable for the depth of the compressively stressed layer resulting from peening to be several thousandths of an inch (cm) thick, other factors being considered, in order to minimize the effect of light surface scratches that could result from handling the tanks during cleaning and refurbishment prior to use. Therefore, an investigation was conducted to determine the distribution of induced residual stresses in titanium specimens peened by using the parameters required to produce specific Almen "N" deflections.

The titanium specimens were peened by using parameters which produced Almen "N" deflections of 0.018, 0.014, and 0.010 inch (0.46, 0.36, and 0.25 mm) and the stress distributions are shown in figure 12 where the residual stress resulting from peening is plotted against depth. Each data point shown is the average value for two specimens. The residual compressive stress existing on the surfaces of the specimens examined exceeds 100 ksi (700 MN/m^2). The magnitude of the residual compressive stress remains above 80 ksi (550 MN/m^2) for the specimens peened by using parameters which produced Almen "N" deflections of 0.014 inch (0.36 mm) or greater to a depth of approximately 0.002 inch (0.05 mm). The stress then decreases rapidly with depth and

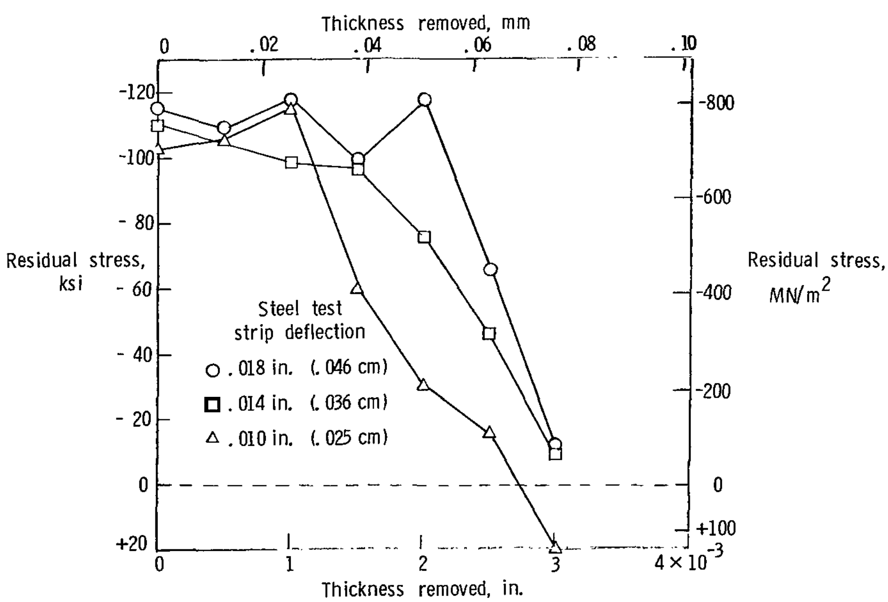


Figure 12.- Residual stress distributions for peened titanium test strips employing parameters that produce Almen "N" deflections of 0.010, 0.014, and 0.018 inch (0.025, 0.036, and 0.045 cm). Negative values indicate compressive stress; positive values indicate tensile stress. Each point is an average of two specimens.

approaches zero in the vicinity of 0.0035 inch (0.089 mm) beneath the surface. These data indicate that compressive stresses of the nature desired to minimize the effect of scratches can be obtained when Ti-6Al-4V is peened by using parameters which produce Almen "N" deflections of 0.018. However, it was felt that the distortion and residual tensile stresses resulting from peening by using these parameters would be excessive. Therefore, the parameters selected for use were those which produced Almen "N" deflections of 0.012 to 0.014 inch (0.30 to 0.36 mm).

Peening of Dummy Tanks

Procedure.- The glass-bead peening parameters utilized for treating various titanium alloy tanks were based on the results obtained from the investigation of the factors affecting glass-bead peening on test strips and from the parameters established by peening dummy steel tanks having the same configuration and size as the actual titanium alloy tanks.

