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**PILOT PRODUCTION OF POWDER FORGED STEEL COMPONENTS
FOR THE 25-mm M242 CHAIN GUN**

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19. ABSTRACT (CONT.)

Powder forging was shown to be a viable manufacturing process for this type of component. The blueprint design requirements for the sprocket were achieved. The requirements in the military specification were also met and found to be reasonable from the perspective of a powder forging manufacturer.

The next step in the implementation process will be qualification testing of powder forged components, including field testing and comparison with the performance of the currently used wrought product.

During the course of the program, data were developed on sintering powder metal parts in a dissociated ammonia atmosphere enriched with natural gas (methane).

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INTRODUCTION

Powder forging manufacturing technology is now well established. The process is well understood and its feasibility has been demonstrated. Several types of parts are currently produced on a commercial basis, particularly for automotive applications.¹ However, for powder forging to achieve its full potential as a metalworking process, two barriers must still be overcome.

First, there must be a clearly defined and widely promulgated set of decision criteria so that design engineers will understand the capabilities of the process and will know when a powder forged part is appropriate for a given application.

Second, there must be an accepted standard so that powder suppliers, powder forging manufacturers, and users of powder forged parts can develop mutually acceptable expectations. Specifically, in the case of 4600 series alloy steels, the subject of the present program, such a standard would allow the substitution of powder forged steels for conventional wrought steels.

These issues were initially addressed through ARDEC Contract DAAK10-84-C-0022 entitled "Military Process Specification for Type 46XX Powder-Forged Weapon Components." In this program, four components were selected as primary candidates for powder forging. This selection was made on the basis of geometry and anticipated finish machining requirements after detailed review of thirty part designs. This earlier program also developed the data base to begin a military specification for series 4600 alloy steel powder forgings. It is anticipated that the inspection methods contained in this specification will be incorporated into ASTM Standard Test Methods. A copy of the current draft of this military specification is included as an appendix to this report.

The purpose of the present program was to continue this work of selection criteria and standardization. The program plan included powder forging of two of the components previously selected as primary candidates for powder forging. The components, shown in Figures 1 and 2, were the aft feed sprocket and the drive sprocket for the 25 mm M242 chain gun. The powder forging of these parts was intended to further build the experience base with components which had been found to be the best candidates for powder forging. Thus, actual forging experience could be compared with the theoretical analysis done earlier, thereby refining the criteria for selection of powder forged parts. Production of the components was designed to be in accord with the draft military specification, thereby serving as a trial of the utility of the specification as applied to actual powder forging operations.

RAW MATERIAL

Water atomized, prealloyed 4600 series steel powder (marketed under the tradename Ancorsteel 4600V) was procured from Hoeganaes Corporation, a large, well-known powder producer. The chemical composition of the powder met the specification for the 4600 grade and is given in the Quality Assurance section of this report. The sieve analysis reported by the powder supplier is shown in Table 1.

After the powder was received, it was decided to sieve out the particles larger than 100 mesh. It was believed that this would result in more uniformity throughout the compacted preform and that a finer, more uniform powder would specifically aid in maximizing the density at the tips of the four arms of the aft feed sprocket. Sieving the powder also limited the maximum size of non-metallic inclusions that could be present in the microstructure.

The powder supplier reported inclusion content in terms of average number of particles per 100 mm² (0.16 inch²) area as 101 particles greater than 30 micrometers (0.0012 inch), 3.3 particles greater than 100 micrometers (0.004 inch), and 0.83 particles greater than 150 micrometers (0.006 inch). Iron contamination was less than 1 weight percent. These data were obtained by the methods prescribed in the draft military specification appended to this report. Inclusions are further discussed in the Quality Assurance chapter of this report.

Carbon was added to the alloy steel powder by blending with natural graphite. Prior to mixing with the alloy powder, the carbon powder was placed in a vacuum chamber (furnace) to be sure that it was completely dry, i.e. free of any adsorbed moisture. The powder was heated slightly to 38°C (100°F) to enhance its outgassing while under vacuum.

A powder mix lot of 0.59 weight percent graphite in 4600 alloy powder was blended for production of the aft feed sprockets. The amount of powder blended was sufficient to produce fifty-nine (59) compacted preforms to meet all program requirements for deliverable prototype parts and in-process samples. The 0.59 weight percent carbon level was based on the results of sintering and forging trials detailed in the Forge Process section of this report. No lubricant (e.g. zinc stearate) was admixed to the powder since the die walls of the compaction die were lubricated directly.

A prototype powder mix lot for the drive sprocket was not blended because the forge tooling for the drive sprocket failed during setup trials and no prototype drive sprockets were produced. This is described further in the Forge Process section of this report.

TOOLING DESIGN AND OPERATION

A compaction die set and a forge die set were designed and built for each of the components to be powder forged (i.e. the aft feed sprocket and the drive sprocket). Some modifications were also made to the forge die nest which holds the forge dies in the forging press.

For each component, the design of the forge dies was based on the dimensions of the finished part. Then, based on the forge die designs, the compaction die sets were designed.

Forge Tooling Design

The design methodology for precision forge tooling has been well established. The general concepts are reviewed below. These provide a framework for specific details regarding the aft feed sprocket and the drive sprocket which follow.

General Concepts

For each component, the forge die set consisted of an upper and lower punch and a die ring. The die set for the drive sprocket included a core rod so that the bore could be forged.

The die rings and the core rod for the drive sprocket were designed so that the corresponding portions of the forgings would be produced to net shape. Specifically, the contours of the arms of the aft feed sprocket and the sprocket teeth and internal spline of the drive sprocket would require no subsequent machining. Machining of these complex surfaces is relatively expensive. The capability to forge these surfaces to net shape and avoid the cost of machining provides much of the motivation for the powder forging approach.

Because the surfaces of the powder forging formed by the die ring, and core rod in the case of the drive sprocket, were to be net forged, the forge dies were designed with no draft allowance. (In traditional forging practice, vertical surfaces are modified by a draft angle to facilitate removal of the forging from the die.) The lower punch was included in the design to provide for the increased ejection forces required with no draft angle. With the lower punch, the ejection forces were distributed over the entire lower surface of the forging.

The major portion of the forging die design analysis was devoted to determining appropriate dimensions for the ring dies and core rod so that net shape would be achieved. Net shape die design concepts for powder forging have been well-established in previous work (e.g. Ref. 2). The application of the design methodology to the drive sprocket and aft feed sprocket was developed as follows.

It was assumed that for these two parts, only temperature effects on dimensions were important, i.e. thermal contraction of the part and thermal expansion of the tooling. Specifically:

It was assumed that the forged part geometry conformed perfectly to the die cavity geometry at the instant the forging was completed. The thickness of the lubricant layer and any oxide layer was neglected.

The elastic compliance or distortion of the die cavity due to the forging loads was neglected.

The elastic expansion or "springback" of the forged part after it was removed from the die cavity was neglected.

Thermal gradients within the workpiece (preform) were neglected. Actually, the surface of the workpiece starts to cool as soon as it is removed from the furnace. It cools at a faster rate when it is in contact with the tooling which is at a lower temperature. It continues to cool after forging prior to ejection. An average workpiece temperature was estimated to calculate the tooling dimensions.

For the type of geometry and tolerance requirements of the parts in this program, detailed analysis and actual forging experience have shown that it is reasonable to consider only the effect of temperature on workpiece dimensions. Temperature effects are more significant than the effect of the other variables which were neglected.

The equation used to calculate an ambient temperature die cavity dimension (D_D) corresponding to a part dimension (D_P) is

$$D_D(1 + \alpha_D \Delta T_D) = D_P(1 + \alpha_P \Delta T_P) \quad (1)$$

where the subscripts D and P refer to the die and part respectively, α is the linear coefficient of thermal expansion, and ΔT is the difference between the ambient and operating temperature. As indicated above, this equation is based on the die cavity dimensions being equal to the part dimensions at the instant the forging is completed. Therefore, the temperature of the die and the temperature of the part just prior to ejection must be known or estimated. (Except in the special case of isothermal forging, these temperatures are different.) These values can be substituted in the equation, along with the desired ambient temperature part dimension, to calculate an ambient temperature dimension of the die.

Rearranging the equation in this way yields

$$D_D = \frac{D_P(1 + \alpha_P \Delta T_P)}{(1 + \alpha_D \Delta T_D)} \quad (2)$$

The values of thermal expansion coefficient for 4600 alloy steel and H-13 die steel are

$$\alpha_p = 13.5 \times 10^{-6} \text{ mm/mm/}^\circ\text{C} = 7.5 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

$$\alpha_D = 11.7 \times 10^{-6} \text{ mm/mm/}^\circ\text{C} = 6.5 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

The forge dies were to be preheated to 177°C (350°F). For an ambient temperature of 21°C (70°F) then

$$\Delta T_D = 156^\circ\text{C} = 280^\circ\text{F}$$

Through the above analysis, design of the forge die cavity was reduced to estimating the average temperature of the part at the point of die closure.

Aft feed sprocket

Through heat transfer analysis and previous forging experience, the temperature of the aft feed sprocket at the completion of the forging process was estimated to be approximately 600°C (1112°F). This compares with a sintering temperature of 1205°C (2200°F). Chilling of the aft feed sprocket in the forge die was very significant because the aft feed sprocket is a relatively thin part, with a thickness of only 8 mm (0.315 inch). With this estimate of part temperature

$$\Delta T_p = 579^\circ\text{C} = 1042^\circ\text{F}$$

Substituting into equation 2 yields

$$D_D = (1.006)D_p \quad (3)$$

Thus, the die cavity dimensions for the aft feed sprocket were expanded from the part dimensions by a factor of 1.006.

The potential for thermal distortion of the arms of the aft feed sprocket was recognized due to their relatively long thin cross section. A machining allowance of 0.75 mm (0.030 inch) was provided for surface grinding each side of the aft feed sprocket after forging.

Drive Sprocket

The temperature of the drive sprocket at completion of forging was estimated to be 955°C (1750°F). Chilling of the drive sprocket was considerably less than the aft feed sprocket due to the larger mass and thicker cross section. With this estimate of part temperature

$$\Delta T_p = 934^{\circ}\text{C} = 1681^{\circ}\text{F}$$

Substituting into equation 2 yields

$$D_D = (1.011)D_p$$

Thus, the die cavity dimensions for the drive sprocket were expanded by a factor of 1.011.

Potential problems with contraction around the core rod were recognized and the core rod was designed integral with the upper punch so that it was removed from the forging as quickly as possible.

Forge Tooling Operation

The forge tooling fixture (die nest) is shown in Figure 3. This fixture was used for both the drive and aft feed sprocket tooling. The following paragraphs, aided by Figures 4 through 8, will describe how the tooling functions to manufacture a finish forged component. The description will begin with the drive sprocket forging process.

Referring to Figures 4 and 5, one can see the punch insert in the punch half of the tooling fixture along with the core rod that will form the internal splines of the forged part. The die insert is located in the die half of the tooling fixture. These two pieces of tooling engage with the die ring which is also located in the die half of the forge fixture. These three pieces of tooling function together, along with the core rod, to produce the final forged shape in the sintered preform. Photographs of these basic components are shown in Figure 6. In this figure, the die ring is located in the center, the die ring holder is shown at the left, and the upper punch, with core rod, and lower punch are shown engaged at the right as they would be at final forge position within the die ring.

The kinematic motion of the tooling is very straightforward. The punch fixture which is mounted on the press ram, travels downward in a straight path causing the core rod and upper punch to engage with the die ring and lower punch, as shown in the photograph. At press bottom dead center, the distance between the upper punch and lower punch should be at final part dimension. At this position the preform material will have flowed into the sprocket tooth forms and also filled

into the internal spline recesses machined onto the core rod. As the press completes its cycle, causing the upper punch and core rod to retract from the die ring, the forged part will remain in the die ring. After the cycle has been completed and the ram is again at top dead center, the ejector linkage raises the lower punch through the die ring causing the forged component to be exposed above the tooling fixture kiss pads so that the part may then be manually removed. The linkage is then withdrawn back into its original position in preparation for the next forging.

The aft sprocket forge tooling functions in a very similar manner to the drive sprocket tooling with the exception being that there is no core rod. The aft feed sprocket tooling is shown schematically in Figure 7. The essential components of this schematic are photographed in Figure 8. The die ring is on the left, next the upper punch, the die ring holder, and on the right is the lower punch. Note that the upper and lower punches are shown with protective coating on the forging surfaces. (The coating protects the precision surfaces of the tool during shipping and handling, but is removed prior to forging.)

As with the drive sprocket kinematics, the punch travels down in a straight motion and the upper punch engages with the die ring causing the preform to be forged within the space created by the upper punch, lower punch and die ring. After the punch travels to bottom dead center and cycles back to its starting position, the ejector mechanism raises the lower punch causing the part to rise above the fixture kiss pads so that the finished part can be manually extricated. The ejector linkage then retracts causing the lower die to reseal in preparation for the next forging cycle.

Compaction Tooling Design

The first consideration in designing the compaction tooling is that the preform must easily fit into the forge die cavity when it is heated to forging temperature. Furthermore, the preform must undergo sufficient deformation during forging to eliminate porosity, but the deformation and state of stress must not be such that the preform ruptures.

The volume of the preform will be greater than the volume of the forging because the preform is porous. However, the mass of the preform must be precisely controlled. If the preform is too massive, the forge tooling could be damaged by the extra material. If the preform is not large enough, the forging will not be filled and/or will not be fully dense.

Control of preform density is also important because too great of a compacted density would eliminate interconnected porosity which is required to flush the preform of oxide reduction by-products during sintering. Too low of a compacted density would result in cracking during forging and would also promote reoxidation as the forging was transferred from the furnace to the forging press.

For each component, the compaction die set consisted of an upper and lower punch and a die ring. The die set for the drive sprocket included a core rod so that the bore could be formed.

Aft Feed Sprocket

For the aft feed sprocket, a minimum deformation forging process was used. As discussed with respect to the design of the forge tooling, the preform chills rapidly due to its thin cross section, so the amount of deformation possible was limited. Therefore, a preform similar in shape to the final forging was designed by allowing for a clearance of 0.38 mm (0.015 inch) between the perimeter of the preform and the forge die ring. In calculating the dimensions of the preform to provide the clearance, the thermal expansion of the preform at the forging temperature, 1205°C (2200°F) was calculated using the thermal expansion coefficient given previously.

The preform was of uniform thickness. The thickness was calculated so that the volume of metal in the compact, V_C , would be equal to the volume of the forging, V_F . Expressing the density of the compact, ρ_C , as a percentage gives

$$\begin{aligned}(V_C)\rho_C &= V_F \\ t_C A_C \rho_C &= t_F A_F \\ t_C &= (1/\rho_C)(t_F A_F/A_C)\end{aligned}\tag{4}$$

where the subscripts C and F refer to the compact and forging respectively, t is the thickness, and A is the area. For this calculation, the thickness and area are taken at ambient temperature.

A computer aided design (CAD) system was used to calculate the areas of the finish forging and the preform. A compacted density of 80 percent was assumed. The compaction tooling was designed so that thickness could be adjusted to compensate for a compacted density different than 80 percent. The ring die was deep enough to allow for the required amount of powder at an assumed fill density of 38 percent.

Drive sprocket

A ring shaped preform was designed for the drive sprocket. With this type of preform, the internal spline and external teeth of the drive sprocket are formed entirely by lateral flow during forging. The external diameter of the ring was calculated to allow sufficient clearance so that the preform could be dropped into the die cavity of the forge tooling. The internal diameter of the ring was calculated to provide clearance for core rod of the forge tooling.

The height (thickness) of the preform was calculated in a manner similar to that described above for the aft feed sprocket, again assuming a preform density of 80 percent. However, instead of using a CAD system to calculate the area of the drive sprocket, the total area was divided into several regions and the mathematical functions defining the perimeter were integrated.

Compaction Tooling Operation

The compaction tooling operates with the objective of achieving uniform compaction throughout the preform by evenly compacting from both the top and the bottom of the charge. This function will be explained further in this section. The compaction fixture used to press both the drive sprocket and aft feed sprocket preforms is shown in Figure 9. In this photograph the aft feed sprocket tooling is in the fixture. Note that the bulk of the tooling comprises the die half of the fixture while the punch is sitting upside down on top of the die fixture surface.

Schematics of the compaction tooling for the drive sprocket and aft feed sprocket are shown in Figures 10 and 11, respectively. The essential components of both sets of tooling are the upper punch, lower punch and die ring. These three components for the aft feed sprocket are photographed in Figure 12.

In Figures 10 and 11, the die ring is fixtured in a floating die holder. This holder is supported by four air cylinders. This apparatus is key to achieving uniform compaction from both the top and bottom of the charge.

The following is the sequence of events necessary to compact a preform. (Refer to Figure 10 or 11.) The upper punch is retracted and is at the top of its stroke. The die ring is raised, by means of the air cylinders, to the proper fill height. Mechanical stops, not shown, determine where the die ring assembly stops. The lower punch does not move, thus the fill height is determined by the amount of travel of the die ring assembly.

The loose powder is poured into the open cavity and any excess is wiped away by a stainless steel straight edge. The punch comes down, activated by a large hydraulic cylinder. As the punch enters the cavity, it can be observed that the top portion of the charge tends to compact first. After the punch has entered the tooling by the amount ΔX , the two posts on the punch proceed to force the die ring assembly downward, overcoming the air cylinder resistance. This causes the die ring to travel downward over the lower punch. The net effect is that the lower punch appears to travel into the die ring after the upper punch has also traveled into the die ring. With this method, compaction has been achieved by moving both the upper and lower punch into the die ring, achieving as uniform compaction as possible at both ends of the preform. This process is shown in Figure 13.

After compaction, the upper punch is withdrawn. The air-cylinder pressure is reversed, causing the die ring assembly to be lowered to its extreme position. Since the lower punch is fixed, the preform is exposed as the die ring is lowered; this method of ejection is identical to that of a withdrawal press. At this point, the operator may manually remove the preform. Figures 14 and 15 are photographs of the die fixture with the floating die holder in the down position exposing the lower punch. In both photographs, the preform was previously removed.

POWDER FORGING MANUFACTURING PROCESS

The powder forging manufacturing process for the aft feed sprocket consisted of the following operations:

1. Compact powder (after blending graphite, as described in the Raw Material chapter)
2. Sinter compacted preforms
3. Forge sintered preforms
4. Drill bore hole
5. Restore carbon
6. Heat treat to required hardness
7. Finish machine - surface grind, ream and chamfer bore

The processing of the drive sprocket was similar to that of the aft feed sprocket, except the internal spline in the bore was to be forged net. Details of each of the above listed operations are given in subsequent paragraphs and differences in the processing details between the two parts are noted. Unfortunately, the core rod of the forge tooling for the drive sprocket failed during tooling setup trials, so no finished drive sprockets were produced.

Compacting Powder

Procedures for compacting the powder were similar for both the aft feed sprocket and the drive sprocket and were typical of established powder forging practice. The compaction tooling was installed in a 1.33 MN (150 ton) hydraulic press. Prior to pressing of each preform, the compaction tooling was lubricated with zinc stearate applied via an acetone carrier.

For this experimental program, in which the required number of prototypes was relatively small, the most effective way to control the preform mass was to weigh the powder for each preform individually prior to compaction. In this way, the preform mass was controlled to within ± 1 g. This corresponded to approximately ± 0.4 percent of the total preform mass of 240 g for the aft feed sprocket.

Mechanical stops were set on the die assembly to achieve a compacted density of approximately 80 percent. As noted with respect to the design of the compaction tooling, control of density is important because too great of a compacted density would eliminate interconnected porosity which is required to flush the preform of oxide reduction by-products during sintering. Too low of a compacted density would result in cracking during forging and would also promote reoxidation as the forging

was exposed to the open atmosphere during transfer from the furnace to the forging press.

The total compacting load for the aft feed sprocket was 1.1 MN (125 tons). This corresponded to a compacting pressure of 370 MPa (27.2 tons/inch²) over the 30 cm² (4.6 inch²) area of the aft feed sprocket preform. This is slightly less than the pressure of approximately 410 MPa (30 tons/inch²) found to be necessary to compact 4600 powder to the 80 percent density level in previous powder forging work. This can be explained because the thin cross section of the aft feed sprocket would develop relatively less friction with the walls of the compacting die.

In compacting the drive sprocket preform, the hydraulic press was operated to generate a total load of 0.89 MN (100 tons). For a pressure of 410 MPa (30 tons/inch²) over the 11 cm² (1.75 inch²) area of the drive sprocket preform, only 0.49 MN (55 tons) would have been required. The excess load was supported by the mechanical stops in the die set. As indicated above, the thickness of the preform, and therefore its density, was controlled by weighing the powder and setting mechanical stops in the die set. Compacting pressure was not used as a control variable.

Sufficient aft feed sprocket preforms were compacted to provide pieces for sintering trials, forging setup, in-process samples, metallographic and quality evaluation samples, setup pieces for the finish machining operations, and deliverable prototype parts. There was concern regarding the density at the ends of the arms of the aft feed sprocket preforms due to the tight radii there. During filling of the compacting die, a small spatula was used to physically push as much powder as possible into the corners. This procedure was acceptable for a relatively small number of prototype parts. Another method to assure adequate powder at the tips of the arms would be required in production.

As previously noted, the forge tooling for the drive sprocket fractured and no finished drive sprockets were produced. Relatively few drive sprocket preforms were compacted, a number sufficient only to verify the operation of the compaction tooling and to provide workpieces for setup of the drive sprocket tooling prior to its fracture.

Sintering Preforms

As described in the Raw Material chapter, a prototype powder mix lot of 0.59 weight percent graphite 4600 alloy powder was blended for production of the aft feed sprockets. The blend composition was based on the results of sintering trials.

Sintering Process

The material specified for the aft feed sprocket is 4640 alloy steel, nominally 0.40 weight percent carbon. Excess carbon was blended with the powder to

allow for carbon loss in deoxidizing the powder during sintering. Deoxidation was confirmed by comparison of the oxygen content of the powder with that after forging, as detailed in the Quality Assurance chapter.

The average decrease in oxygen content during sintering was found to be 0.155 weight percent. This corresponds to a decrease in carbon of 0.12 weight percent, assuming deoxidation by formation of carbon monoxide (CO) only. However, the observed decrease in carbon content after forging was significantly higher, indicating that significant decarburization was occurring, beyond that associated with deoxidation of the powder.

The preforms had been placed within a nickel base superalloy muffle which had been inserted into the sintering furnace. The muffle was used to prevent reaction between the ceramic lining of the sintering furnace and the sintering atmosphere (although the furnace had been well-conditioned) and to minimize leaks into the sintering atmosphere. The muffle had its own door in addition to the door of the sintering furnace itself.

The cross section of the muffle was approximately 200 mm (8 inches) square and it was approximately 1.2 m (48 inches) long. The preform was placed at the approximate midpoint of the muffle, midway between the atmosphere gas entering the muffle at the rear and the door at the front of the muffle. Parts were loaded into the sintering furnace and removed manually with tongs. Due to concern about the mixing of the sintering atmosphere with the outside air while the doors were opened, the preforms were sintered one at a time. Thus, the preform was only exposed to the atmosphere when it was placed into the muffle and when it was removed. Sintering the preforms one at a time also assured a consistent sintering time.

The steps of sintering and preheating for forging were combined. That is, the preforms were transferred from the sintering furnace directly to the forging press. The sintering cycle was 20 minutes at 1205°C (2200°F). The sintering atmosphere, which was introduced directly into the muffle, was composed of 5 volume percent hydrogen with the balance nitrogen. The dew point was measured and found to be no greater than -43°C (-45°F). This level of dew point had been found to be acceptable in previous powder forging work.

As indicated above and in spite of the sintering procedures employed, which had been found to be successful in previous programs, the forgings were excessively decarburized. A carbon restoration heat treatment was required and is described in a subsequent section of this chapter.

It is believed that the excessive decarburization occurred during removal of the preform from the sintering furnace and transfer to the forging press. Textron does not have any facilities to provide a protective atmosphere to the preform during this transfer. In the past, the protection afforded by the sintering atmosphere trapped in the pores of the preform had been sufficient. Approximately two to three seconds (and sometimes longer) were required to reach into the muffle with the tongs and remove the preform. Approximately seven seconds were required to transfer the preform to the forging press and orient it properly to fit into the tooling. The thinness of the preform made it more difficult to grab with the tongs and its shape was more difficult to insert in the forging die cavity in comparison

with a cylindrical preform. Its relatively high surface to volume ratio would have promoted decarburization through reaction with the air.

This hypothesis is consistent with an investigation conducted by Hoeganaes Corporation⁶. For preforms compacted to approximately 80 percent density, sintered at 1120°C (2050°F), and exposed to air for varying times, decarburization was measured for exposure times greater than 8 seconds. Furthermore, oxidation started immediately upon exposure to the air. Due to the higher sintering temperature of 1205°C (2200°F) employed with the aft feed sprockets, the critical time for decarburization would have been less than that reported by Hoeganaes for the 1120°C (2050°F) sintering temperature.

Hoeganaes also found⁶ that a graphite coating was helpful in preventing oxidation and decarburization of the preforms during exposure to air. However, in the case of the aft feed sprocket, a graphite coating was tried and it was found that the coating reacted with the metal to form a solution at the surface whose melting point was less than the sintering temperature, 1205°C (2200°F). This is in accord with the iron-carbon phase diagram. The iron-carbon eutectic point occurs at approximately 4.26 weight percent carbon and 1150°C (2102°F).

Decarburization during the sintering process itself cannot be completely ruled out. While the procedures employed for sintering had been successfully employed in the past, there is very little data in the literature regarding gas - metal equilibria in multi-component systems at sintering temperatures. Most of the gas - metal equilibrium data has been developed for carburization heat treatment, which is conducted at lower temperatures. Specifically, the relatively high sintering temperature of 1205°C (2200°F) may require a sintering atmosphere with an even lower dew point than the -43°C (-45°F) measured in this case.

Sintering Process Development Data

In the initial portion of the program, before it had been concluded that decarburization was occurring during transfer to the forging press, some sintering trials were conducted with a dissociated ammonia (75 volume percent hydrogen/25 volume percent nitrogen) sintering atmosphere enriched with different levels of natural gas. (It should be noted that natural gas is not pure methane, but can contain small amounts of other hydrocarbons such as propane or inert gases such as nitrogen. Natural gas was added to the furnace atmosphere rather than a laboratory grade of purified methane because natural gas is what would most likely be used in a production situation.) The purpose of the natural gas enrichment was to counteract the decarburizing effect of hydrogen by itself and of whatever water vapor was present in the furnace atmosphere.

Although the sintering process employed for the prototype parts did not include natural gas enrichment, the results of these trials are included in this report, as they may be of value in other powder forging applications.

Theoretical Background. It is recognized in the literature that an atmosphere such as dissociated ammonia can be decarburizing, especially in the presence of moisture, as indicated by the following quotation:

"An inspection of reaction VII, $\text{Fe} + \text{CH}_4 = [\text{Fe}, \text{C}] + 2\text{H}_2$, between a solid solution of carbon in austenite and hydrogen forming low carbon austenite and methane would lead to the conclusion that sintering an iron-carbon alloy in pure hydrogen or dissociated ammonia, both of which are practically free of methane, should lead to decarburization of the iron-carbon alloy. On the basis of thermodynamics this reaction would certainly be expected. However, it has been found that, if the hydrogen or dissociated ammonia is sufficiently dry, the decarburizing reaction is very slow. Iron-carbon compacts may be sintered in dissociated ammonia with only minimal decarburization during the usual sintering times, if care is taken that the dewpoint in the sintering furnace stays sufficiently low. The use of such an atmosphere involves a risk, since its carbon potential is not in thermodynamic equilibrium with the activity (concentration in weight percent) of the carbon in the steel, while during sintering in endothermic gas, thermodynamic equilibrium between atmosphere and the iron-carbon compacts may be maintained."⁴

Figure 16⁵ shows the Fe-C-H equilibrium diagram. While there is no data plotted for a carbon composition of 0.4 percent at 1205°C (2200°F), extrapolation would indicate that the appropriate amount of methane is somewhat less than 0.1 percent. This is somewhat less than the amount used in the sintering trials, which were based on experience and review of the literature as well as theoretical analysis. The difference can be explained by the fact that equilibrium conditions are not always maintained during sintering and that furnace atmospheres are not mixed uniformly in the vicinity of the workpieces. It should be noted that Figure 16 corresponds to a base atmosphere of pure hydrogen. Actually, a dissociated ammonia base atmosphere was used. This would shift the curves to the left. There does not appear to be much additional thermodynamic data in the literature for dissociated ammonia base atmospheres at high temperatures.

The carbon content of powder compacts during sintering is dependent upon a complex combination of inter-related factors which include:

1. The carbon potential of the atmosphere, which in turn is based on its temperature and composition, including dew point

2. Flow rate of the atmosphere through the furnace. If the flow rate is low relative to the volume of the furnace, the concentration of reaction products may increase and shift the equilibrium. If the flow rate is high, the flow may generate thermal gradients in the furnace

3. Sintering time, to the extent that carburization or decarburization require a finite time to occur

4. Sintering temperature, which affects the carbon equilibrium, the diffusion rate, and the rate of chemical reactions, including the reaction of carbon to reduce oxides in the powder as well as the reaction of carbon with the sintering atmosphere

Experimental data. In an attempt to prevent the decarburization of the preforms, a series of trials was conducted with a dissociated ammonia sintering atmosphere enriched with different levels of natural gas. All of the trials employed aft feed sprocket preforms. However, the muffle which was inserted into the furnace for sintering of the prototype sprockets as previously described was not used for these sintering trials. The experimental matrix and results of the trials are shown in Table 2. As detailed in the table, the volume percent natural gas, flow rate through the sintering furnace, sintering time, and weight percent of blended carbon were all varied systematically.

The results of the sintering trials must be interpreted with care. As previously indicated, it is believed that at least some of the decarburization which was observed occurred during the transfer of the preforms from the sintering furnace to the forging press. Furthermore, leaks in the furnace seemed to be causing a high dew point in the furnace atmosphere and the dew point increased with temperature. A dewpoint of -7°C (20°F) was measured at 538°C (1000°F) vs. approximately 6°C (42°F) at 871°C (1600°F) and 16°C (60°F) or higher at 1093°C (2000°F) and above. It was not believed that these high dew point readings were due to leaks in the sampling lines because the fittings on the sample lines were sealed to prevent leakage and the dewpoint of 16°C (60°F) observed at the sintering temperature corresponded to a moisture level higher than that of the ambient air.

The dew point of the incoming dissociated ammonia was acceptable. Readings of -49°C (-57°F) and -62°C (-80°F) were obtained respectively on two occasions. (A small amount of residual moisture in the instrument or sampling line might have been responsible for the higher reading.) Thus, leaks in the furnace, which would result in additional moisture due to reaction of the oxygen in the air with the furnace atmosphere, or reactions of the atmosphere with the furnace lining were suspected. It was noted that variations in the gas flow into the furnace in the range 0.39 L/s and 1.57 L/s (50 cfh and 200 cfh) did not change the observed dew point significantly.

Several trends can be discerned in the chemical analysis data of Table 2. First, considerable scatter was noted in the cases in which multiple readings of carbon content were obtained. Also, there was not a consistent relationship between the carbon blended in the powder and the carbon content after sintering and forging. The analysis of carbon was accurate to within ± 0.01 weight percent. The scatter was due to non-uniformity in the microstructure as the decarburization was most severe at the surface. Each chemical analysis reading corresponds to a small amount of material, approximately 1 g.

There did not seem to be any clear effect on the carbon content associated with change in gas flow rate or sintering time. For no natural gas

addition to the atmosphere and for the levels of natural gas below 2.0 volume percent, the preforms were decarburized. At a level of 2.0 volume percent natural gas enrichment, the preforms were carburized. The exact amount of carbon gained with 2.0 volume percent natural gas is difficult to assess due to the scatter in the data. In addition to being carburized during sintering, these preforms were also most likely decarburized during transfer to the forging press.

One anomaly appeared in the results of the baseline sintering trials, with no natural gas addition. As shown in Table 2, a control sample (#13) with no blended carbon was processed and analyzed. The analysis indicated a carbon content of 0.028 weight percent carbon. This was not consistent with the analysis of the powder supplied by the vendor which indicated a carbon level of less than 0.01 weight percent. In contrast, the analysis of trial #23 showed only 0.012 weight percent carbon, despite being sintered in an atmosphere of 0.75 volume percent natural gas.

Metallographic samples were prepared from forgings #21, #26, and #27. There was a relatively deep but non-uniform decarburized layer on each sample. The depths of decarburization which were measured ranged from 0.28 mm (0.011 inch) to 1.14 mm (0.045 inch). The metallographic analysis also revealed significant surface oxidation, including oxide networks and surface finger oxides. This was consistent with the relatively high oxygen readings which were obtained. Oxidation of the metal would have occurred under the same circumstances as the decarburization.

While the carbon level achieved with 2.0 volume percent natural gas had suggested that methane enrichment could compensate for a high dew point in the furnace atmosphere, it was clear that the control required for the 4640 specification could not be achieved in this way. The decarburization, oxidation, and non-uniformity in the microstructure were all unacceptable.

To meet the quality requirements regarding chemical composition and to minimize delay in the program schedule, it was decided to insert a nickel alloy muffle into the furnace, flow the atmosphere gas directly into the muffle, and use a carbon restoration heat treatment to achieve the required carbon content. The purpose of using the muffle was to reduce the possibility of contamination of the sintering atmosphere by leaks from the outside. The potential for contamination of the atmosphere by reaction with the ceramic furnace lining should have also been eliminated. To avoid relocating the existing dissociated ammonia lines which service the sintering furnace, cylinder gas (5 volume percent hydrogen, balance nitrogen, and no natural gas) was used in the muffle. This composition had been used successfully in previous programs. The dew point was measured and found to be no higher than -43°C (-45°F), a level of dew point found to be acceptable in previous powder forging work.

Table 3 summarizes the results obtained with the muffle in sintering three preforms with differing carbon blends. While all of the samples met the oxygen requirement, none of them met the carbon requirement. Nevertheless, the use of the muffle did result in improvement in controlling the carbon level in the forgings. The carbon readings in forgings #29 and #30 were consistent and close to the 4640 requirement. However, loss of carbon was greater than that which would be anticipated from deoxidation of the powder alone and the higher carbon in the

powder mix of forging #30 was not reflected by a significant increase in carbon after sintering and forging. These observations indicated that there was still a general decarburization of the compact during sintering and/or during transfer to the forging press.

During the sintering of forging #28, the door to the muffle was inadvertently left off. The low carbon content of that sample confirmed that decarburization could occur due to contamination of the sintering atmosphere.

The sintering process previously described was based on the trials in the muffle. A powder blend of 0.59 weight percent carbon was chosen for the prototype parts. The sintering procedures established in the trials #29 and #30 were maintained. The metallographic evaluation of forgings sintered in the muffle is presented in the Quality Assurance chapter of this report.

Forging Preforms

For each component, the forge tooling was installed in the die nest previously shown in Figure 3. The die nest then was installed in a 6.3 MN (700 ton) mechanical crank forging press. This press generated a forging strain rate of approximately 10 s^{-1} , with a contact time under load of approximately 0.05 seconds.

Heated preforms were transferred manually directly from the sintering furnace to the forge dies. Thus, the nominal forging temperature was the same as the sintering temperature. Transfer time was less than 7 seconds for the aft feed sprocket and less than 5 seconds for the drive sprocket. Extra time was required to place the aft feed sprocket preform in the forge die due to the relative complexity of its shape.

As anticipated during the die design, the forge tooling was heated to approximately 176°C (350°F) with a combination of cartridge heaters and an auxiliary gas torch. Prior to each forging, the dies were sprayed with Acheson Colloids Company's "DeltaForge 182," diluted 2:1 with water. There was no buildup of the lubricant on the die or core rod walls. A small amount of buildup on the punch faces was manually removed as required.

The preforms were not coated prior to forging. A few trials had been run using a graphite coating on the preforms to provide additional lubrication and protection from oxidation during transfer from the sintering furnace. However, it was found that the graphite reacted with the surface metal to depress the melting point (iron-carbon eutectic). Small pools of molten metal were actually formed on the surface of the preform during sintering. Graphite coatings have been used satisfactorily in wrought forging. However, the porosity in a powder preform promotes the reaction with the coating.

Prior to production of the prototype forgings required under the program, trial or setup pieces were forged to achieve the proper thickness and full density. Because the tooling was designed to produce net-shape surfaces, there was no allowance for any excess material (e.g. forging flash). A preform which was too large would overload the tooling and the press itself. A preform which was too

small would result in underfill of some portion of the geometry and/or less than full density. Therefore, the setup process consisted of forging a series of preforms with small increases in mass until the required thickness and density were achieved. While the mass of the preform had been theoretically computed during the tooling design, some variation was found due to the tolerance variations. The setup of the forge tooling is complicated because the frame of a mechanical forge press stretches under the forging load and results in a slightly thicker forging than is expected based on the position of the dies themselves. Therefore, the setup must compensate for the compliance of the press frame and the load train.

Aft Feed Sprocket

Figure 17 shows a sintered preform and an as-forged part. As detailed in discussion of the tooling design, the shape of the preform is similar to that of the forging. The forging operation produces minimum deformation, primarily reducing the thickness of the preform to achieve full density.

It was found that there was some warping of the aft feed sprocket forging and that the top and bottom surfaces were not perfectly flat. Therefore, the thickness of the forging was increased to provide a machining allowance for a subsequent surface grinding operation. The complex contours of the arms were forged net as planned.

The sintering temperature (nominal forging temperature) was 1205°C (2200°F). The temperature of the top surface of the forging as it was ejected from the tooling varied between approximately 538°C and 816°C (1000°F and 1500°F) depending on the total elapsed time between removal of the preform from the sintering furnace and ejection of the forging from the die cavity. The estimate made during the tooling design was in this range. The variation in temperature at ejection was not great enough to significantly affect the dimensions of the forging. After removal from the tooling, the forgings were carefully laid on a flat surface and continued to cool in air.

Figures 18 through 20 show the forging operations in sequence. In Figure 18, the preform is being placed into the die cavity. In Figure 19, the forged part has been ejected. Note that the workpiece has chilled considerably in comparison with the radiant preform in Figure 18. Figure 20 shows the tooling with the lower punch raised, as it would be after the forging has been removed.

It should be noted that precision forgings are sometimes slowly cooled in sand or a similar material to minimize surface oxidation and achieve a slow cooling rate to minimize distortion and residual stresses. However, there would have been little benefit in cooling the aft feed sprocket forgings in this way as they had already cooled through the critical temperature regions while still in the tooling due to their thin cross section.

Drive Sprocket

The forge tooling setup procedure was described above in general terms. During the initial trials to setup the drive sprocket tooling, it was found that the internal and external teeth of the forgings were not completely filled due to the mass of the preform being slightly less than required. Forgings in which the external teeth were not well defined hampered progress because the forging tended to stick to the core rod (rather than remain in the die) and was not always easily removed.

During a subsequent trial with a slightly larger preform, the forging load became excessively high and the tooling was damaged. Flash was forced into the clearance between the core rod and the lower punch. That portion of the lower punch which was not constrained by the die ring was upset by the force of the forging.

Due to the flash and the upset of the lower punch, the force of the hydraulic ejector mechanism was insufficient to eject the forging from the die. The tooling was removed from the press and disassembled to extricate the forging and assess the damage. During this process, the core rod completely fractured. The fracture was located approximately where the core rod was drawn up against the lower surface of the upper die.

To meet program budget and schedule constraints, it was decided not to pursue forging of the drive sprocket. If this work is pursued in the future, two separate issues, non-fill of the sprocket teeth and fracture of the core rod, must be addressed.

As described above, the increased mass of a larger preform contributed to the high forging load which damaged the tooling. However, this load was still not sufficient to fill the sprocket teeth. For these initial setup forgings, the sintering temperature (and nominal forging temperature) was 1149°C (2100°F). A first step to achieve greater fill in the teeth would be to increase forging temperature to 1205°C (2200°F). The forging temperature for the aft feed sprocket was selected on this basis. If the higher forging temperature did not allow the teeth to be completely filled, the next step would be to redesign the compact to more closely match the external sprocket geometry. However, this would complicate the insertion of the preform into the forge tooling.

It is believed that the fracture of the core rod occurred through a low cycle fatigue mechanism. Tensile stresses are developed in the core rod as it is removed from the forging. The surface area of the internal spline of the drive sprocket is high compared with a circular hole and increases the force required to remove the core rod, and therefore the tensile stress. The removal force is further increased because as the forging cools, it shrinks around the core rod. Thermal stresses could also have developed in the core rod during the heating prior to forging. The design of the core rod might have contributed to the failure as well. Its toughness might have been unnecessarily low because it was fully hardened.

Thus, changes in the tooling design to prevent fracture of the core rod could include:

Revising the heat treatment specification to require only case hardening, thus providing increased toughness in the interior.

Redesigning to prevent stress concentration associated with the change in cross section of the core rod where it passes through the upper punch.

Eliminating the forging of the internal spline in favor of a slightly undersize bore. This would reduce the force required to remove the core rod from the forging and allow the spline to be broached as a secondary operation.

Redesigning the tooling to incorporate the core rod into the bottom die assembly. (This option would not be possible with the existing ejection system.)

Improving the speed of the ejection system and decreasing the time delay between withdrawal of the top punch from the die cavity and ejection. These changes would greatly reduce the thermal shrinkage and the force of the forging on the core rod.

Drilling Bore Hole.

The material condition after forging was such that the center holes could be drilled prior to carbon restoration and heat treatment. This was done to minimize the amount of hardened material to be removed after heat treatment. Drilling before heat treatment also allowed for more equal cooling between the arms and the center of the sprocket. Uneven cooling can generate internal stresses, leading to residual stress and distortion of the part.

Restoring Carbon.

As discussed above, the control of the sintering process was not adequate to maintain the required carbon content in the preforms. It was also suspected that some carbon was lost during the transfer of the preforms from the sintering furnace to the forging press. Therefore, the required carbon content was obtained by a deep (through the entire cross section) carburization treatment. In comparison with conventional carburization, the heat treatment industry has relatively little experience with carbon restoration of this type.