The dummy tanks were fabricated from mild steel, and both Almen "N" and titanium test strips were placed along the length of the tank as well as around the circumference at specific locations. Each test strip was secured to the tank surface by means of 4 sheet holders. The interior surfaces of the dummy tanks containing the test strips were then peened by using a distance from nozzle to work of 4 or 5 inches (10 or 13 cm) depending on whether the multiple- or single-nozzle arrangement was used, and a prescribed air pressure and an angle of impingement of 85° to 90°.

In programing the necessary peening motions, the effective spot size was assumed to be smaller than the established value in order to increase the probability of complete surface coverage. The assumed values for programing purposes were 1.5 by 1.5 inches (3.8 by 3.8 cm) for the multiple nozzle and 0.63 by 0.63 inch (1.6 by 1.6 cm) for the single nozzle. Consequently, an overlap existed as the nozzles were advanced during the peening of the tank, and a safety factor regarding surface coverage was inherent in the peening process. The peening motions were programed so that each point in the tank would be exposed to the stream of beads for a period of 0.5 second (no overlap being assumed) during each peening cycle. The equations used for programing the peening operations are given in appendix B.

Results.- After one peening cycle of the dummy tank was completed, the Almen "N" test strips were removed and the deflections measured. The deflection measurements of the test strips were found to vary by less than 10 percent, and thereby attest to the uniformity of the peening operation. From these measurements, correlation was then obtained between the specimen deflection obtained in the dummy tank and from specimens in the specimen peening chamber. (See fig. 1.) On this basis, saturation curves were established identical to the curves in figures 8 and 9 except that the abscissa indicates the number of peening passes rather than elapsed peening time in seconds. Consequently, both figures 8 and 9 have a double abscissa. The deflection of the steel strips removed from the dummy tank at the completion of 6 peening cycles was measured and found to correspond to an accumulated peening time double that required to reach saturation. The use of 6 cycles for the peening of the titanium tanks would, therefore, provide a safety factor of two regarding the peening time required to obtain the desired residual compressive surface stress of approximately 100 ksi (700 MN/m^2).

Bead breakup.- The effect of bead breakup was investigated by peening a dummy tank containing Almen "N" test strips. An elapsed peening time of approximately 2 hours was required to peen the entire inside surface area of the 14-foot-long (4.3 m) dummy tank. During continuous operation, the cyclone separator could not efficiently separate the broken beads from the bead supply when the multiple-nozzle configuration was used. Therefore, samples of the 0.0058- to 0.0097-inch diameter (0.15 to 0.25 mm) glass beads were removed from the bead supply periodically during the peening of the tank and the percentage of broken beads in the bead supply was determined by a sieve analysis of the bead sample. When the percentage of broken beads in the supply became such that only 60 percent of the 100-gram sample was retained on a 100 mesh screen, all the used beads were discarded, the peening equipment was cleaned, and new beads were added.

The results of a sieve analysis of new beads showed that approximately 90 percent of the sample was contained on a 100 mesh screen after 15 minutes of shaking by a commercial sieve shaker. A sieve analysis of a bead sample taken after an elapsed peening time of 60 minutes showed approximately 80 percent retained on a 100 mesh screen. After 2 hours of peening, only 60 percent was retained on the 100 mesh screen. Almen "N" test strips removed from the dummy tank indicated that a gradual decrease in specimen deflection occurred as the percentage of broken beads increased. Almen "N" strips peened with the beads having an accumulated peening time of 2 hours exhibited a loss of deflection of 0.0015 to 0.002 inch (38 to 51 μm) as compared with the deflections obtained by using new beads. It was found that the decrease in deflection as a result of an increase in the percentage of broken beads could be alleviated by increasing the air pressure used for peening. Therefore, to maintain the desired peening uniformity, the air pressure was increased approximately 5 psi (35 kN/m^2) when only 75 percent of bead sample was retained on a 100 mesh screen. When only 60 percent of the bead sample was retained, the beads were discarded as noted previously.

APPLICATION OF GLASS-BEAD PEENING EQUIPMENT TO Ti-6Al-4V ALLOY TANKS

The equipment and peening parameters developed in this investigation were utilized to peen Ti-6Al-4V alloy spacecraft tanks with glass beads for several aerospace programs. The number of tanks peened and the size of each are shown in table I. Thirteen of the tanks are intended for use in flight vehicles and 13 are to be used for test purposes. The sizes of the tanks that were peened with glass beads ranged from 12.5 to 51 inches (0.3 to 1.3 m) in diameter and from 20 inches to 14 feet (0.5 to 4.3 m) in length.

The uniformity with which the tanks were peened was verified by the peening of dummy tanks having a diameter similar to the titanium tank with Almen "N" and titanium test strips placed along the length and around the circumference of the tank. The deflection of the Almen "N" test strips removed from the tank after peening, ranged from 0.012 to 0.014 inch (0.30 to 0.36 mm) whereas the residual compressive surface stress determined from the titanium strips was found to be 120 ± 15 ksi (830 ± 100 MN/m^2). The programed motions used for peening were monitored and recorded during the peening of the titanium spacecraft tanks to verify that they did not deviate from the values used for uniformly peening the dummy tanks.

TABLE I.- NUMBER AND SIZE OF Ti-6Al-4V TANKS PEENED

Tank type	Proposed use		Tank size (Nominal)			
			Length		Diameter	
	Test	Flight	in.	cm	in.	cm
A	1	2	168	427	51	130
B	1	1	51	130	51	130
	1	2	68	173	51	130
	4	2	39	99	12.5	32
C	5	6	39	99	12.5	32
D	1		20	51	12.5	32
Total	13	13				

EFFECT OF GLASS-BEAD PEENING ON THE MECHANICAL PROPERTIES AND BEHAVIOR OF Ti-6Al-4V

Ti-6Al-4V alloy can be glass-bead peened such that residual compressive stresses are induced into the surface to a depth of several thousandths of an inch. The compressive stresses are accompanied by residual tensile stresses in the remaining thickness of the material. In view of the possible effect of the residual stresses on the mechanical properties of the titanium alloy tanks, a brief study was undertaken to determine the effect of peening on the mechanical properties of Ti-6Al-4V.

Procedure

Tensile tests were conducted to determine the effect of glass-bead peening on the uniaxial yield and ultimate tensile strength of 0.045-inch thick (0.114 cm) Ti-6Al-4V specimens in the annealed condition.

The specimens were tested with a screw-powered testing machine at a strain rate of 0.005 per minute to just beyond yield and then at a rate of 0.05 per minute to fracture. Strain was measured by means of a single three-wire 120-ohm foil strain gage located in the center of the 2.5-inch long (6.4 cm) test section of the tensile strip. Load was recorded against strain by an X, Y type recorder.

A total of eight specimens were tested: two unpeened, three peened on one side, and three peened on both sides. The surfaces were peened by using parameters which produced Almen "N" deflections of 0.013 ± 0.001 inch (0.33 ± 0.025 mm).

The effect of glass-bead peening on the notch strength of Ti-6Al-4V sheet was also investigated. The specimens were peened with glass beads after machining of the V-notches. The 1-inch wide (2.5 cm) ASTM type notched specimens had sharp V-notches with a notch radius of less than 0.001 inch (25 μm), a width between the notches of approximately 0.7 inch (1.8 cm), and a reduced test section of 2 inches (5.1 cm). The specimens were loaded at the ends through pins and a yoke and were tested in a hydraulic testing machine having a 100 kip (445 kN) capacity.

The effect of applying various levels of uniaxial tensile strain on the residual compressive stresses induced by glass-bead peening was studied by using a standard tensile specimen of Ti-6Al-4V sheet with one surface peened to an Almen "N" deflection of 0.013 ± 0.001 inch (0.33 ± 0.025 mm). The magnitude of the compressive stresses induced by peening was determined with X-ray diffraction techniques. The tensile strip was then stressed in tension to a strain of 0.01 and the load was removed. When the load was released, a permanent tensile strain of 0.001 was indicated. The magnitude of the compressive stresses existing on the peened surface of the specimen was again determined by means of X-ray diffraction. This procedure was repeated several times until the specimen had experienced a strain of 0.016 under load and a permanent tensile strain of 0.006 after the load had been removed.