The carburization consisted of holding the parts in a gas carburizing furnace for 75 hours. This time was required to diffuse carbon through the as-forged part thickness of approximately 9.5 mm (0.37 inch). The carbon potential of the furnace atmosphere corresponded to at least a 0.40 percent carbon content in the steel. At the beginning of the carburization, a slightly higher potential was used ("boost and diffuse" cycle). The temperature of the furnace during the carbon restoration was initially 870°C (1600°F). It was increased to 925°C (1700°F) part way through the cycle, based on evaluation of in-process samples by the heat treater.

Heat Treating to Required Hardness.

After the carbon restoration cycle was completed, the aft feed sprockets were normalized by cooling to below 815°C (1500°F) in the furnace. The parts were then austenitized at 870°C (1600°F) for 1.5 hours and quenched in oil. Through a series of trials at successively higher temperatures, it was found that a temper at 510°C (950°F) would achieve the required hardness level. The tempering process was controlled so as to maintain the flatness of the parts. Figure 21 shows the forgings after heat treatment.

Finish Machining.

The final operations in the manufacture of the prototype aft feed sprockets were to grind the top and bottom surfaces and ream and chamfer the bore. As noted above, a machining allowance of 0.75 mm (0.030 inch) had been provided on each side of the forging. Removal of this layer eliminated any warping as well as any surface defects.

The part thickness and bore diameter were checked with calibrated gauges, as described in the Quality Assurance chapter. A finish machined aft feed sprocket is shown in Figure 22.

QUALITY ASSURANCE

The quality assurance plan included dimensional inspection, analysis of chemical composition, measurement of density, and evaluation of the metallurgical microstructure of the powder forged weapon components. Initially, the plan had included detailed inspection of the components with production gauges and mechanical testing by McDonnell-Douglas Helicopter, the builder of the 25 mm M242 chain gun, as a subcontractor. However, McDonnell-Douglas was not able to participate in the program.

Dimensional and Surface Finish Requirements

Forty prototype aft feed sprockets were produced and delivered to ARDEC. The contour dimensions of the aft feed sprockets were checked by means of a "go-no go" gauge set built by MMTC Textron and shown in Figure 23. This gauge set was constructed from steel plate by wire EDM and was designed to verify that the overall contour of the forgings was within specification. All parts were checked and found to be acceptable. As shown in Figure 24, an acceptable sprocket will fit through the hole in the "go" gauge but will not fit through the "no go" gauge. The contour of the aft feed sprocket is defined by a series of radii. It is conceivable (but not considered likely) that an individual radius might be out of tolerance but not be detected by the contour "go-no go" gauges. The production gauges used by McDonnell-Douglas Helicopter are designed to check the radii individually.

The thickness of each aft feed sprocket was checked after surface grinding with a calibrated micrometer. All of the parts were within specification. The diameter of the bore was checked with a calibrated bore dial gauge. The tolerance on the bore is very tight, with a total range of 0.02 mm (0.0008 inch). Six parts were found to have oversize bores by amounts ranging from 0.018 mm (0.0007 inch) to 0.056 mm (0.0022 inch). The surface finish of the aft feed sprockets was evaluated and was superior to the design requirement of 1.6 micrometer (63 micro-inch).

A "go-no go" gauge was also built for inspection of the internal spline of the drive sprocket. The few drive sprocket forgings which were produced during setup of the forge tooling were checked with this gauge and the as-forged bore was found to be acceptable.

Chemical Composition Requirements

A sample for analysis of carbon and oxygen was taken from each of two finished aft feed sprockets. Carbon was analyzed by a Leco Model CS244 Carbon Sulfur Analyzer. Oxygen was determined by a Leco Model 136 Oxygen Nitrogen Analyzer.

Other elements were alloyed in the powder and their compositions were provided by the powder supplier. The powder analysis was confirmed in one of the early

sintering trials. The chemical composition data is summarized in Table 4. The table includes data for a drive sprocket composition which was also analyzed in the sintering trial.

Based on the samples taken from the two aft feed sprockets, it appeared that the carbon restoration heat treatment resulted in a higher carbon content in some parts than in others. The carbon content in one sample was within specification. The average carbon content in the other was 0.015 weight percent below the lower limit of the specification. The reason for this difference could have been variations in carbon content and carbon gradient within the pieces themselves in the as-forged condition. Several extra forgings were sampled at intervals during the carbon restoration to monitor the progress of carbon diffusion during the heat treatment. It was assumed that these samples were typical of the microstructures of the prototype parts.

The nickel content in the aft feed sprocket sample taken during sintering trials was reported to be 0.03 weight percent below the lower limit of the nickel specification and 0.06 weight percent below the value reported for the powder. It was assumed that this represented normal variation in a chemical analysis of this type. The nickel content reported for the drive sprocket composition, which was blended from the same powder, was 0.07 weight percent above the lower limit of the specification and 0.04 weight percent above the value reported for the powder.

With the exception of the two discrepancies above, the chemical composition of the aft feed sprocket prototypes met all requirements and was consistent with the reported composition of the powder. It should be noted that the chromium content of the powder was somewhat higher than normal, but it was still not excessive.

The powder was deoxidized by reaction with carbon both during sintering as well as during the carbon restoration. The oxygen content was within specification in both samples checked. It is perhaps an indication of the progress of deoxidation during carbon restoration that the sample with lower carbon content also had a higher oxygen content. In both samples, it is believed that the oxygen content was somewhat higher than it would be otherwise due to oxygen being combined with chromium.

Density Requirements

The densities of samples from two aft feed sprocket forgings were measured by the method of weighing a small sample in both water and air, as described in ASTM Standard B311. Densities ranging from 7.704 g/cm³ to 7.869 g/cm³ were obtained, with the lowest density being observed only at the extreme ends of the fingers. This is due to the sharp radii and minimum forging deformation there. Based on the maximum density measured of 7.869 being equivalent to 100% (compared with a theoretical value of 7.84 g/cm³), the densities ranged from 97.90% to 100%.

Metallurgical Evaluation

Metallurgical microstructures were examined from sprockets at each stage of processing, i.e. after sintering, after forging, after carbon restoration heat treatment, and after quenching, tempering, and finish machining. Samples for metallography were sectioned from the aft feed sprocket perpendicular to the plane of the arms.

Compacted Structure

Figure 25 shows the microstructure at two locations in an aft feed sprocket sintered preform. Due to the relatively sharp radius at the tips of the aft feed sprocket arms, there was concern that the compacted density there might be lower than at other locations in the preform. However, through comparison of the two microstructures in Figure 25, it appears that the density at the tip of the arm is approximately the same as at the mid-length of the arm. If anything, the porosity at mid-length appears to be slightly greater. This was consistent with the density measurements, in which the variation in density was sufficiently slight that it would not be readily apparent metallographically.

It should be noted that the section represented by Figure 25(a) was located approximately 6 mm (0.25 inch) from the tip of the arm so that a reasonable sample could be obtained for metallography. The porosity may be greater closer to the end of the tip. While the microstructures shown in Figure 25 are valid for comparison purposes, no attempt was made to estimate compacted density by quantitative metallography because the area represented by pores in a metallographic section is very dependent upon the sample preparation and the focus of the metallograph.

Surface Finger Oxides

Surface finger oxides were evaluated in accord with Appendix A of the draft military specification "Forgings, Prealloyed Steel Powder, P/F-4620, P/F-4640 and P/F-4660." A copy of the current draft of this specification is included as an appendix of this report.

No portion of the aft feed sprocket was defined as a critical area. Samples were sectioned from the tip of an arm and from the center section of a sprocket in the as-forged condition. Figure 26 shows two typical surface finger oxides. As measured on the photomicrograph, these surface finger oxides extend approximately 0.086 mm (0.0034 inch) below the surface (oxide layer-metal) interface. It is believed that most of the oxidation occurred while the preform was being removed from the sintering furnace and transferred to the forging press. While the transfer time from the furnace to the press was approximately 7 seconds or less, this may not have been sufficient to prevent appreciable oxidation. Furthermore, oxidation may have started when the door to the sintering furnace and the door to the muffle were opened to remove the preform.

A minimum amount of surface oxidation may be unavoidable in the aft feed sprocket forgings due to the limited amount of forging deformation and the high surface to volume ratio. The aft feed sprocket forging introduced minimum deformation into the microstructure. Higher amounts of deformation would have tended to break up the oxides at the surface more than seen here.

The surface finger oxides photographed were on the top surface of the forging, but they were typical of those on the other surfaces. The largest surface finger oxide observed was on the bottom surface of the part and extended 0.20 mm (0.008 inch) from the surface. Approximately 0.75 mm (0.030 inch) of material was removed from the top and bottom surfaces of the aft feed sprockets by surface grinding. This was sufficient to remove all surface finger oxides. Thus, in the finish machined parts, oxides would only be present on the contoured side surfaces of the arms. As discussed below, these oxides would be less severe than observed in the as-forged condition because they were reduced by the carbon restoration heat treatment.

Interparticle Oxide Networks

The evaluation of interparticle oxide networks in an as-forged aft feed sprocket was similar to the evaluation of surface finger oxides described above. Appendix A of the draft military specification also applies to interparticle oxide networks and the same metallographic samples were examined. Figure 27 shows a typical example of interparticle oxide networks observed. As measured on the photomicrograph, these networks extended approximately 0.10 mm (0.004 inch) below the surface. Because the definition of the network deteriorates gradually with distance from the surface, measurement of its exact depth is somewhat arbitrary. The comments above regarding the origin of the surface finger oxides and their removal by grinding apply to interparticle oxide networks as well.

Effect of Carbon Restoration Heat Treatment on Surface Oxides

Figure 28 shows typical surface finger oxides in an aft feed sprocket forging after carbon restoration heat treatment. They extend approximately 0.025 mm (0.001 inch) below the surface. The largest surface finger oxides noted extended 0.05 mm (0.002 inch) below the surface. While it is difficult to generalize, it appears that there was significant reduction (in the chemical sense) of the oxides during carburization. No interparticle oxide networks were observed at the surface. The surface finger oxides appeared to be smaller than in the as-forged condition and their contours were more rounded.

Decarburization

Because the forgings were through carburized, there was essentially no decarburization in the finished parts. (Decarburization was extensive in the as-forged parts, as discussed with respect to the sintering trials.) This was

confirmed both metallographically and through microhardness measurements in accord with SAE Aerospace Recommended Practice (ARP) 1341A, as revised 1 July 1987. The microhardness data for a forging after heat treatment is shown in Table 5. The reading at the 0.051 mm (0.002 inch) position seems slightly low, but this is not believed to indicate any significant decarburization. There is no discernible difference between the hardness at the surface and in the interior of the forging. In addition to their relevance with respect to discussion of decarburization, these data also indicate that the forging was fully heat treated throughout the cross section.

Iron Contamination

Iron contamination was evaluated in accord with Appendix D of the draft military specification "Forgings, Prealloyed Steel Powder, P/F-4620, P/F-4640 and P/F-4660." An example of an apparent unalloyed iron particle in an as-forged aft feed sprocket is shown in Figure 29. Only one or two of these particles were found in an entire metallographic cross section of 100 mm² (0.16 inch²). This amount of iron contamination is much less than the maximum three (3) percent by area allowed for these parts and is consistent with the powder producer's report (included in the the Raw Material chapter) of less than one (1) percent iron contamination. No unalloyed iron particles were observed in samples taken after carbon restoration heat treatment.

Non-metallic Inclusions

Non-metallic inclusions were evaluated in accord with Appendix C of the draft military specification "Forgings, Prealloyed Steel Powder, P/F-4620, P/F-4640 and P/F-4660." The requirement for the aft feed sprocket is less than 100 particles per 100 mm² (0.16 inch²) greater than 30 micrometers (0.0012 inch) in diameter and less than 4 particles per 100 mm² (0.16 inch²) greater than 100 micrometers (0.004 inch) in diameter.

The powder supplier's report of inclusion content, included in the Raw Material chapter, indicated 101 particles greater than 30 micrometers (0.0012 inch) and 3.3 particles greater than 100 micrometers (0.004 inch) per 100 mm² (0.16 inch²). The reported density of inclusions greater than 30 micrometers (0.0012 inch) is slightly greater than the specification for the aft feed sprocket.

Metallographic examination of the aft feed sprocket microstructure after heat treatment did not confirm the relatively high inclusion content reported by the powder supplier. After survey of approximately 50 mm² (0.08 inch²) area, the inclusion density was found to be only 55 particles greater than 30 micrometers (0.0012 inch) per 100 mm² (0.16 inch²). This survey was done manually, without the benefit of automated image analysis equipment. Without automated equipment, it was not practical to survey the full 350 mm² (0.54 inch²) area required by Appendix C of the above referenced specification.

The reason for the discrepancy in inclusion count is not fully known. However, one possible explanation can be found in the apparent reduction of the surface finger oxides by the carbon restoration heat treatment which was discussed above. The apparent decrease in inclusions might also have been due to reduction of oxide particles during carburization.

The issue of powder cleanliness was not pursued further as the powder supplier indicated that current powder cleanliness is significantly better than that of the powder used in this program, which was purchased in 1986. Current inclusion content is typically less than 65 particles greater than 30 micrometers (0.0012 inch) and less than 3 particles greater than 100 micrometers (0.004 inch) per mm² (0.16 inch²).

Figure 30 shows a typical inclusion particle greater than 30 micrometers (0.0012 inch). The size of this particle, as measured on the photomicrograph, is approximately 65 micrometer (0.0025 inch) in diameter. Most inclusions of this size were discrete particles as in the figure. Relatively few aggregates or spotty inclusions were observed.

Heat Treated Microstructure

Figure 31 shows the microstructure of the aft feed sprocket after final quench and temper heat treatment. As would be anticipated, the microstructure is a tempered martensite and was reasonably uniform throughout the cross sections examined.

Hardness

The hardness requirement for the aft feed sprocket is 36 - 40 on the Rockwell C scale (R_C). Hardness readings were obtained on samples from two finished aft feed sprocket forgings. One sample showed an average R_C hardness of 38.4. The other seemed to be slightly harder, with an average hardness of 40.3, 0.3 points higher than the maximum specified. The samples used for hardness readings were from the same sprockets from which the samples for chemical analysis were sectioned. The harder sprocket corresponded to the one with the higher carbon content in Table 4. This suggests that the variation in hardness was a result of variation in carbon content. As discussed in the Forge Process section, the tempering temperature was selected based on trials with sample parts. It was assumed that the samples were representative of the prototype parts.

The calibration of the Rockwell hardness machine was checked with a calibrated test block. The Rockwell C hardness readings were consistent with the microhardness readings taken to assess decarburization, as shown by the R_C equivalents in Table 5.

Comments on Proposed Standard.

Through the course of this program, there was nothing unreasonable found in the draft military specification "Forgings, Prealloyed Steel Powder, P/F-4620, P/F-4640 and P/F-4660." This specification is included as an appendix to this report. A minor clarification might be made regarding the definition of surface when measuring the depth of penetration of surface finger oxides and interparticle oxide networks. In the case of a part which might have an oxide layer on the surface, depth of penetration should be measured from the oxide - metal interface.

It should be noted that inclusions and iron contamination in a powder forged part reflect the quality of the raw material powder. These can be avoided by starting with good quality powder.

Surface finger oxides, interparticle oxide networks, and decarburization reflect the sintering and forging process. While problems with oxidation of the aft feed sprockets were experienced with the prototype laboratory facilities, commercial equipment is available to protect sintered preforms from oxidation in production operations. Thus, requirements for minimal surface finger oxides, interparticle oxide networks, and decarburization should present no obstacle to implementation of powder forging processes and the substitution of powder forgings for wrought parts.

Two aspects of the procedures in the proposed standard were noted. First, the requirement to survey at least 350 mm^2 (0.54 inch^2) of polished specimen to determine inclusion content (Appendix C) could be burdensome to a powder forging company which did not have access to automated image analyzing metallographic facilities. Second, when assessing the porosity of critical areas metallographically (Appendix B), it should be recognized that the edges of the pores may be rounded, even with the good metallographic technique which is emphasized in the Preparation of Specimens paragraph. If the edges of the pores are rounded, the size of the pores may appear somewhat larger or smaller depending on the focus of the metallograph.

MANUFACTURING COST ANALYSIS

One of the primary motivations for considering powder forging is the potential to reduce manufacturing cost by eliminating machining operations. Furthermore, in many cases the mechanical properties and performance of the powder forged part may be superior due to its homogeneous, forged microstructure.

To provide a framework for budgeting and planning the procurement of powder forged components, production costs of the powder forged aft feed sprocket were estimated. The present method of manufacturing the aft feed sprocket and the associated costs were not provided to MMTC Textron. Therefore, it was not possible to comment regarding any potential cost saving for this component.

Tables 6 and 7 present detailed cost estimates for powder forging the aft feed sprocket. They include estimates of the current (mid-1988) costs of raw material, labor, tooling, and overhead which would be required. Allocations and profit which are added to cost to arrive at the selling price were not considered. The costs associated with facilities (e.g. compaction and forging presses) and engineering are included in overhead. Note that the compaction and forging tooling for the aft feed sprocket have already been designed and built under the present program and are the property of the U.S. Government. Gages are also owned by the government. As discussed below, the volume requirements for the aft feed sprocket are relatively low and might not be sufficient to fully amortize the cost of new tooling.

One factor in manufacturing cost is the size of the production run. Table 6 assumes an annual requirement of 1,000 pieces per year produced in one lot. For comparison purposes, a lot size of 5,000 pieces was assumed for Table 7. The effect of the larger lot size is to decrease the per piece cost from \$23.73 to \$22.48. The cost of setup, which is a constant regardless of the lot size, was allocated over a larger number of pieces in the larger lot.

The decrease in cost associated with a larger lot size is a small fraction of the total cost. Due to the relatively low production volumes, it was assumed that little automation would be used in the manufacturing process, so the labor and overhead costs constitute the largest portion of the total piece cost.

The costs of labor, equipment, and overhead in the table were based on experience in the present program and knowledge of the powder forging industry. Sufficient detail has been provided to enable the reader to substitute alternate values which would be more accurate for a given situation.

MMTC Textron does not presently manufacture powder forged components on a production basis. Therefore, quotations were solicited from several powder forging companies to validate the cost estimates. Two vendors were found with the capability to manufacture the aft feed sprocket as a powder forging, but neither was willing to quote on low production volumes. One vendor stated a minimum annual lot size of 50,000 pieces. The other had a minimum of 30,000 pieces, but recommended 50,000 for better pricing.

Manufacturing cost savings can be maximized when a component is designed with knowledge of the capabilities and limitations of the manufacturing process. In the case of the aft feed sprocket, it is believed that the thickness of the part and the flatness of the top and bottom surface are not critical to the function of the sprocket. Savings could be achieved if the surface grinding operation after forging were eliminated.

Although a carbon restoration was required after forging of the prototype parts, this would not be required in production. The cost analysis includes heat treatment only to quench and temper the sprockets to the required hardness.

The reaming of the bore of the aft feed sprocket is relatively costly due to the tight tolerance requirement. However, the cost of this operation would be essentially the same whether the sprocket is produced by powder forging or some other method. Therefore, the cost of reaming the bore cannot be a factor in evaluating powder forging versus the present practice or other alternatives. Note that it would not be practical to forge the bore to size, but some saving might be achieved by forging an undersize bore.

As mentioned in the Introduction, the manufacture of the aft feed sprocket was previously studied.³ In addition to powder forging, it was recommended:

"Alternative processes are feasible and should be considered as production candidates. This shape could be milled in bar stock; individual pieces could then be sectioned. This approach offers setup cost savings. Another approach to consider is blanking followed by gang milling. This approach saves material and still derives the benefit of milling more than one part at a time. A third possible approach involves sectioning bar stock into blanks, clamping these in stacks, and cutting the sprocket fingers by wire EDM on a multi-head wire machine. Although wire EDM is expensive, the ability to cut many parts simultaneously may make this method economical."