Tensile Properties

The data from the tensile tests are given in table II and the stress-strain curves obtained are shown in figure 13. Figure 13 shows that glass-bead peening appears to

TABLE II.- TENSILE AND NOTCH PROPERTIES FOR ANNEALED

Ti-6Al-4V TITANIUM ALLOY SHEET, 0.045 INCH (0.114 cm) THICK

Specimen condition	Tensile properties							Notch properties		
	Tensile strength		Yield strength		Elongation in 2 in. (5.08 cm), percent	Young's modulus		Notch strength		Notch strength ratio*
	ksi	MN/m^2	ksi	MN/m^2		ksi	GN/m^2	ksi	MN/m^2	
Unpeened	162.5	1120	151.0	1041	8.5	15.2×10^3	105	155.3	1071	0.96
	161.8	1116	146.2	1008	9.5	15.1	104	154.5	1065	.95
								152.4	1051	.94
								159.4	1099	.98
								154.4	1065	.95
Peened one side	163.5	1127	139.8	964	9.5	14.8	102	147.6	1018	.91
	162.8	1123	142.4	982	9.0	15.3	106	148.0	1020	.91
	161.5	1114	141.5	976	9.0	15.1	104	150.8	1040	.93
								150.8	1040	.93
Peened both sides	162.5	1120	136.8	943	8.0	14.7	101	153.1	1056	.95
	160.2	1105	137.0	945	8.0	14.8	102	153.0	1055	.94
	162.6	1121	139.6	963	11.5	15.0	103			

*Based on average tensile strength.

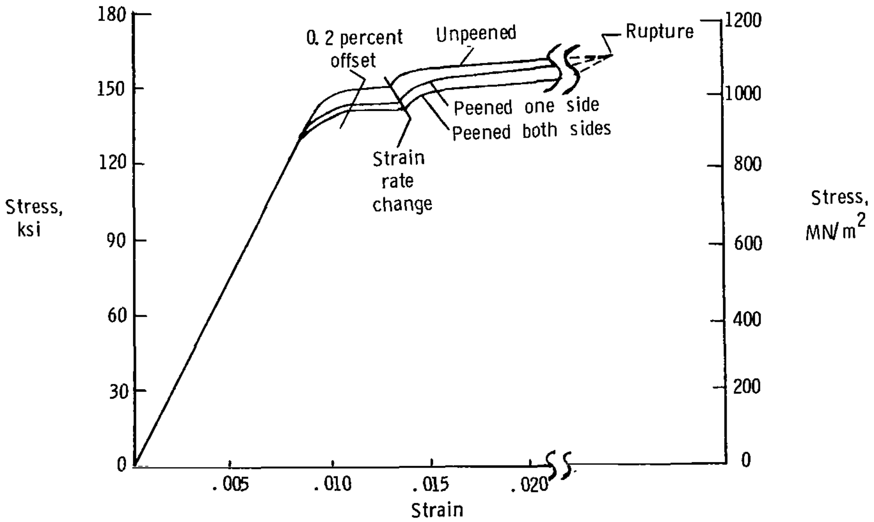


Figure 13.- Effect of glass-bead peening on the tensile stress-strain behavior of Ti-6Al-4V alloy.

lower the tensile yield strength of the material by 8 to 10 ksi (60 MN/m^2) depending on whether one or both surfaces of the specimen had been peened. The apparent decrease in yield strength may be explained by the results obtained from the peening of a 0.025-inch thick (0.64 mm) tank which had been instrumented with strain gages on the outer surface. The strain gages were monitored during the peening operation.

After the inner surface of the 39-inch (99-cm) long tank had been peened by using parameters which produced an Almen "N" deflection of 0.013 ± 0.001 inch (0.33 ± 0.025 mm), the resulting strain recorded on the outer surface of the tank was 450 microinches (11 μm) corresponding to a hoop stress of approximately 11 ksi (76 MN/m^2) in tension. The apparent decrease in the yield strength of the peened specimens may be accounted for if this residual tensile stress is assumed to be additive to the applied stress.