Table 1. Sieve analysis of alloy steel powder raw material

<u>U.S. Standard Mesh Size</u>		<u>Weight percent retained</u>
	+60	0
-60	+80	4.2
-80	+100	6.5
-100	+325	66.6
-325		22.7

Table 2. Effect of sintering atmosphere on carbon and oxygen content of powder forged parts

Part: Aft Feed Sprocket									
Alloy: 4640									
Carbon Requirement: 0.35 - 0.46 wt. percent									
Oxygen Requirement: 0.05 wt. percent maximum (500 ppm)									
Natural Gas in Furnace Atmosphere, vol. %	Gas Flow, L/s	Gas Flow, cfh	Sint. Time, min.	Sample No.	Blended Carbon, wt. %	Chemical Analysis After Sintering & Forging			
						Carbon wt. %	Oxygen wt. %		
0.00 (Baseline)	1.57	200	20	10	0.49	0.19			
	1.57	200	20	11	0.54	0.15			
	1.57	200	20	12	0.59	0.24			
	1.57	200	20	13	0.00	0.028			
0.00 (Reduced flow & sintering time)	0.79	100	10	14	0.49	0.18			
	0.79	100	10	15	0.54	0.17			
	0.79	100	10	16	0.59	0.23			
0.50	0.79	100	10	17	0.49	0.17			
	0.79	100	10	18	0.54	0.21			
	0.79	100	10	19	0.59	0.35			
0.75	0.79	100	10	20	0.49	0.29			
	0.79	100	10	21	0.54	0.26			0.027
	0.79	100	10	22	0.59	0.30			0.036
	0.79	100	10	23	0.00	0.012			
0.90	0.79	100	10	24	0.54	0.26, 0.25, 0.25, 0.22	0.020		
	0.79	100	10	25	0.54	0.21, 0.11, 0.26, 0.33	0.15		
1.1	0.79	100	10	26	0.54	0.30, 0.22, 0.31, 0.34	0.15		
	0.79	100	10	27	0.54	0.17, 0.27, 0.27, 0.21	0.084		
2.0	1.57	200	20	4	0.49	0.61, 0.50, 0.53	0.0066/0.0072	0.0083	
	1.57	200	20	5	0.54	0.57, 0.76, 0.76	0.0096/0.0093	0.042	
	1.57	200	20	6	0.59	0.53, 0.61, 0.61	0.0069/0.0062	0.0083	

Table 3. Results of sintering trials using a muffle

Sample no.	Blended carbon, wt %	Chemical analysis after sintering & forging	
		Carbon, wt %	Oxygen, wt %
28	0.49	0.16, 0.10	0.012, 0.038
29	0.54	0.29, 0.29	0.043, 0.020
30	0.59	0.30, 0.30	0.013, 0.012

Table 4. Chemical analysis of 46XX powder forgings

Element	4620 (Drive Sprocket Blend)		4640 (Aft Feed Sprocket Blend)		Powder
	Required Analysis Wt. %	Actual Analysis Wt. %	Required Analysis Wt. %	Actual Analysis Wt. %	Actual Analysis Wt. %
Carbon			0.35 - 0.46	0.42, 0.42* 0.34, 0.33*	<0.01
Oxygen			0.050 max.	0.016, 0.016* 0.036, 0.035*	0.18
Nickel	1.75 - 2.00	1.82	Same as 4620	1.72	1.78
Molybdenum	0.5 - 0.6	0.52	"	0.56	0.54
Manganese	0.25 max.	0.21	"	0.21	0.20
Phosphorus	0.02 max.	0.011	"	0.011	0.010
Sulfur	0.03 max.	0.016	"	0.019	0.023
Silicon	0.03 max.	<0.10	"	<0.10	0.021
Chromium	-	0.11	-	0.11	0.09
Copper	-	-	-	-	0.11
Nitrogen	-	-	-	-	0.0056

* Two readings on each line are from one sample.

Table 5. Microhardness of aft feed sprocket forging after heat treatment

Depth, <u>in.</u>	<u>Hardness</u>	
	<u>KHN</u>	<u>HRC</u>
0.002	376	37.6
0.004	406	40.3
0.006	409	40.6
0.010	409	40.6
0.015	415	41.1
0.020	412	40.8
Core	415	
	418	
	<u>406</u>	
Avg.	412	40.8

Table 6. Cost analysis for powder forging of 1000 aft feed sprockets

Summary of Input Data: 1,000 in 1 lot with 5% reject (including setup pieces).

Production Times and Labor Costs

<u>Operation</u>	<u>Rate Pcs./Min.</u>	<u>No. People</u>	<u>Labor \$/Hr.</u>	<u>Total Labor</u>	<u>% Ovhd. Burden</u>	<u>Ovhd. Burden</u>
Compact	0.2	1	12	\$1,050	350	\$3,675.00
Sinter	0.4	1	12	525	350	1,837.50
Forge	0.4	2	12	1,050	400	4,200.00
Inspect	0.2	1	12	1,050	350	3,675.00
Setup Compact		1	12	96	350	336.00
Setup Forge		1	12	96	400	384.00
				<u>\$3,867.00</u>		<u>\$14,107.50</u>

Tooling Requirements and Cost: Tool Item Cost Life (Pcs.)

	Compaction Tools	\$3,980	50,000
	Forge Tools	\$5,000	10,000
Total Tooling Cost Per Lot		\$608.58	

Raw Material Requirements and Cost:

	<u>Raw Material</u>	<u>Lbs./ Part</u>	<u>Cost/ Lb.</u>	<u>Cost/ Part</u>
	4640 Steel Powder	0.53	0.525	0.2783
Total Raw Materials Cost Per Lot				<u>\$292.16</u>

Finishing Costs Per 20 Parts: Operation Labor Burden

Heat Treat	\$12	\$35
Finish Machine	\$15	\$35

<u>Summary of production costs per part:</u>	Raw Materials	\$ 0.292
	Tooling	0.609
	Powder Forge Labor	2.625
	Inspection Labor	1.050
	Setup Labor	0.192
	Overhead	14.108
	Finishing	<u>4.850</u>
		<u>\$23.726</u>

Table 7. Cost analysis for powder forging of 5000 aft feed sprockets

Summary of Input Data: 5,000 in 1 lot with 2% reject (including setup pieces).

Production Times and Labor Costs

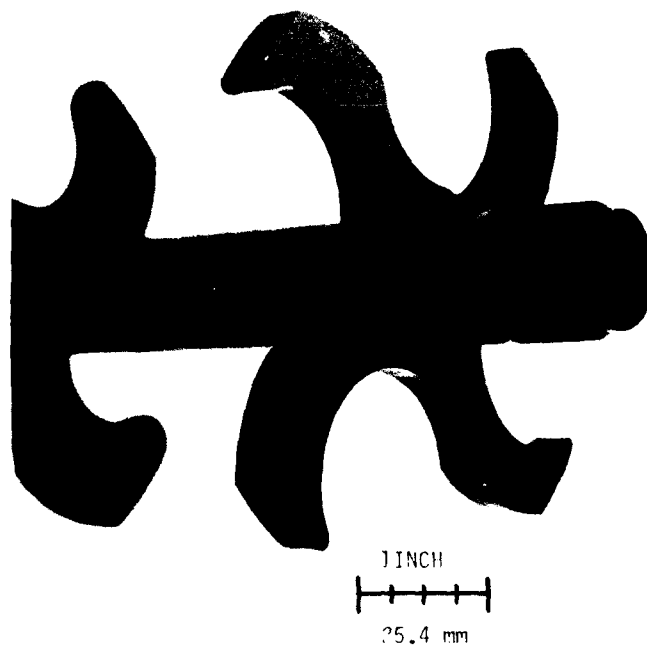
<u>Operation</u>	<u>Rate Pcs./Min.</u>	<u>No. People</u>	<u>Labor \$/Hr.</u>	<u>Total Labor</u>	<u>% Ovhd. Burden</u>	<u>Ovhd. Burden</u>
Compact	0.2	1	12	\$5,100	350	\$17,850.00
Sinter	0.4	1	12	2,550	350	8,925.00
Forge	0.4	2	12	5,100	400	20,400.00
Inspect	0.2	1	12	5,100	350	17,850.00
Setup Compact		1	12	96	350	336.00
Setup Forge		1	12	96	400	384.00
				<u>\$18,042</u>		<u>\$65,745.00</u>

<u>Tooling Requirements and Cost:</u>	<u>Tool Item</u>	<u>Cost</u>	<u>Life (Pcs.)</u>
	Compaction Tools	\$3,980	50,000
	Forge Tools	\$5,000	10,000
Total Tooling Cost Per Lot		\$2,955.96	

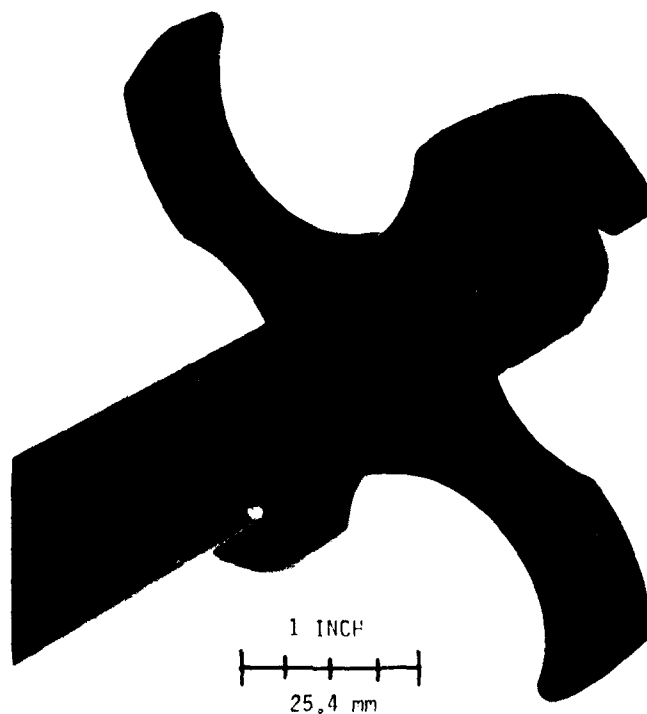
<u>Raw Material Requirements and Cost:</u>	<u>Raw Material</u>	<u>Lbs./ Part</u>	<u>Cost/ Lb.</u>	<u>Cost/ Part</u>
	4640 Steel Powder	0.53	0.525	0.2783
Total Raw Materials Cost Per Lot				\$1,419.08

<u>Finishing Costs Per 20 Parts:</u>	<u>Operation</u>	<u>Labor</u>	<u>Burden</u>
	Heat Treat	\$12	\$35
	Finish Machine	\$15	\$35

<u>Summary of production costs per part:</u>		
	Raw Materials	\$ 0.284
	Tooling	0.591
	Powder Forge Labor	2.55
	Inspection Labor	1.02
	Setup Labor	0.038
	Overhead	13.149
	Finishing	<u>4.850</u>
		22.482

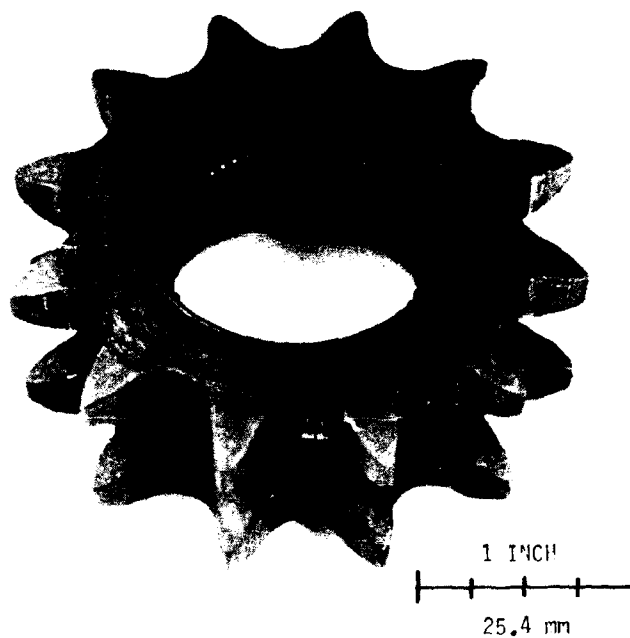


(a) Shaft assembly

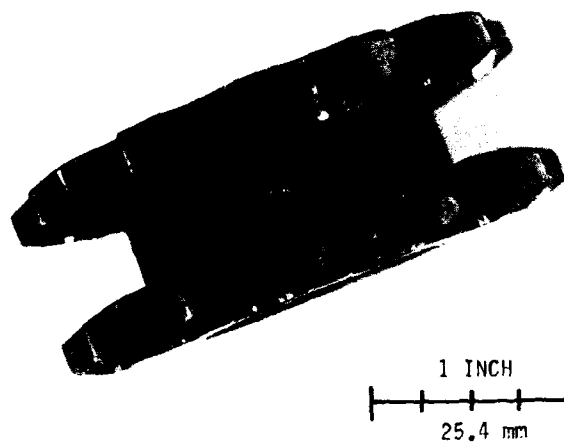


(b) Close-up view

Figure 1. Aft feed sprocket shaft assembly of the 25 mm M242 chain gun



(a) Tooth and bore contour



(b) Double strand capability

Figure 2. Finished drive sprockets used in the 25 mm M242 chain gun



Figure 3. Forge tooling fixture with aft feed sprocket dies

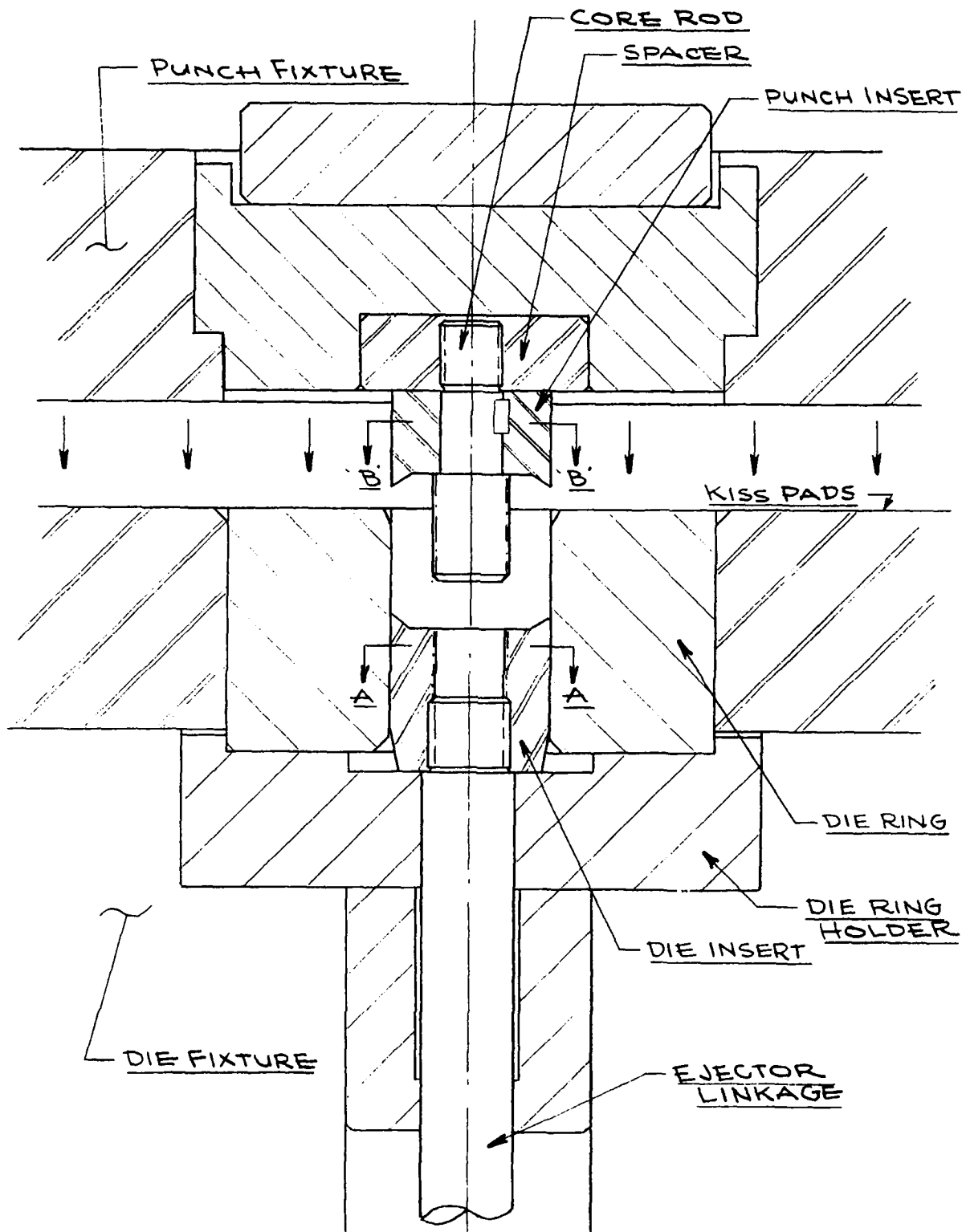


Figure 4. Tooling schematic showing drive sprocket forging dies and fixture in open position

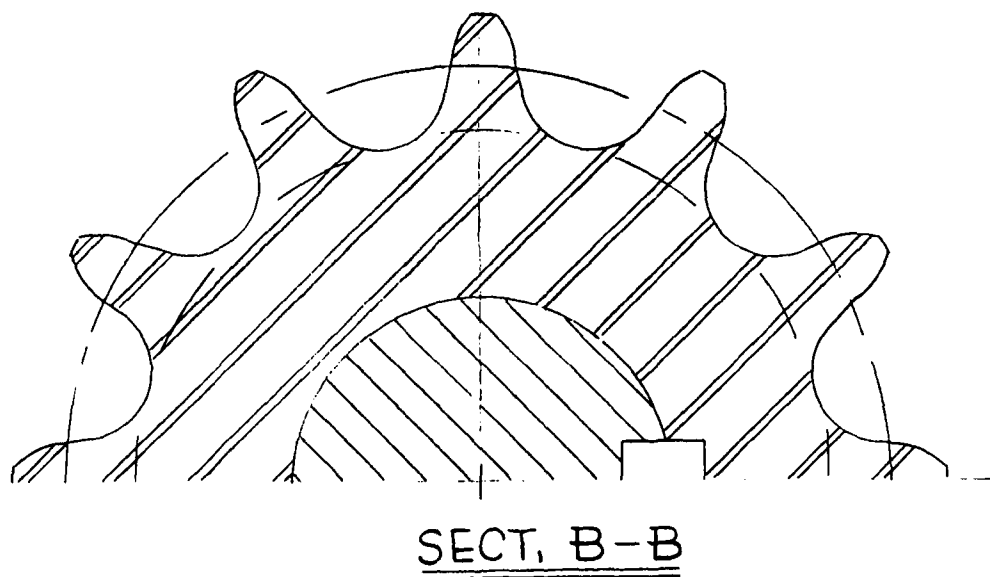
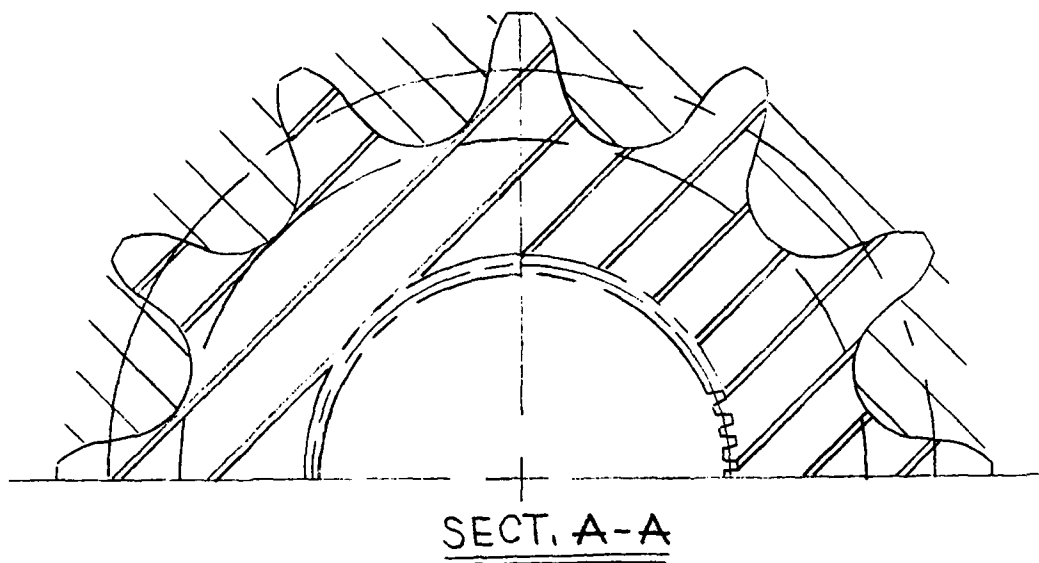


Figure 5. Cross sections through upper and lower drive sprocket forging dies

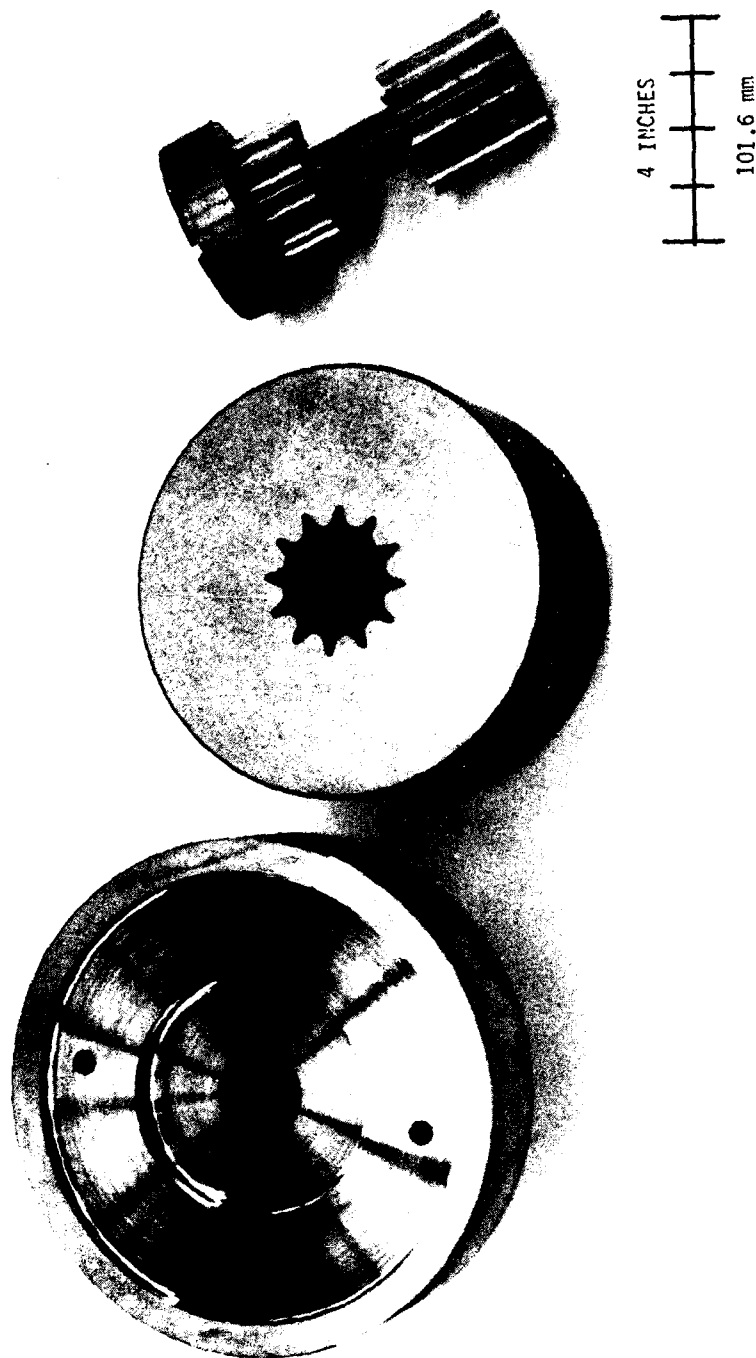


Figure 6. Drive sprocket forge tooling consisting of die ring holder (1), die ring, and upper punch/core rod/lower punch assembly