The data in table II indicate that glass-bead peening does not appear to affect the ultimate tensile strength, elongation, and Young's modulus of Ti-6Al-4V. The effect of glass-bead peening on the tensile strength of Ti-6Al-4V was also studied by means of a burst test conducted with a spacecraft tank which had been peened. The tank was pressurized hydrostatically after having been exposed in N_2O_4 for 30 days and burst at a pressure approximately equal to the burst pressure for unpeened tanks. This test tends to confirm the conclusion that glass-bead peening does not significantly affect the ultimate tensile strength of Ti-6Al-4V.

Notch Strength

The results obtained from the notch tests are given in table II. The notch strength of the specimens peened on one side was approximately 6 ksi (40 MN/m^2) less than the unpeened specimens. The notch strength of specimens peened on both sides, however, showed no significant change from the unpeened specimen data. It appears that the decrease in notch strength may be related to the decrease in the yield strength noted previously from the residual tensile stresses induced by peening. It should be noted, however, that the ratio of notch strength to tensile strength for the peened specimens was approximately 0.93 and that the fractures exhibited a ductile shear lip. On the basis of these results, glass-bead peening does not appear to affect significantly the notch strength of Ti-6Al-4V alloy.

Effect of an Applied Uniaxial Tensile Stress on the Residual Compressive Stresses

In many proof tests the spacecraft tanks are pressurized to a stress corresponding to approximately 70 to 80 percent of the yield strength of the material. It was of interest in this study to determine whether the application of proof stresses or greater would significantly relieve the magnitude of the induced stress produced by peening.

The effect of applied strain on the magnitude of the residual compressive surface stress resulting from peening is shown in figure 14. The dotted vertical line represents a strain corresponding to the 0.2 percent offset yield stress in figure 13. The induced compressive stress remained above 85 ksi (590 MN/m^2) until an applied strain exceeding the strain corresponding to the yield strength of the material had been experienced. As a result of these tests, it was concluded that the magnitude of the residual stress induced into the tank surface by peening would not be significantly affected by proof testing.

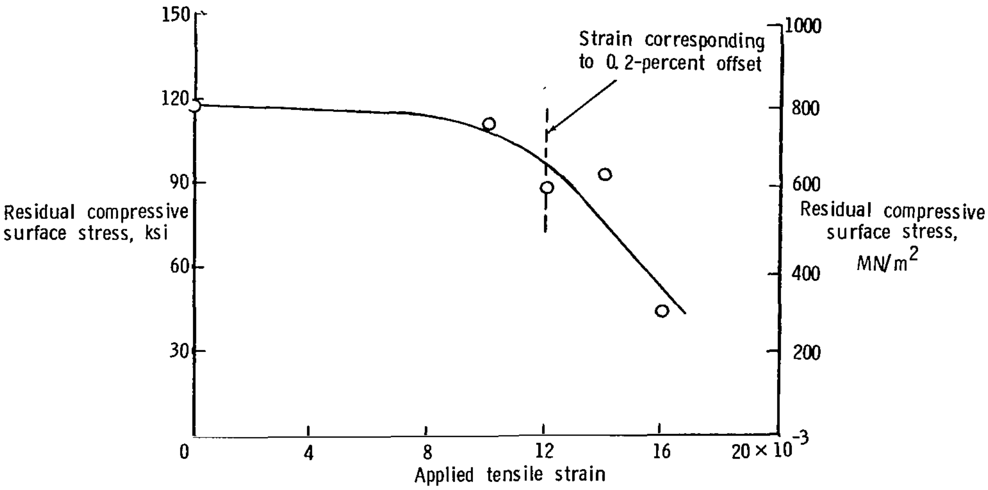


Figure 14.- Effect of applied tensile strain on the residual compressive surface stress in annealed Ti-6Al-4V sheet.

Dimensional Changes Resulting From Glass-Bead Peening

The thin-walled tanks that were peened in this study were produced to meet established dimensional tolerances. It was of interest to determine dimensional changes resulting from glass-bead peening in order to establish overall growth of the tanks.