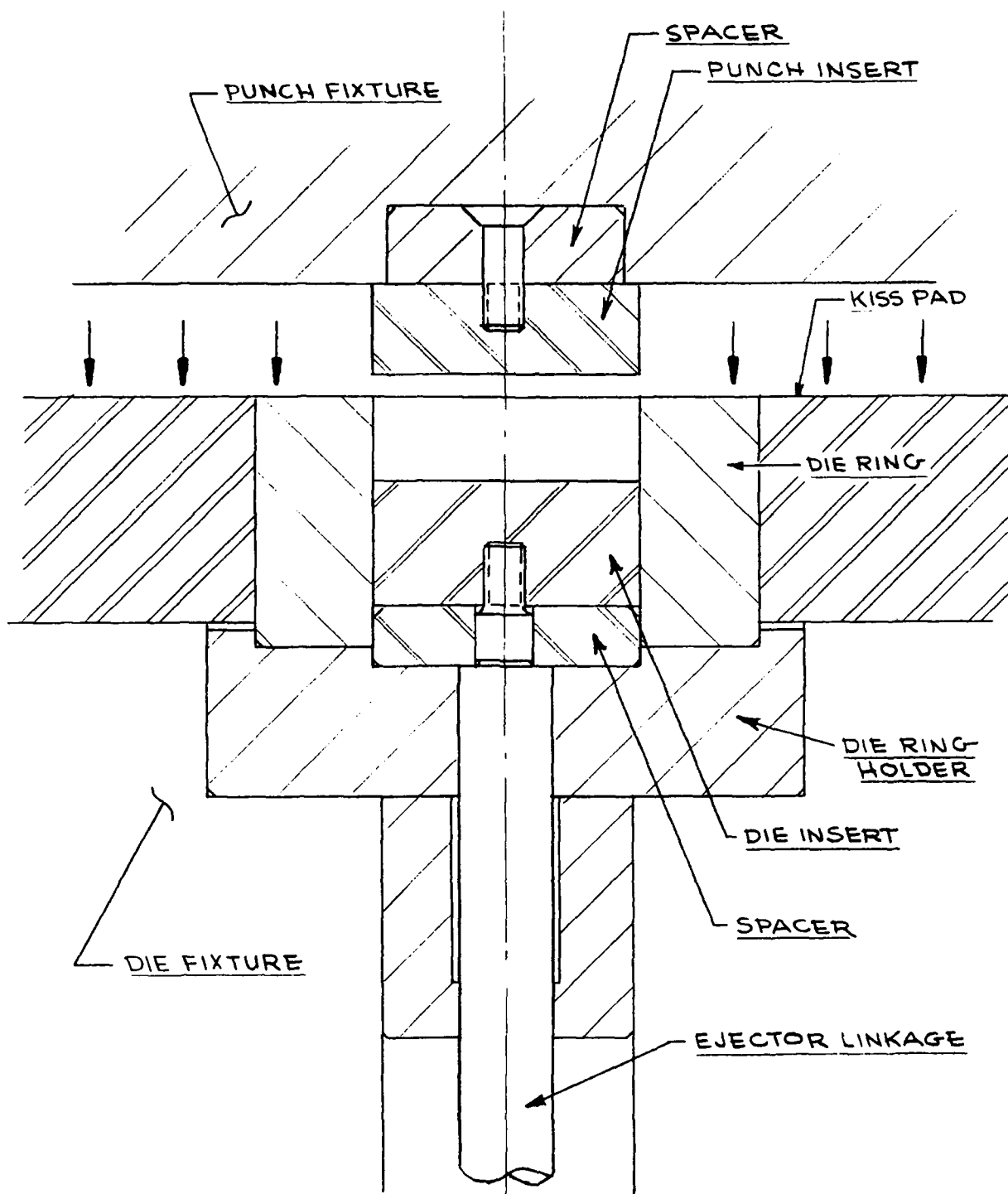


Figure 7. Tooling schematic showing aft feed sprocket forging dies and fixture in open position

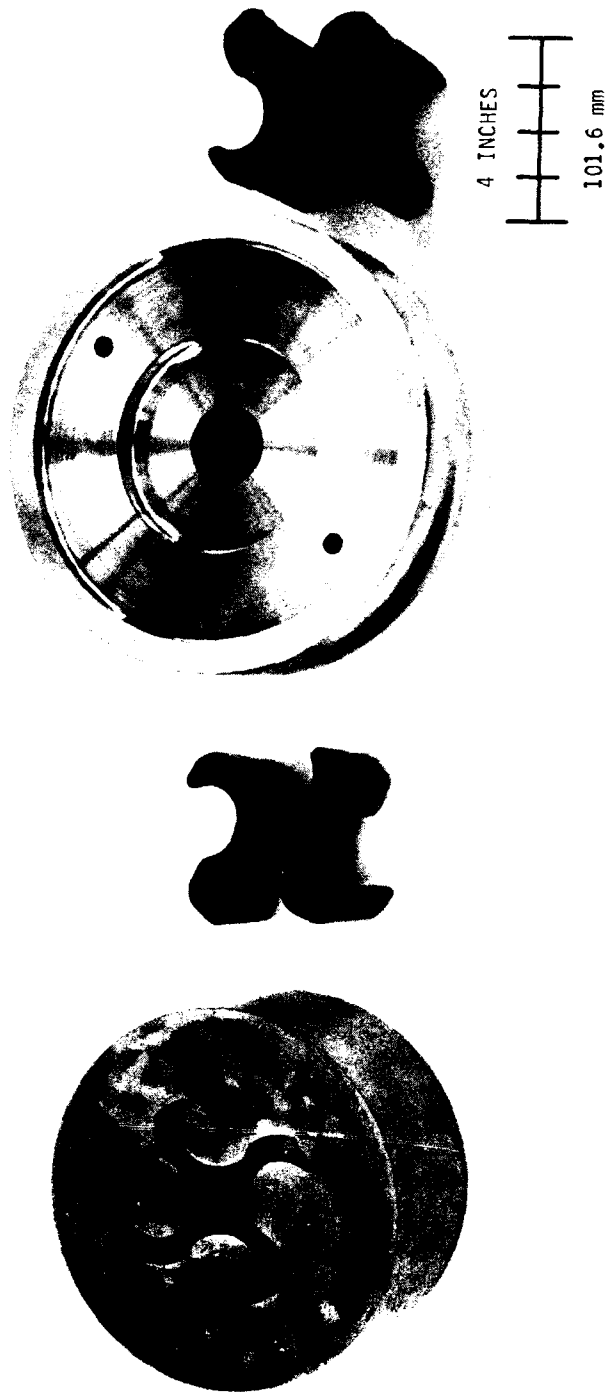


Figure 8. Aft feed sprocket forge tooling consisting of die ring (1), upper punch, die ring holder, and lower punch



Figure 9. Compaction tooling fixture with aft feed sprocket dies

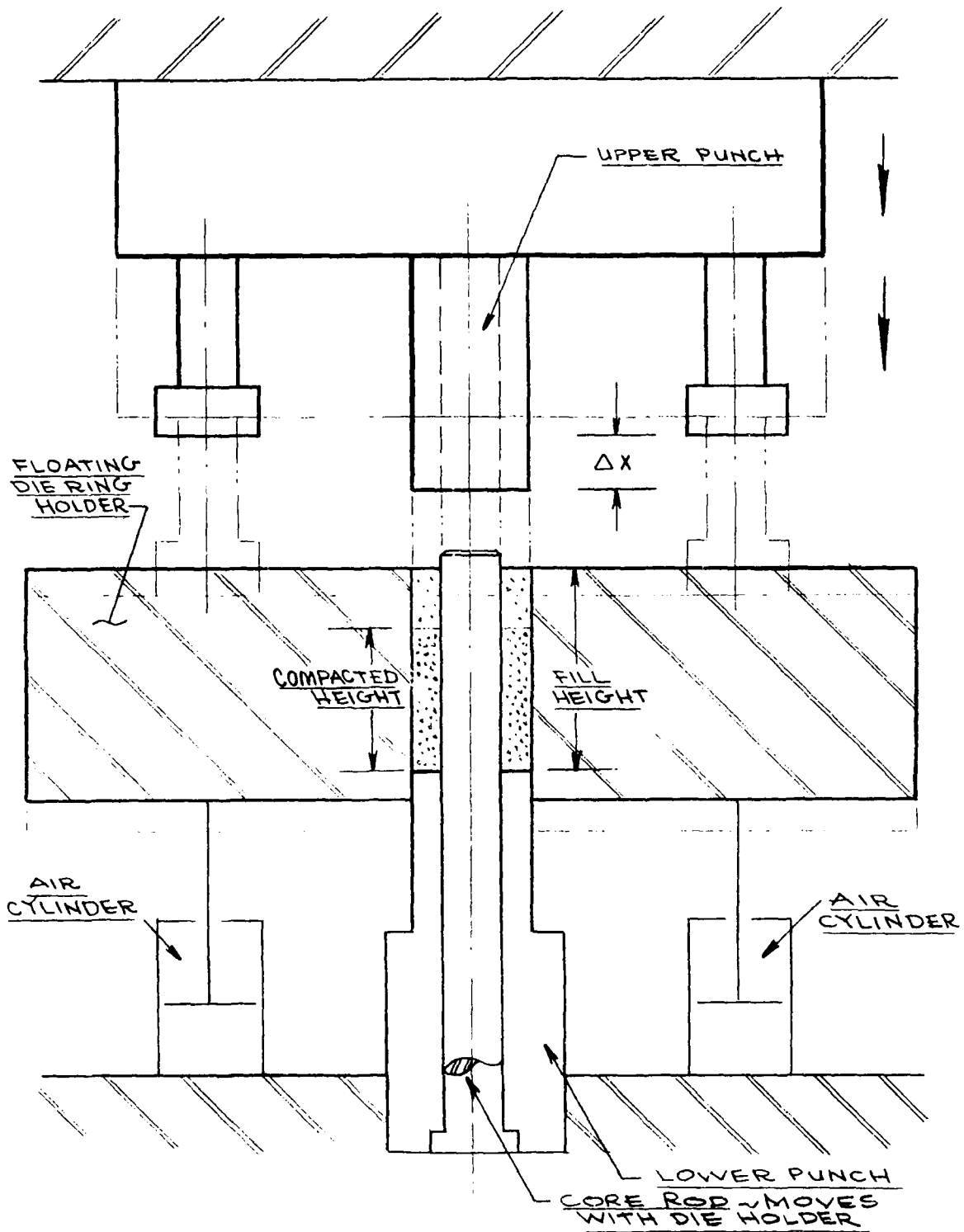


Figure 10. Tooling schematic showing drive sprocket compaction dies and fixture

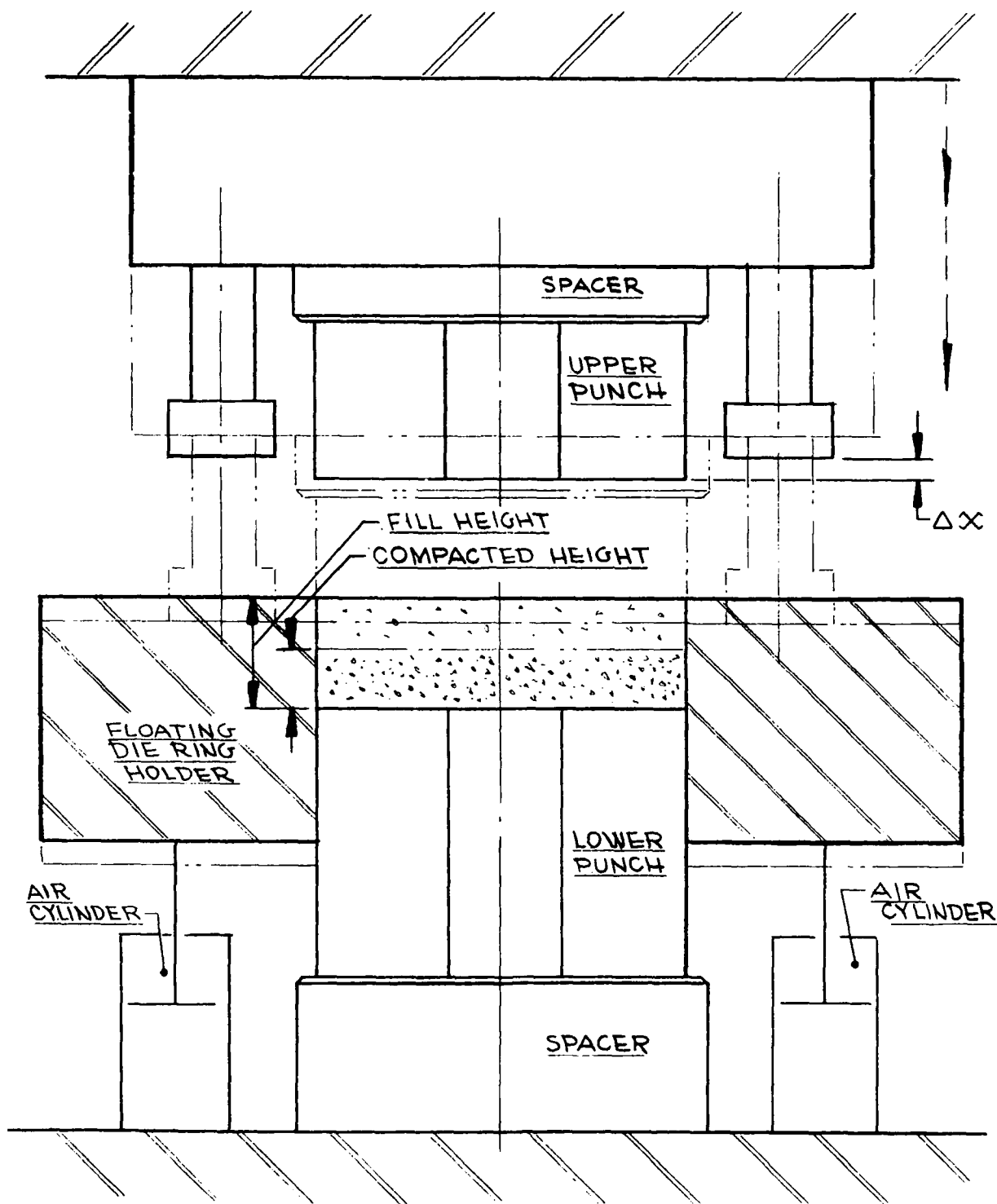


Figure 11. Tooling schematic showing aft feed sprocket compaction dies and fixture

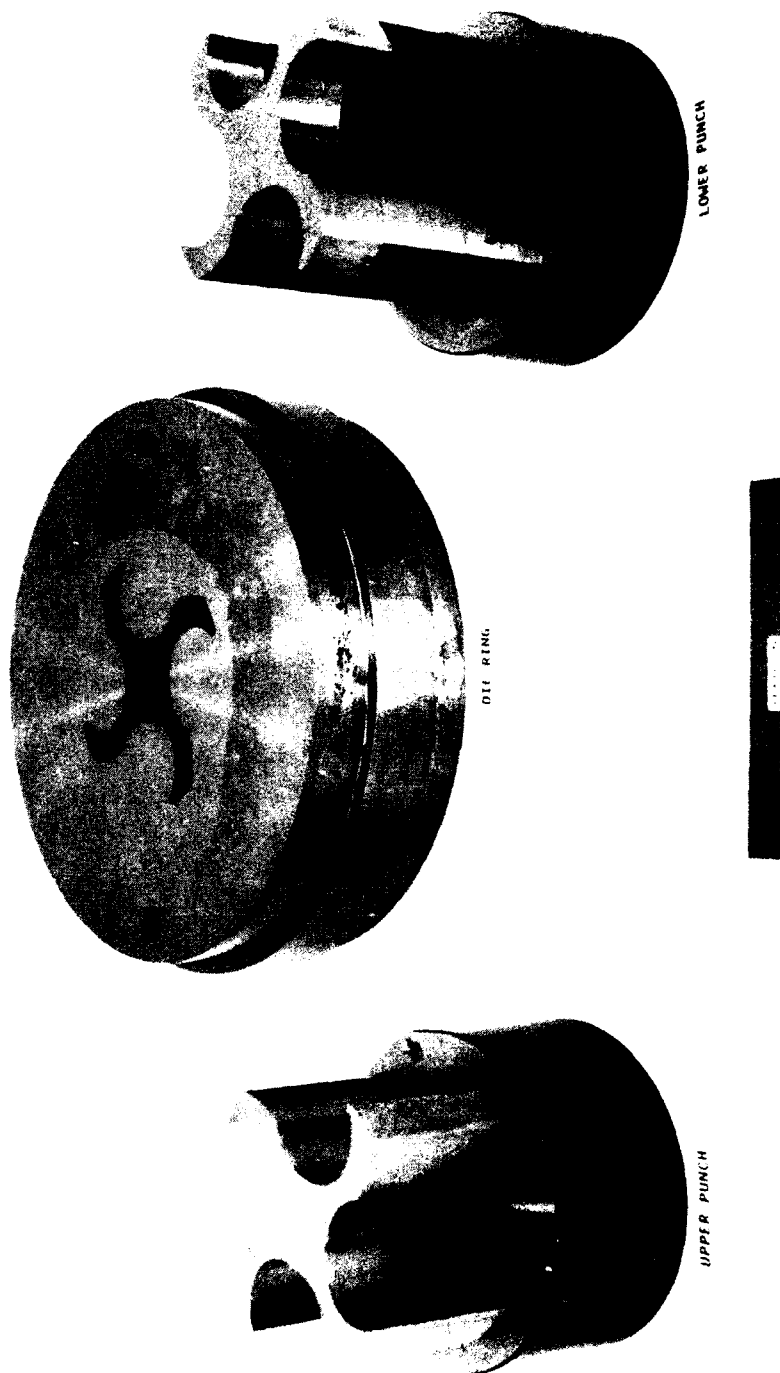


Figure 12. Aft feed sprocket compaction tooling consisting of upper punch (1), die ring, and lower punch

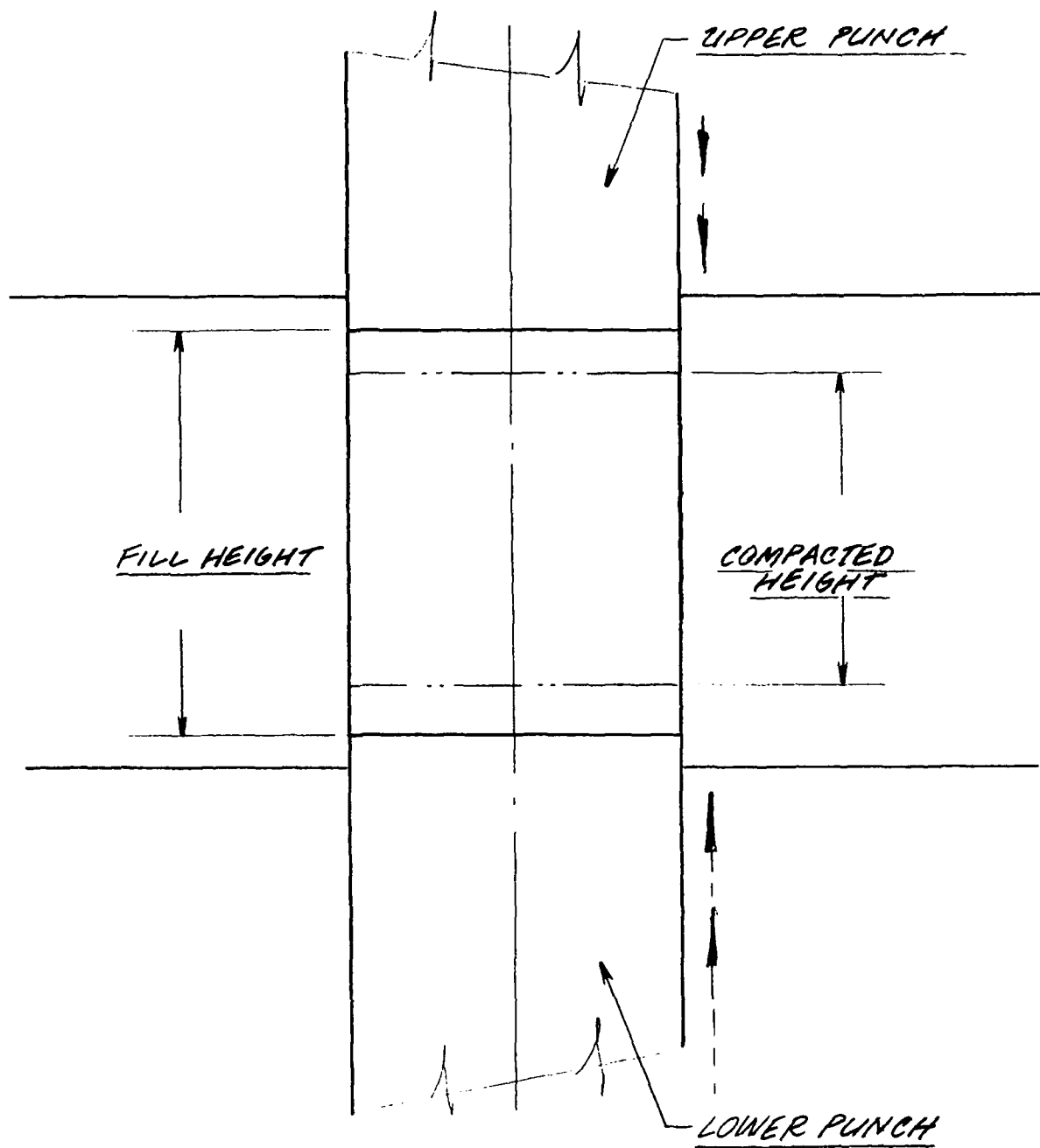


Figure 13. Tooling schematic illustrating double action floating die compaction

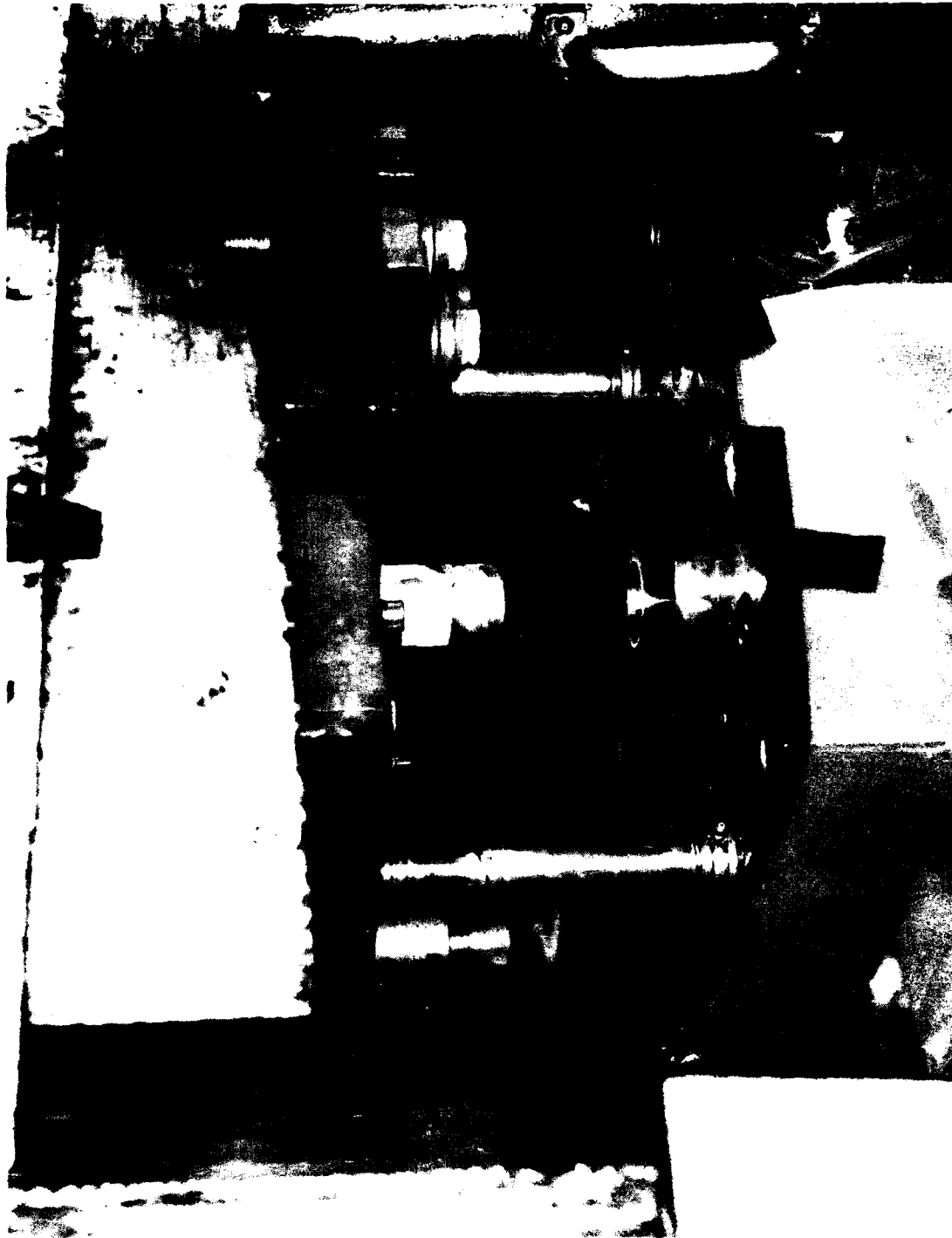


Figure 14. Drive sprocket compaction tooling and fixture installed in compaction press



Figure 15. Aft feed sprocket compaction tooling and fixture installed in compaction press

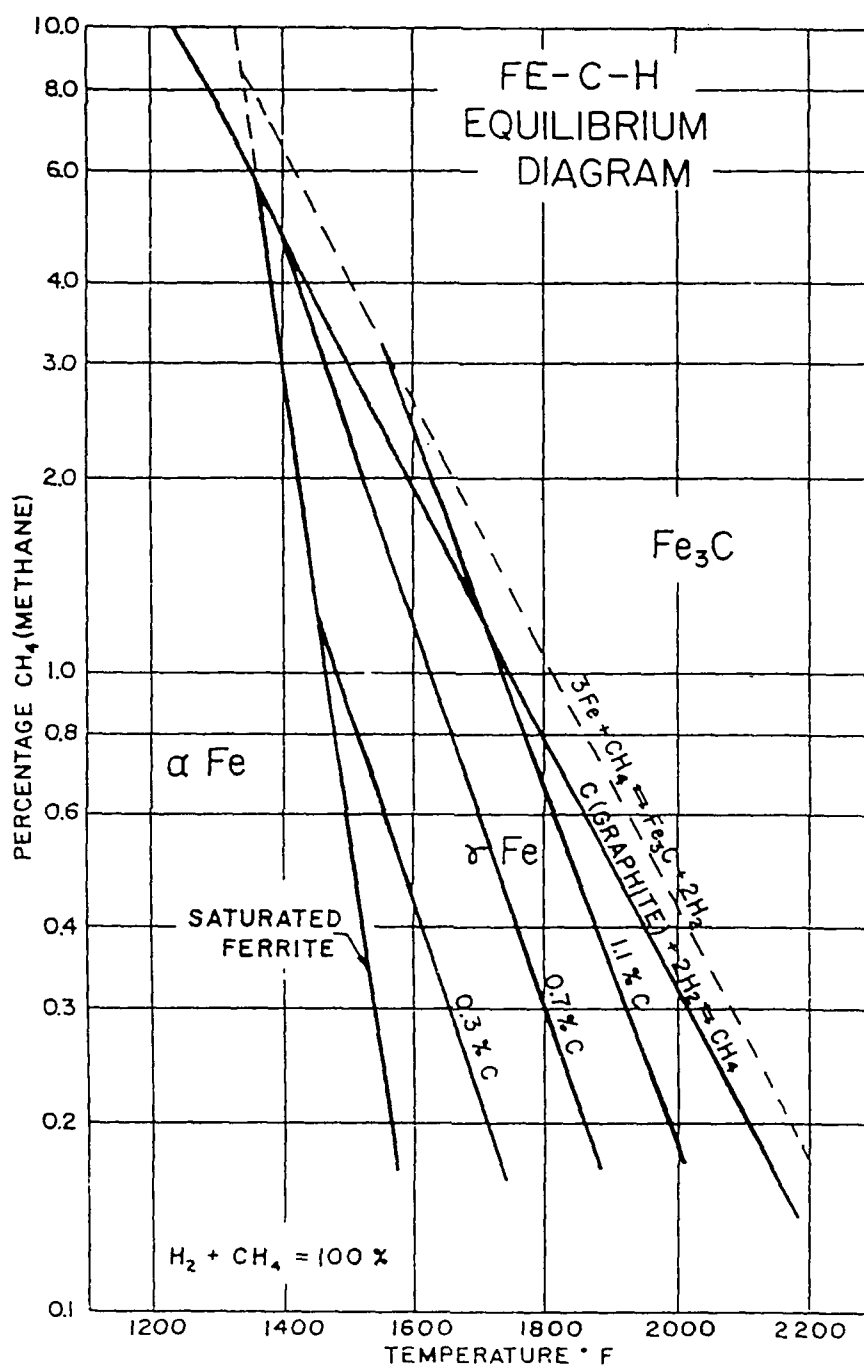


Figure 16. Iron-carbon-hydrogen equilibrium diagram⁵

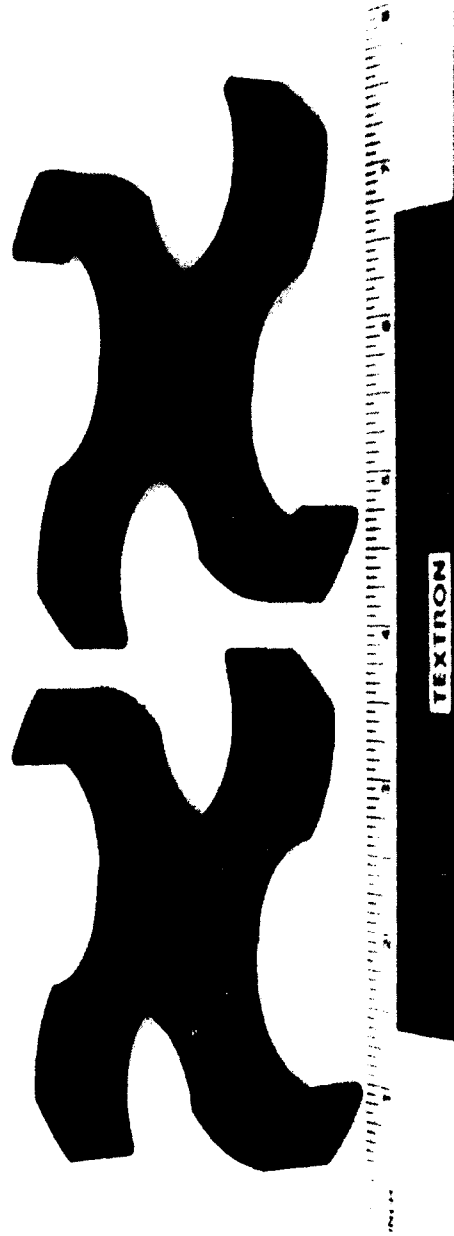


Figure 17. Aft feed sprocket sintered preform (1) and forging

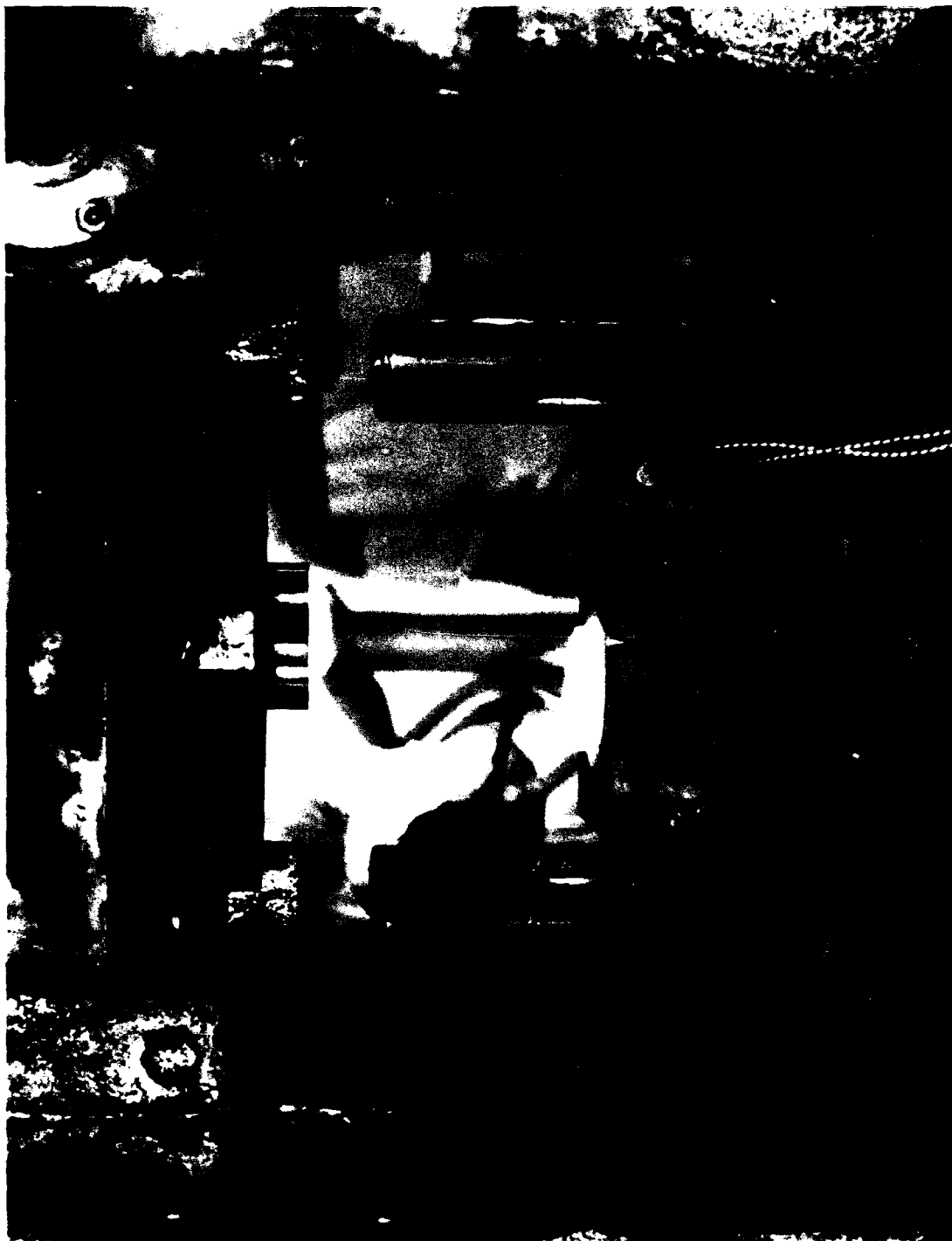


Figure 18. Aft feed sprocket preform being placed in die cavity prior to forging



Figure 19. Aft feed sprocket being ejected from die after forging

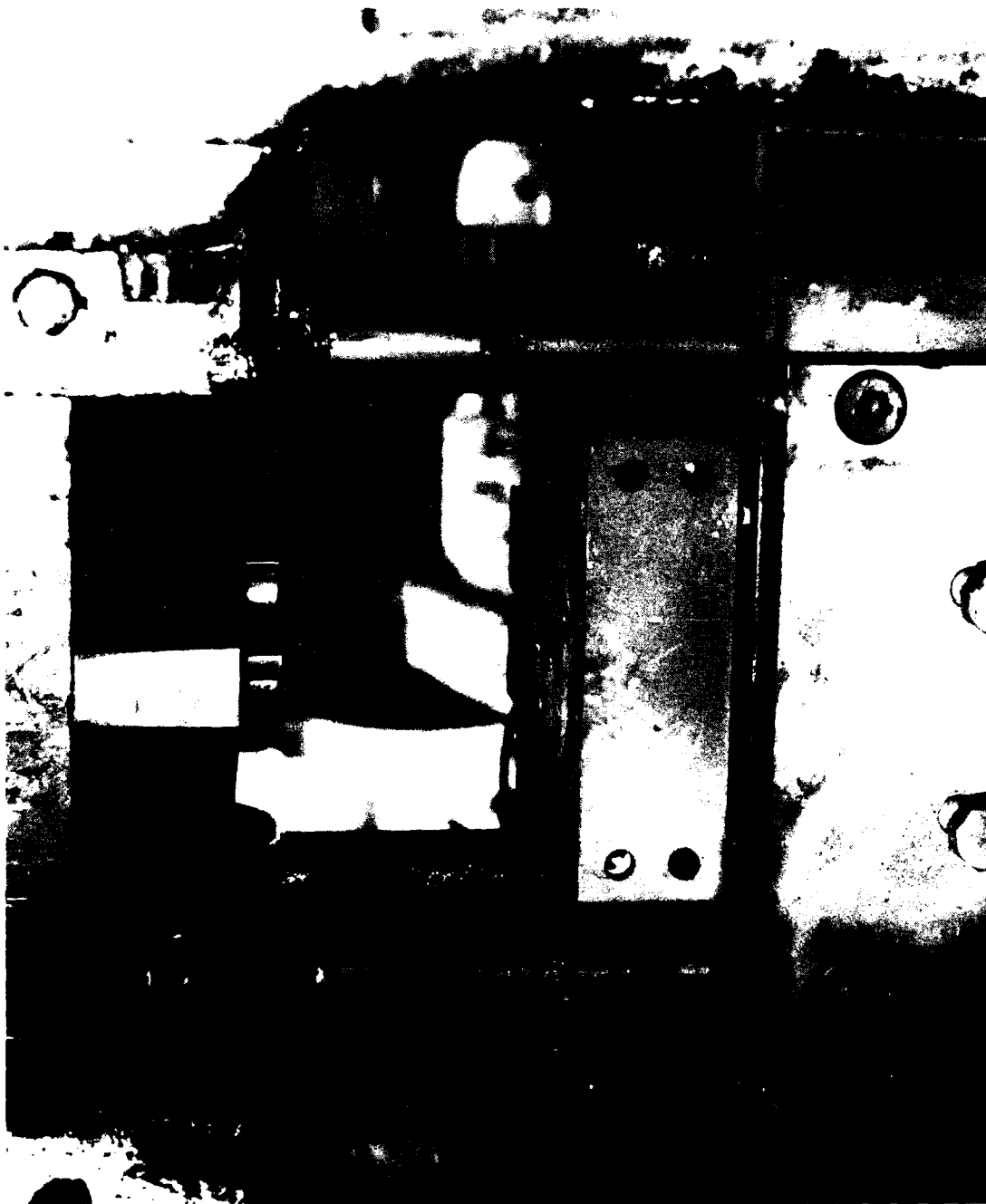


Figure 20. Aft feed sprocket forge tooling showing lower punch in raised (ejection) position