The diameter and length of each tank was measured before and after peening. The dimensional changes noted were dependent on the geometrical configuration and wall thickness of the tanks treated. The 39-inch-long (99 cm) reaction control system tanks which were $12\frac{1}{2}$ inches (32 cm) in diameter and possessed a wall thickness of approximately 0.025 inch (0.64 mm) experienced an average growth in diameter of approximately 0.0035 inch (89 μm) and an increase in length of approximately 0.010 inch (0.25 mm). The dimensional changes experienced by the larger tanks were percentagewise even less significant. The results of this work indicate that the dimensional changes occurring from glass-bead peening were not particularly significant.

CONCLUDING REMARKS

Equipment was developed and methods for glass-bead peening titanium alloy tanks were investigated. The following remarks are based on the results of this study.

Equipment was designed, fabricated, and put into operation that permitted the uniform and controlled glass-bead peening of the inner surface of thin-wall spacecraft tanks of solution treated and aged Ti-6Al-4V titanium alloy in a reproducible manner. The versatility of the equipment was demonstrated by the controlled peening of 26 spacecraft tanks ranging in length from 20 inches to 14 feet (0.5 to 4.3 m) and from 12.5 to 51 inches (0.3 to 1.3 m) in diameter.

Peening parameters were established and utilized to produce a residual compressive stress of approximately 120 ksi (830 MN/m^2) on titanium test strips. These parameters were then used to peen the surface of the titanium tanks.

The induced residual compressive surface stress caused by glass-bead peening resulted in a decrease in yield strength of 8 to 10 ksi (60 MN/m^2), but there was no significant effect on the tensile strength, elongation of the titanium Ti-6Al-4V or on the burst strength of a tank.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 12, 1967,
129-03-07-04-23.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures held in Paris, October 1960, in Resolution No. 12 (ref. 3). Conversion factors required for units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Force	pounds (lb)	4.44822	newton (N)
Length	inches (in.)	0.0254	meters (m)
	foot (ft)	0.3048	meters (m)
Stress	kips per square inch (ksi)	6.895	meganewton per square meter (MN/m^2)
Temperature	(^oF + 459.67)	(5/9)	degrees Kelvin (^oK)
Volume	$foot^3$	0.028317	$meters^3$ (m^3)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
giga (G)	10^9
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}

APPENDIX B

RELATIONSHIPS FOR PROGRAMING GLASS-BEAD PEENING OF CYLINDRICAL TANKS WITH HEMISPHERICAL DOMES

By Stephen K. Park
Langley Research Center

As explained in the text, the movement of the peening nozzle along the inside surface of both the cylindrical and hemispherical portions of the tanks is controlled by drum-type programers into which the equations of motion of the peening nozzle have been programed. The development of these equations is presented herein. The symbols used are as follows:

k	constant
l	length of cylindrical portion of tank
r	radius of tank
ΔS	nozzle spray width
S_φ,S_θ	distances along hemispherical surface measured in $-\hat{\varphi}$- and $\hat{\theta}$-directions, respectively
t	time
t_o	initial time
v	velocity along hemispherical surface
v_z	velocity parallel to Z-axis of cylindrical portion of tank
$\dot{\varphi} = \frac{d\varphi}{dt}$	
$\omega = \frac{d\theta}{dt}$	
ω_o	tank rotational velocity

x,y,z rectangular coordinates

r,θ,φ spherical coordinates

$\hat{\varphi},\hat{\theta}$ unit vectors in φ- and θ-directions, respectively

Uniform peening of the cylindrical section of the tanks is easily accomplished by advancing the peening nozzle at a constant velocity v_z along the longitudinal axis of the tank (see fig. 15) while maintaining a constant rate of tank rotation ω_o. For a fixed value of nozzle spray width (ΔS), this longitudinal velocity v_z is given by

$$v_z = \frac{\omega_o(\Delta S)}{2\pi} \tag{B1}$$

where ω_o is in radians/sec. The total time required to peen the cylindrical section may be obtained from equation (B1) and is

$$\text{Total time} = \frac{l}{\Delta S\omega_o} \tag{B2}$$

where l is the length of the cylindrical section.