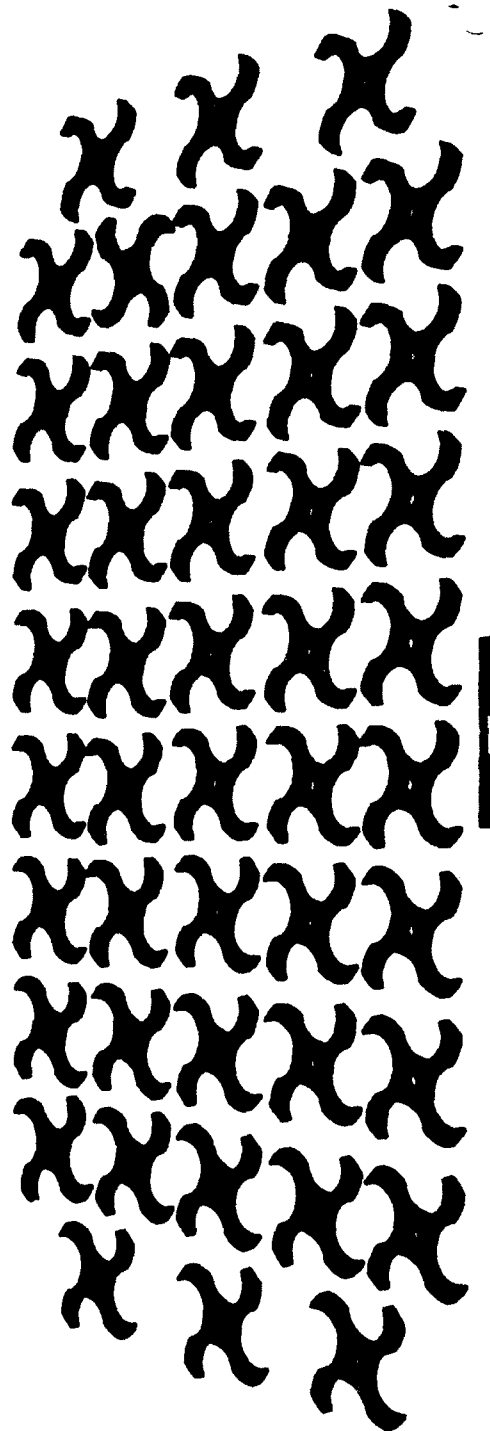


Figure 21. Aft feed sprocket forgings after heat treatment

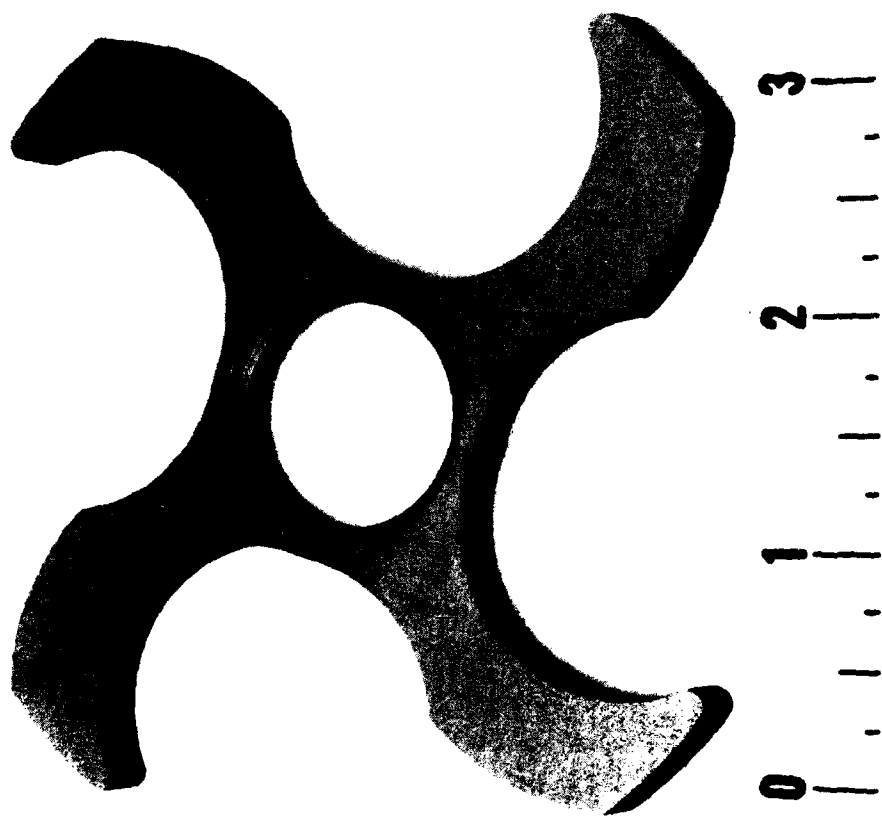


Figure 22. Aft feed sprocket forging after finish machining

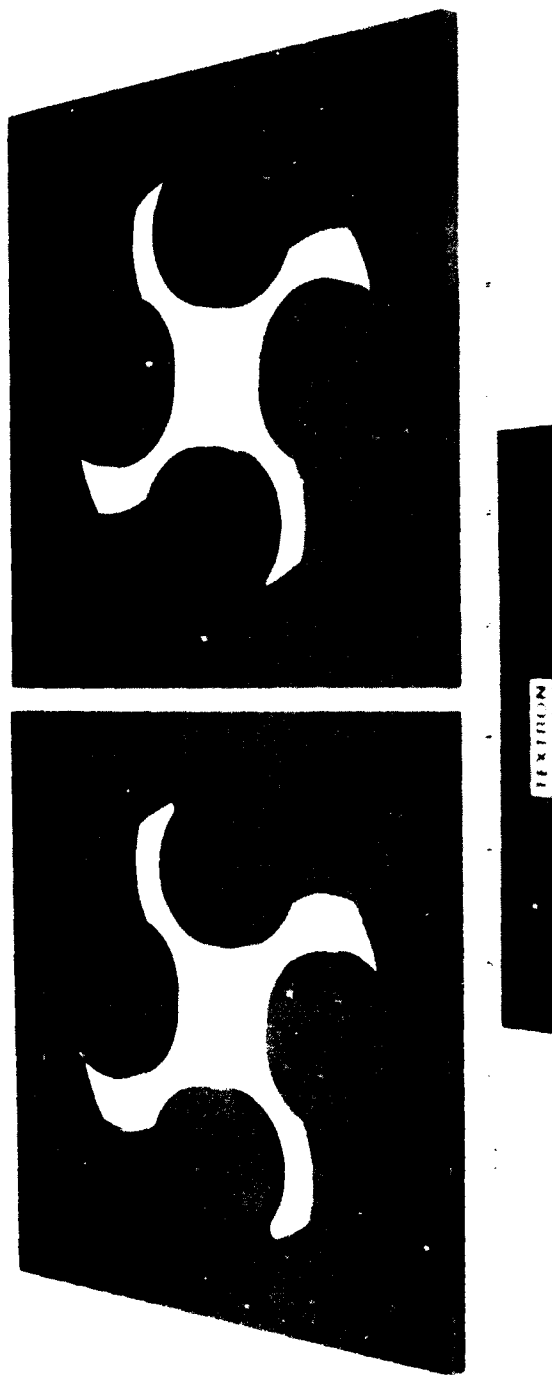


Figure 23. "Go no-go" gauge set used for inspection of contours of aft feed sprocket forging

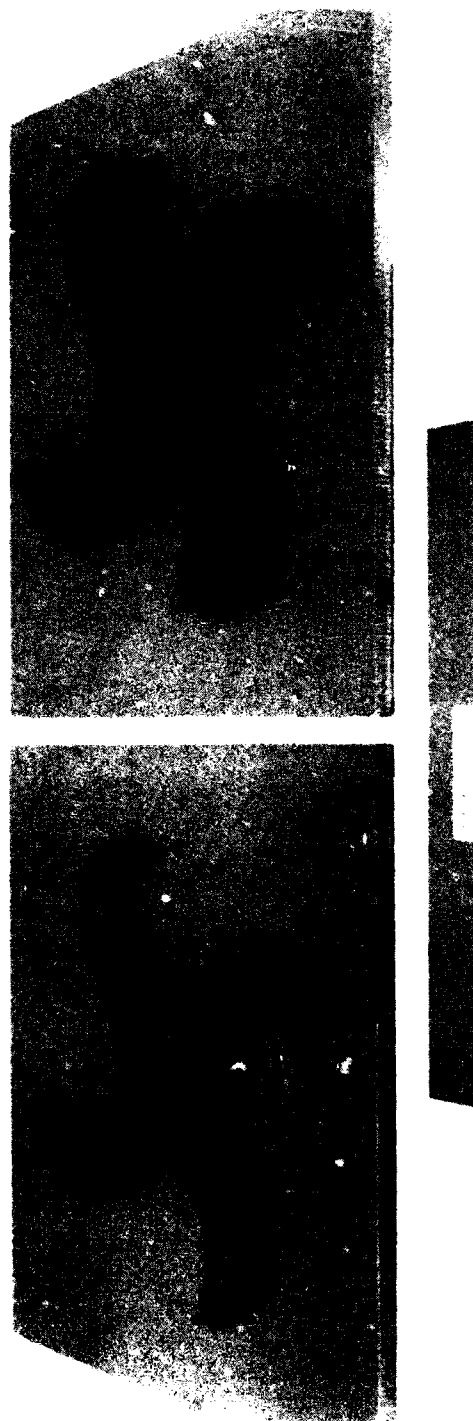


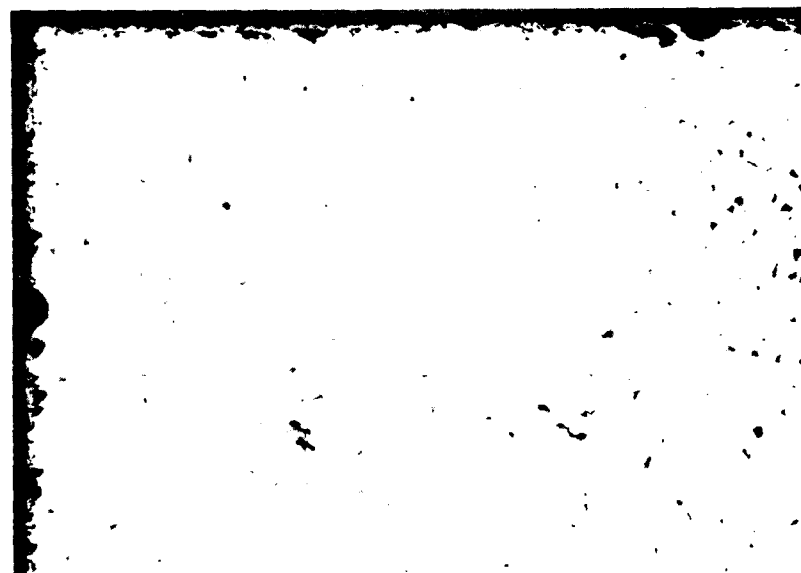
Figure 24. "Go no-go" gauge set with two acceptable aft feed sprocket forgings



Unetched

(a) Tip of Arm

50X



Unetched

(b) Midlength of Arm

50X

Figure 25. Porous microstructure in aft feed sprocket preform at two locations along length of arm



Unetched

(a)

100X



Unetched

(b)

400X

Figure 26. Surface finger oxides in aft feed sprocket forgings prior to heat treatment



Unetched

(a)

100X



Unetched

(b)

400X

Figure 27. Interparticle oxide networks in aft feed sprocket forging prior to heat treatment



Unetched

(a)

100X



Unetched

(b)

400X

Figure 28. Surface finger oxides in aft feed sprocket forging after heat treatment

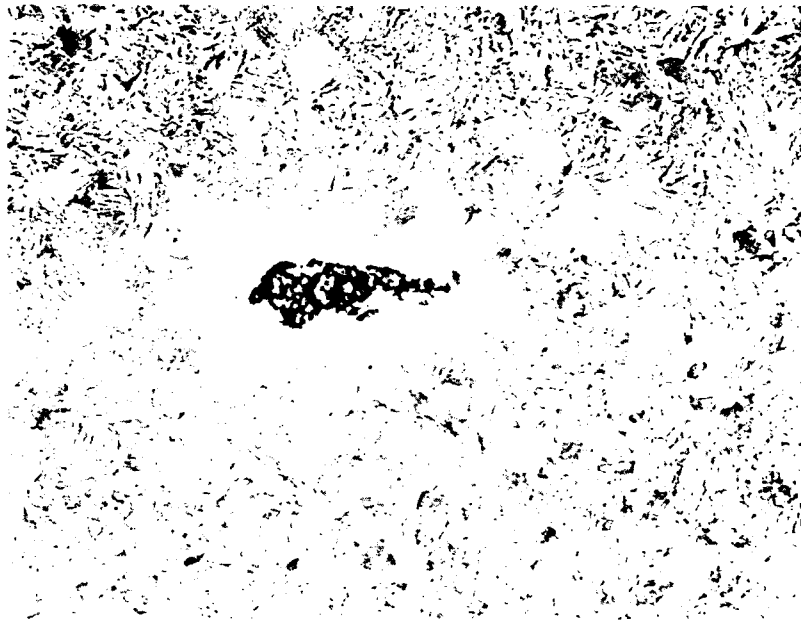


Figure 29. Apparent unalloyed iron particle in aft feed sprocket forging



Unetched

(a)

100X

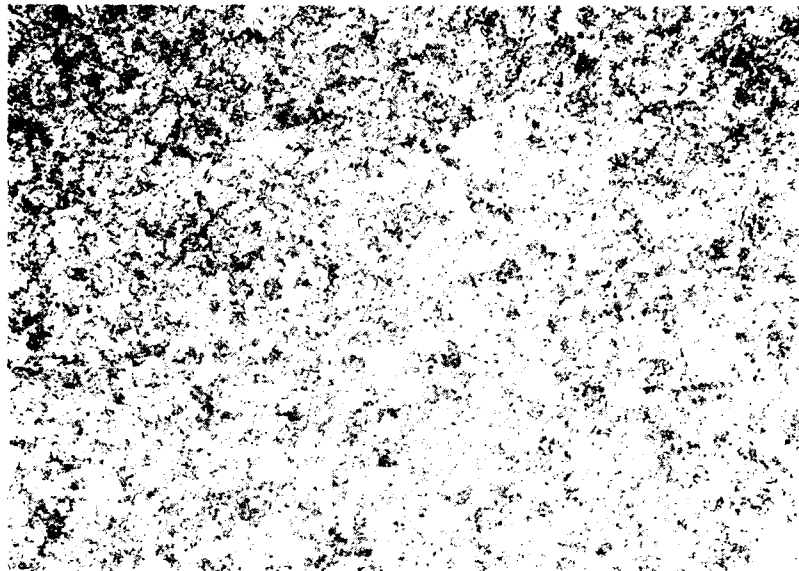


Unetched

(b)

400X

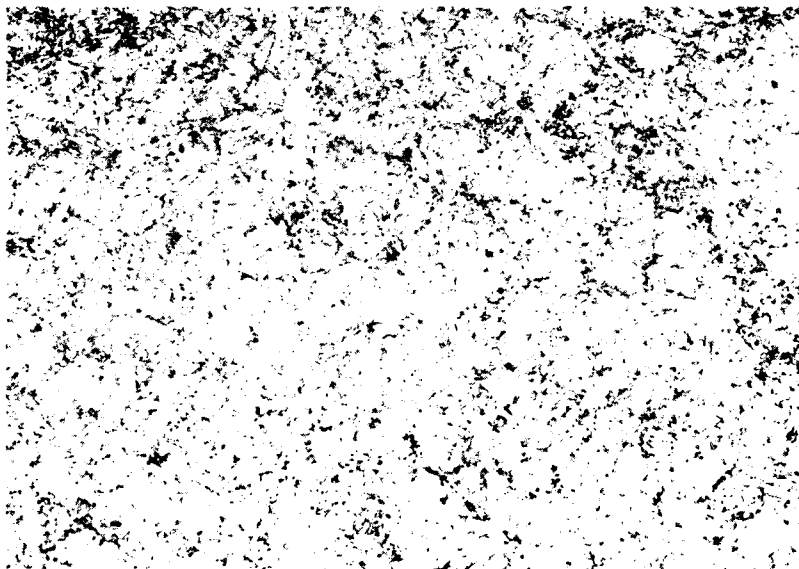
Figure 30. Large inclusion particle in aft feed sprocket forging



2% Nital

(a)

100X



2% Nital

(b)

400X

Figure 31. Tempered martensitic microstructure in aft feed sprocket forging after heat treatment

REFERENCES

1. Buzolits, Steven R., Antes, Harry W., and Burlingame, John W., "Specification for Hot-Forged Powder-Metal Steels," Progress in Powder Metallurgy, vol. 41, 1986, pp. 801-812.
2. Ro, D.H., Ferguson, B.L., Pillay, S., and Ostberg, T., "Powder Metallurgy Forged Gear Development," Contract No. DAAE 07-80-C-9115, U.S. Army Tank Automotive Command, August, 1984.
3. Buzolits, Steven, and Muzik, Joel, "Process Specification for Type 46XX Powder-Forged Weapon Components Phase I - Interim Technical Report," ARDC Contractor Report ARSCD-CR-85002, SPS Technologies, Jenkintown, PA, March, 1985.
4. Lenel, F.V., Powder Metallurgy - Principles and Applications, Metal Powder Industries Federation, Princeton, New Jersey, 1980.
5. Durdaller, Cornelius, Furnace Atmospheres, Technical Bulletin, Hoeganaes Corporation, Riverton, N.J., 1971.
6. Cook, John P., Degradation of P/M Forging Preforms During Interim Exposures in Air, Technical Bulletin, Hoeganaes Corporation, Riverton, N.J.

APPENDIX

DRAFT MILITARY SPECIFICATION

**FORGINGS, PREALLOYED STEEL POWDER,
P/F-4620, P/F-4640, and P/F-4660**

NOTE: This draft, dated October 1987, prepared by US Army Armament, Munitions and Chemical Command, has not been approved and is subject to modification. DO NOT USE FOR ACQUISITION PURPOSES. (FORG A155)

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MILITARY SPECIFICATION

FORGINGS, PREALLOYED STEEL POWDER, P/F-4620, P/F-4640 AND P/F-4660

1. SCOPE

1.1 Scope. This specification covers powder forged steel parts fabricated from a prealloyed 4600 (MPIF designation-see 6.6) steel powder plus admixed graphite.

1.2 Classification. Powder forged steel parts shall be furnished in one of the following compositions, grades and physical conditions, as specified (see 6.2):

Composition.

Composition - P/F-4620 Steel (AISI 4620-modified)

Composition - P/F-4640 Steel (AISI 4640-modified)

Composition - P/F-4660 Steel (AISI 4660-modified)

Grade.

Grade A - Minimum overall quenched and stress-relieved density of 7.73g/cm^3 . Maximum oxygen content of 900 ppm.

Grade B - Minimum overall quenched and stress-relieved density of 7.79g/cm^3 . Maximum oxygen content of 600 ppm.

Grade C - Minimum overall quenched and stress-relieved density of 7.81g/cm^3 . Maximum oxygen content of 350 ppm.

Physical Condition (Core hardness).

Condition 1 - As-forged and slow cooled, or normalized (hardness range as specified).

Condition 2 - As-forged, liquid quenched and tempered (hardness range as specified).

Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document, should be addressed to: Commander, U.S. Army ARDEC, US Army Armament, Munitions and Chemical Command, ATTN: AMSMC-TDA-S(D), Picatinny Arsenal, New Jersey 07806-5000 by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

AMSC N/A

AREA FORG

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

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2. APPLICABLE DOCUMENTS

2.1 Government documents.

2.1.1 Specifications and standards.

The following specifications and standards form a part of this specification to the extent specified herein. Unless otherwise specified, issues of these documents shall be those listed in the issue of the Department of Defense Index of Specifications and Standards (DODISS), and supplements thereto, cited in the solicitation.

STANDARDS

MILITARY

MIL-STD-105 - Sampling Procedures and Tables for
Inspection by Attributes

(Copies of specifications and standards required by contractors in connection with specific acquisition functions should be obtained from the contracting activity or as directed by the contracting activity).

2.2 Other publications. The following documents form a part of this specification to the extent specified herein. Unless otherwise specified, the issues of the documents which are DOD adopted shall be those listed in the issue of the DODISS specified in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS shall be the issue of the non-government documents which is current on the date of the solicitation.

ASTM

ASTM B311-86 Density of Cemented Carbides
ASTM D3951-82 Commercial Packaging
ASTM E3-80 Preparation of Metallographic Specimens
ASTM E8-86 Tension Testing of Metallic Materials
ASTM E18-84 Rockwell Hardness and Rockwell Superficial
Hardness of Metallic Materials
ASTM E23-86 Notched Bar Impact Testing of Metallic Materials
ASTM E350-86 Chemical Analysis of Carbon Steel, Low-Alloy
Steel, Silicon Electrical Steel, Ingot Iron, and
Wrought Iron
ASTM E384-84 Microhardness of Materials
ASTM E415-85 Optical Emission Vacuum Spectrometric Analysis of
Carbon and Low-Alloy Steel
ASTM E562-83 Determining Volume Fraction by Systematic Manual
Point Count
ASTM E768-80 Preparing and Evaluating Specimens for Automatic
Inclusion Assessment of Steel
ASTM E1019-85 Determination of Carbon, Sulfur, Nitrogen,
Oxygen, and Hydrogen in Steel and in Iron,
Nickel, and Cobalt Alloys
ASTM E1077-85 Estimating the Depth of Decarburization of Steel
Specimens

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(Application for copies should be addressed to ASTM, 1916 Race Street, Philadelphia, PA 19103.

METAL POWDER INDUSTRIES FEDERATION (MPIF)

MPIF Standard 35-87 Materials Standards for P/M Structural Parts

(Application for copies should be addressed to Metal Powder Industries Federation, 105 College Road East, Princeton, NJ 08540).

SOCIETY OF AUTOMOTIVE ENGINEERS, INC. (Aerospace Recommended Practice)

J423-83 Methods of Measuring Case Depth

(Application for copies should be addressed to the Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096.)

(Non-Government) standards and other publications are normally available from the organizations which prepare or which distribute the documents. These documents also may be available in or through libraries or other informational services.)

2.3 Order of precedence. In the event of a conflict between the text of this specification and the references cited herein, the text of this specification shall take precedence. Nothing in this specification, however, shall supersede applicable laws and regulations unless a specific exemption has been obtained.

3. REQUIREMENTS

3.1 First article. When specified in the contract or purchase order, a sample of the powder forged steel parts shall be subjected to first article inspection (see 4.4.1 and 6.2.2) and functional or simulated functional testing (see 4.4.2 and 6.2.3). First article powder forged parts shall be produced using the same processing practices that will be used during production of the parts.

3.2 Design, finish, dimensions and tolerances. The powder forged steel part design, finish, dimensions and tolerances shall conform to that shown on the applicable part drawing (see 6.2.1).