Peening of the hemispherical portion of the tanks is accomplished with the base of the lance arm held at the fixed position $z = 0$ and the nozzle moved in a $-\hat{\varphi}$ direction from $\varphi = \pi/2$ to $\varphi = 0$. (See fig. 16.)

To provide uniform peening without varying the mass flow of particles from the nozzle, it is necessary to vary both $\omega = d\theta/dt$ (the tank rotational velocity) and $\dot{\varphi} \equiv d\varphi/dt$ (the rotational velocity of the lance arm in the $-\hat{\varphi}$ direction).

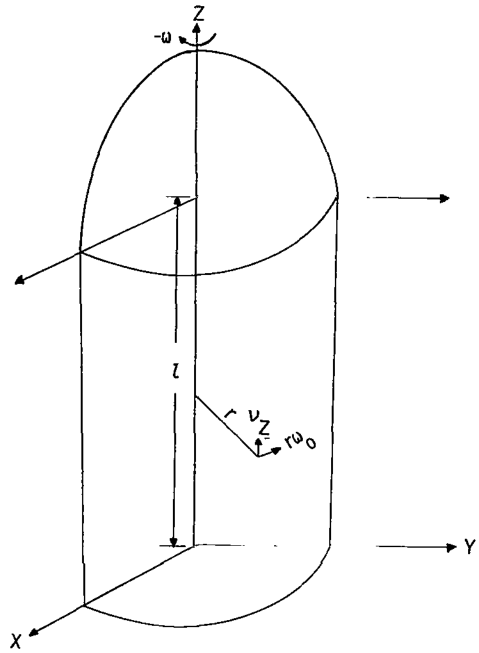


Figure 15.- Angles, directions, and movements used for programing peening motions in the cylindrical section of the tanks.

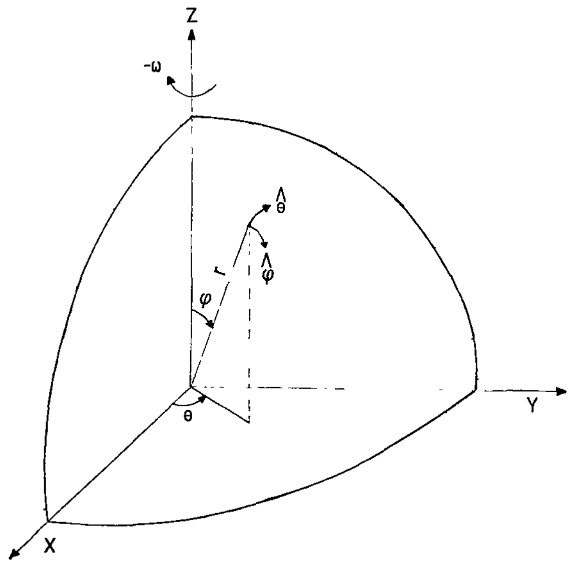


Figure 16.- Angles, directions, and movements used for programing peening motions in the hemispherical dome sections.

APPENDIX B

The variations of these quantities as functions of time, $\omega(t)$ and $\dot{\varphi}(t)$, are obtained in the following manner.

Motion of the nozzle in the $-\hat{\varphi}$ direction must be such that

$$S_\varphi(\theta + 2\pi) - S_\varphi(\theta) = \Delta S \tag{B3}$$

where S_φ is a distance measured in the $-\hat{\varphi}$ direction. That is, at an angle θ, the nozzle must move a distance ΔS (in the $-\hat{\varphi}$ direction) each time the cylinder completes one rotation. Notice that the path of the nozzle during one rotation is essentially arbitrary; thus, it is possible to choose

$$\frac{dS_\varphi}{d\theta} = k = \text{Constant} \tag{B4}$$

Therefore, since

$$\Delta S = \int_{S_\varphi(\theta)}^{S_\varphi(\theta+2\pi)} dS_\varphi = \int_\theta^{\theta+2\pi} k\, d\theta = 2\pi k \tag{B5}$$

and since $dS_\varphi = -r\, d\varphi$, equation (B4) may be written as

$$-d\varphi = \left(\frac{\Delta S}{2\pi r}\right) d\theta \tag{B6}$$

Also the motion of the nozzle must be such that since the mass flow of particles from the nozzle is constant, to avoid over (or under) peening, the tank rotational velocity must be varied in such a manner that the nozzle velocity along the inside surface of the tank is constant. This velocity is given by

$$v = \sqrt{\left(\frac{dS_\varphi}{dt}\right)^2 + \left(\frac{dS_\theta}{dt}\right)^2} = \text{Constant} \tag{B7}$$

where

$$-\frac{dS_\varphi}{dt} = r\,\frac{d\varphi}{dt}$$

$$\frac{dS_\theta}{dt} = r \sin\varphi \frac{d\theta}{dt} = r\omega \sin\varphi$$

and S_θ is a distance measured in the $\hat{\theta}$ direction. Now from equation (B6)

APPENDIX B

$$-\frac{d\varphi}{dt} = \left(\frac{\Delta S}{2\pi r}\right)\frac{d\theta}{dt} = \left(\frac{\Delta S}{2\pi r}\right)\omega$$

so that equation (B7) may be written as

$$v = r\omega\sqrt{\left(\frac{\Delta S}{2\pi r}\right)^2 + \sin^2\varphi} = \text{Constant} \tag{B8}$$

From equation (B8) the velocity v, at $\varphi = \pi/2$, is given by

$$v = r\omega_o\sqrt{\left(\frac{\Delta S}{2\pi r}\right)^2 + 1}$$

where ω_o is simply the rotational velocity at which the cylindrical portion of the tank was peened. Therefore, equations (B3) and (B7) are satisfied by the simultaneous solution of equations (B6) and (B8), respectively, written as

$$-\dot{\varphi} \equiv \frac{d\varphi}{dt} = -\left(\frac{\Delta S}{2\pi r}\right)\omega \tag{B9}$$

$$\omega = \frac{\omega_o\sqrt{\left(\frac{\Delta S}{2\pi r}\right)^2 + 1}}{\sqrt{\left(\frac{\Delta S}{2\pi r}\right)^2 + \sin^2\varphi}} \tag{B10}$$

By eliminating ω from equations (B9) and (B10), separating variables, and evaluating the elliptic integral

$$-\int_{\varphi_o}^{\varphi(t)}\sqrt{\left(\frac{\Delta S}{2\pi r}\right)^2 + \sin^2\varphi}\; d\varphi = \left(\frac{\Delta S}{2\pi r}\right)\omega_o\sqrt{\left(\frac{\Delta S}{2\pi r}\right)^2 + 1}\int_{t_o}^{t} dt \tag{B11}$$

it is possible to obtain values of $\sin^2\varphi(t)$ and, therefore, from equations (B9) and (B10), to obtain values of $\omega(t)$ and $\dot{\varphi}(t)$.

Fortunately, for all the tanks considered $\Delta S/2\pi r \leqq 0.02$ and it was found that equation (B11) could be integrated in closed form to a high degree of accuracy to obtain

$$\sin^2\varphi(t) \approx 1 - \left(\frac{\Delta S}{2\pi r}\right)^2 \omega_o{}^2(t - t_o)^2$$

$$\varphi(t_o) = \frac{\pi}{2}$$

Thus, $\dot{\varphi}(t)$ and $\omega(t)$ became

$$\dot{\varphi}(t) \approx \frac{-\omega_o\left(\frac{\Delta S}{2\pi r}\right)}{\sqrt{1 + \left(\frac{\Delta S}{2\pi r}\right)^2\left[1 - \omega_o^2(t - t_o)^2\right]}} \tag{B12}$$

$$\omega(t) \approx \frac{\omega_o}{\sqrt{1 + \left(\frac{\Delta S}{2\pi r}\right)^2\left[1 - \omega_o^2(t - t_o)^2\right]}} \tag{B13}$$

Equations (B12) and (B13) were used to obtain values of $\dot{\varphi}$ and ω as functions of time which were plotted on the drum-type programers to control the lance arm movement and tank rotation for the peening of the hemispherical domes.

The peening of the cylindrical section was accomplished by using equations (B1) and (B2). The use of these equations facilitated the uniform peening of the titanium spacecraft tanks.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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