3.3 Powder properties. Powder forged steel parts shall be fabricated from a prealloyed 4600 (AISI 4600-modified) powder plus admixed graphite.

3.4 Powder forged properties. Properties of powder forged steel parts shall be in accordance with the requirements specified herein.

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3.4.1 Composition. Composition of powder forged steel parts shall be in accordance with the requirements of tables I, II and III when tested in conformance with 4.6.1. (Note: Chemistry of powder forged steel parts is a modification of the corresponding AISI designation).

TABLE I. Chemical requirements for powder forged steel parts.

<u>Element</u>	<u>Analysis (weight percent)</u>
Nickel	1.75 - 2.00
Molybdenum	0.5 - 0.6
Manganese	0.10-0.25
Copper	0.15 max.
Chromium	0.10 max.
Sulfur	0.03 max.
Silicon	0.03 max.
Phosphorus	0.02 max.
Total Iron	Balance*

*For information only. Quantitative determination of this element is not required.

TABLE II. Carbon content requirements for powder forged steel parts.

<u>Composition</u>	<u>Core Carbon Content (Weight Percent)</u>
P/F-4620	0.16-0.25
P/F-4640	0.36-0.45
P/F-4660	0.56-0.65

TABLE III. Oxygen content requirements for powder forged steel parts.

<u>Grade</u>	<u>Core Oxygen Content (ppm)</u>
A	900 max.
B	600 max.
C	350 max.

3.4.2 Density. The minimum overall density of powder forged steel parts or those sections of powder forged steel parts so designated by the applicable part drawing or contract or purchase order shall be in accordance with table IV when tested in conformance with 4.6.2.

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TABLE IV. Minimum overall density for powder forged steel parts.

Grade	Composition	Minimum Overall Density (g/cm ³)	
		Slow Cooled or Normalized	Quenched and Stress-Relieved
A	P/F-4620	7.76	7.74
	P/F-4640	7.76	7.74
	P/F-4660	7.75	7.73
B	P/F-4620	7.82	7.80
	P/F-4640	7.82	7.80
	P/F-4660	7.81	7.79
C	P/F-4620	7.84	7.82
	P/F-4640	7.83	7.81
	P/F-4660	7.83	7.81

Note: Density of carbonitrided or carburized parts to be not less than that of quenched and stress-relieved parts.

3.4.3 Mechanical and physical properties.

3.4.3.1 Hardness. The core hardness range of sectioned parts shall be in accordance with the applicable part drawing when tested in conformance with 4.6.3.1. The surface hardness range, if specified, shall be in accordance with the applicable part drawing when tested in conformance with 4.6.3.1.

3.4.3.2 Tensile and impact properties.

3.4.3.2.1 Grade A and B parts. Typical tensile and impact properties of Grade A and B parts are shown in table VII. These properties will have been met if all other requirements specified herein are met.

3.4.3.2.2 Grade C parts.

3.4.3.2.2.1 Small parts. When test specimens cannot be removed from the part, the typical tensile and impact properties for grade C parts shown in table VII will have been met if all other requirements specified herein are met.

3.4.3.2.2.2 Large parts. When test specimens can be removed from the part average tensile and impact properties of Grade C parts shall be not less than the average properties measured on first article parts when tested in conformance with 4.6.3.2 and 4.6.3.3. The applicable part drawing, contract or purchase order will designate the location from which the test specimens shall be removed and the type of test specimen to be tested.

3.4.4 Microstructure.

3.4.4.1 Surface finger oxide penetration. Maximum depth of penetration of surface finger oxides from the finished part surface in mm for each designated critical area of a powder forged steel part shall not exceed that measured on first article parts or as agreed upon between the contractor and the government when tested in conformance to 4.6.4.1 and Appendix A. Critical areas shall be designated by the applicable part drawing or the contract or purchase order.

3.4.4.2 Interparticle oxide networks. Presence of interparticle oxide networks in each designated critical area of a powder forged steel part shall not exceed that measured on first article parts or as agreed upon between the contractor and the Government when tested in conformance to 4.6.4.2 and Appendix A. Critical areas shall be designated by the applicable part drawing or the contract or purchase order.

3.4.4.3 Decarburization depth. Maximum depth of complete decarburization (only free ferrite present) of surfaces of powder forged steel parts shall not exceed 0.02mm (0.001 in.) and the depth of total or effective decarburization (depth at which core carbon content is reached) of surfaces shall not exceed 0.25mm (0.010 in.) when tested in conformance with 4.6.4.3.

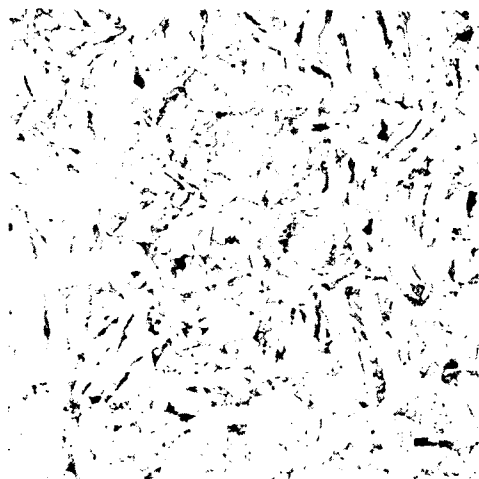
3.4.4.4 Case depth. Effective case depth of surface hardened (carburized or carbonitrided) powder forged steel parts shall meet the range specified by the applicable part drawing when tested in conformance with 4.6.4.4.

3.4.4.5 Critical area porosity. Maximum area percent porosity plus inclusions of each designated critical area of a powder forged part shall not exceed that measured on first article parts or as agreed upon between the contractor and the Government when tested in conformance to 4.6.4.5 and Appendix B. Critical areas shall be designated by the applicable part drawing or the contract or purchase order.

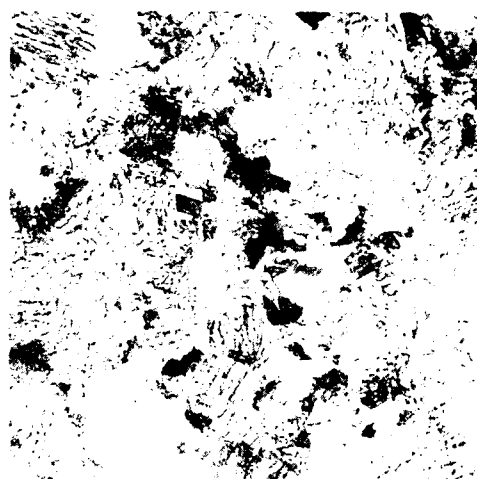
3.4.4.6 Non-metallic inclusion level. Non-metallic inclusion levels of Grade C powder forged parts shall not exceed 150 inclusion particles per 100 square mm greater than 30 μ m in length, 4.0 inclusion particles per 100 square greater than 100 μ m in length and 1.5 inclusion particles per 100 square mm greater than 150 μ m in length when tested in conformance to 4.6.4.6 and Appendix C. Non-metallic inclusion levels of Grade A and B parts shall not exceed that measured on first article parts or as specified in the contract or purchase order.

3.4.4.7 Iron contamination. Iron contamination of powder forged steel parts shall not exceed two percent by area when tested in conformance with 4.6.4.7 and Appendix D.

3.4.4.8 Microstructural uniformity. Microstructural uniformity of powder forged steel parts shall be equal to or better than the microstructure shown in figure 1 for slow cooled or normalized 4620 and 4660 forged parts and the microstructure shown in figure 2 for quenched and tempered 4620 and 4660 forgings when examined in conformance to 4.6.4.8. Microstructural uniformity of 4640 forgings shall fall in-between the microstructures shown for 4620 and 4660 forged parts.

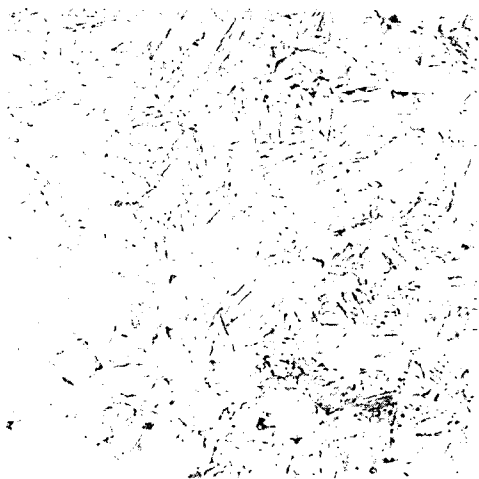


P/F 4620



P/F 4660

Figure 1. Examples of acceptable microstructure for powder forged steel parts slow cooled or normalized. Etched 2% Nital. 500X



P/F 4620



P/F 4660

Figure 2. Examples of acceptable microstructure for powder forged steel parts austenitized at 900°C (1652°F), liquid quenched in 65°C (149°F) oil with agitation and tempered at 177°C (350°F). Etched 2% Nital. 500X

3.5 Workmanship. Powder forged steel parts shall be uniform in quality and composition. Powder forged steel parts shall be free of tool marks, grinding scratches, laps, laminations, entrapped lubricant or other surface defects which may be detrimental to their performance.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the contractor is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or purchase order, the contractor may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.1.1 Responsibility for compliance. All items must meet all requirements of sections 3 and 5. The inspection set forth in this specification shall become a part of the contractor's overall inspection system or quality program. The absence of any inspection requirements in the specification shall not relieve the contractor of the responsibility of assuring that all products or supplies submitted to the Government for acceptance comply with all requirements of the contract. Sampling in quality conformance does not authorize submission of known defective material, either indicated or actual, nor does it commit the Government to acceptance of defective material.

4.2 Classification of inspections. The inspection requirements specified herein are classified as follows:

- a. First article inspection (see 4.4).
- b. Quality conformance inspection (see 4.5).

4.3 Inspection conditions. Unless otherwise specified, all inspections shall be performed under ambient conditions in accordance with the test methods specified in 4.6.

4.4 First article.

4.4.1 First article inspection. First article inspection samples shall be examined for all requirements specified herein (3.2, 3.3, 3.4 and 3.5) in accordance with the test methods specified in 4.6. The number of first article inspection samples to be examined will be specified in the contract or purchase order (see 6.2.2).

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4.4.2 First article functional testing. Testing procedures for functional or simulated functional testing and the number of samples to be tested will be specified in the contract or purchase order (see 6.2.3).

4.4.3 First article sample rejection. Failure of the first article samples to conform to the requirements specified herein (4.4.1 and 4.4.2) shall result in first article disapproval. Determination as to acceptability of any first article sample shall be based upon results of initial tests only and no second tests shall be permitted on that first article inspection sample.

4.5 Quality conformance inspection.

4.5.1 Inspection lot. An inspection lot shall consist of powder forged steel parts of the same design and size, produced from a single powder mix batch and from an unchanged process without discontinuity in production.

4.5.2 Design, finish and dimensional examination. Sampling shall be in accordance with MIL-STD-105, Level II, normal. The unit of product for sampling purposes shall be one powder forged steel part. The part shall be examined for defects in design, surface finish and dimensions. Any part not within the dimensional tolerances or surface finish specified on the applicable drawing shall be classified as a defect.

4.5.3 Quality conformance testing. Sampling shall be in accordance with MIL-STD-105 and as specified in table V. The unit of product for sampling purposes shall be one powder forged steel part. Acceptance number shall be zero and rejection number shall be one for all sample units.

TABLE V. Quality conformance tests.

<u>Examination or Test</u>	<u>Requirement</u>	<u>Test Procedure</u>	<u>Inspection Level</u>
Composition	3.4.1	4.6.1	1/Mix Batch
Density	3.4.2	4.6.2.1	II
Mechanical and Physical Properties	3.4.3	4.6.3	II
Surface Figner Oxide Penetration	3.4.4.1	4.6.4.1	S-1
Interparticle Oxide Networks	3.4.4.2	4.6.4.2	S-1
Decarburization Depth	3.4.4.3	4.6.4.3	S-1
Case Depth	3.4.4.4	4.6.4.4	S-1
Critical Area Porosity	3.4.4.5	4.6.2.2	S-1
Non-Metallic Inclusion Level	3.4.4.6	4.6.4.5	1/Mix Batch
Iron Contamination	3.4.4.7	4.6.4.6	1/Mix Batch
Microstructural	3.4.4.8	4.6.4.7	S-1
Workmanship	3.4.5		II

4.5.4 Classification of defects. Classification of defects shall be as specified in table VI. The unit of product for examination shall be one powder forged steel part.

4.6 Methods of test.

4.6.1 Composition test methods.

4.6.1.1 Sampling. Samples for chemical analysis shall be taken from the core area of the part. For oxygen and spectrometric analysis the sample shall consist of a single solid piece carefully cut using a cutting fluid to prevent overheating. After cutting, the piece shall be washed with acetone to remove the cutting fluid and dried at 70-100°C. For carbon and wet chemical analysis, drillings, chips or solid pieces shall be removed without the use of water, oil or other lubricant, and with care to prevent overheating. Care shall be taken to keep dirt and foreign substances out of the sample.

4.6.1.2 Chemical analysis test methods. Chemical analysis for the elements copper, chromium, manganese, molybdenum, nickel, phosphorus and silicon shall be determined in accordance with ASTM E350 or E415 (preferred method). Analysis for the elements carbon and sulfur shall be determined in accordance with ASTM E1019. Analysis for the element oxygen shall be determined using an approved inert gas hot extraction method.

4.6.2 Density test method. Density of complete or sections of parts shall be determined in accordance with ASTM B311.

4.6.3 Mechanical property test methods.

4.6.3.1 Hardness test method. Hardness measurements shall be determined in accordance with ASTM E18. Core hardness measurements shall be made on sectioned parts within the core region (see 6.3.1) of the part. Surface hardness measurements shall be made on the as-forged or machined part surface.

4.6.3.2 Tensile strength and percent elongation test method. Tensile test specimens shall be cut from parts in accordance with the applicable part drawing, contract or purchase description. Tensile specimens shall be tested in accordance with ASTM E8. Yield point shall be determined by the 0.2 percent offset method.

4.6.3.3 Impact energy test method. Charpy V-notch impact test bars shall be cut from parts in accordance with the applicable part drawing, contract or purchase description. Impact test bars shall be tested in accordance with ASTM E23 on a Government qualified machine.

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TABLE VI. Classification of defects.

<u>Category</u>	<u>Defects</u>	<u>Inspection Method</u> (See 4.6)
CRITICAL:		
1	Part not of design and dimensions specified (3.2)	Commercial Inspection Equipment (CIE)
MAJOR:		
101	Part not of composition specified (3.4.1)	CIE
102	Part density below specified limit (3.4.2)	CIE
103	Mechanical properties of large Grade C parts below requirements (3.4.3.2.2)	CIE
104	Surface finger oxide penetration exceeds maximum allowable (3.4.4.1)	CIE
105	Interparticle oxide networks exceeds maximum allowable (3.4.4.2)	CIE
106	Critical area porosity exceeds maximum allowable (3.4.4.5)	CIE
107	Non-metallic inclusion level exceeds maximum allowable (3.4.4.6)	CIE
108	Iron contamination exceeds maximum allowable (3.4.4.7)	CIE
MINOR:		
201	Part surface finish not as specified (3.2)	CIE
202	Part decarburization exceeds maximum allowable (3.4.4.3)	CIE
203	Case depth not well defined or outside of specified range (3.4.4.4)	CIE
204	Microstructural uniformity not as specified (3.4.4.8)	CIE
205	Part not free of tool marks, grinding scratches or other surface defects (3.5)	CIE

4.6.4 Microstructural test methods.

4.6.4.1 Surface oxide penetration test method. Surface finger oxide penetration shall be determined in accordance with the method specified in Appendix A.

4.6.4.2 Interparticle oxide network test method. Interparticle oxide networks shall be determined in accordance with the method specified in Appendix A.

4.6.4.3 Decarburization test method. The depth of complete decarburization shall be determined by the microscopical method in accordance with ASTM E1077. The depth of total or effective decarburization shall be determined by the microhardness method in accordance with ASTM E1077. The total or effective decarburization depth shall be the depth below the surface of the part where the hardness is no more than 30 units on the Knoop scale (200 g load) lower than the core hardness for quenched and tempered parts and 20 units on the Knoop scale (200 g load) lower than the core hardness for slow cooled or normalized parts.

4.6.4.4 Case depth test method. Effective case depth of surface hardened parts shall be determined in accordance with SAE Recommended Practice, J423, using either the hardness traverse procedure or the taper grind procedure of the mechanical methods.

4.6.4.5 Critical area porosity test method. Critical area porosity shall be determined in accordance with the method specified in Appendix B.

4.6.4.6 Non-metallic inclusion level test method. Non-metallic inclusion level shall be determined in accordance with the method specified in Appendix C.

4.6.4.7 Iron contamination test method. Iron contamination shall be determined in accordance with the method specified in Appendix D.

4.6.4.8 Microstructural uniformity test method. A metallographic specimen shall be removed from the powder forged steel part in the condition in which it is to be supplied. The polished surface of the specimen shall represent the core region of the part and shall be etched with a 2 percent nital etch. The etched surface of the specimen shall be compared with figure 1 or 2 depending on physical condition. It is recommended that the procedures described in ASTM E3 be followed for preparing the specimen.

4.6.5 Inspection of packaging. The sampling and inspection of the preservation, packing, and container marking shall be in accordance with the requirements of ASTM D3951.

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5. PREPARATION FOR DELIVERY

5.1 Packaging. The requirements for packaging of parts shall be in accordance with ASTM D3951 (see 6.2.1).

6. NOTES

6.1 Intended use. The powder forged steel parts are intended for use in small caliber (40mm or smaller) automatic weapons.

6.2 Ordering data. Acquisition documents should specify the following:

6.2.1 Acquisition requirements.

- a. Title, number and date of this specification.
- b. Composition, grade and physical condition (see 1.2).
- c. Whether first article inspection is required (see 3.1 and 6.2.2).
- d. Whether first article functional or simulated functional testing is required (see 3.1 and 6.2.3).
- e. Applicable drawings (see 3.2).
- f. Whether overall density or a designated section density is required (see 3.4.2).
- g. Whether mechanical properties of Grade C parts are required. If so, type of specimen and location from which test specimens are to be removed (see 3.4.3.3).
- h. Location of critical areas (see 3.4.4.1, 3.4.4.2, 3.4.4.5)
- i. Detailed packaging instructions (see 5.1).
- j. Provisions for the submission and approval of manufacturing process changes.

6.2.2 First article inspection. When a first article inspection is required, the part will be tested as specified in 3.1, 4.4.1 and 4.6. The number of first article inspection samples required will be specified in the contract or purchase order. The contracting officer should include specific instructions in the contract or purchase order regarding arrangements for inspection and testing of the first article sample. Invitations for bids should provide that the Government reserves the right to waive requirements for samples for first article inspection to those bidders offering a product which has been previously acquired or tested by the Government, and that bidders offering such products, who wish to reply on such production or test, must furnish evidence with the bid that prior Government approval is presently appropriate for the pending contract.

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6.2.3 First article functional testing. When a first article functional test or simulated functional test is required, the part will be tested as specified in the contract or purchase order (see 4.4.2). The contracting officer should include specific instructions in the contract or purchase order regarding the number of test parts required and arrangements for testing the parts.

6.3 Definitions.

6.3.1 Core region. The core region shall be defined as that region below the surface of a powder steel forged part where the microhardness is uniform within 30 units on the Knoop scale (200 g load) for quenched and tempered parts and 20 units on the Knoop scale (200 g load) for slow cooled or normalized parts.

6.3.2 Critical area. A critical area shall be defined by the applicable part drawing or the contract or purchase order.

6.4 Cross reference. Table VII shows typical mechanical properties for Grade A, B and C powder forged steel parts - for design considerations only. Table VIII is a guide for the selection of a Grade C powder forged steel composition and physical condition that will have equivalent mechanical properties to selected wrought steels.

6.5 Subject term (key word) listing.

Powder Metallurgy	Steel Forging
Powder forged steel	Steel

6.6 MPIF designation. MPIF designations specified herein are in accordance with Metal Powder Industries Federation.

Custodian:
Army - AR

Preparing Activity:
Army - AR

Review Activities:
Army -

(Project Forg A155)

User Activities:

TABLE VII. Typical mechanical properties for powder forged steel parts.

Core Hardness HRC	Grade	Yield Strength N/mm ² (KSI)*	Tensile Strength N/mm ² (KSI)	Elongation in 25mm (1 in.)%	Reduction of Area, %	Charpy Impact Energy (V-Notch)	
						Joules (Ft.-lbs)	
28	P/F-4620 Powder Forged Steels						
	A	903 (131)	986 (143)	7	22	8 (6)	
	B	896 (130)	965 (140)	12	45	27 (20)	
38	C	896 (130)	965 (140)	24	65	81 (60)	
	A	1027 (149)	1310 (190)	5	14	5 (4)	
	B	1034 (150)	1275 (185)	10	38	15 (11)	
28	C	1068 (155)	1310 (190)	20	56	47 (35)	
	P/F-4640 Powder Forged Steels						
	A	917 (133)	972 (141)	9	24	8 (6)	
38	B	917 (133)	979 (142)	17	48	28 (21)	
	C	896 (130)	965 (140)	22	58	61 (45)	
	A	1103 (160)	1317 (191)	3	13	5 (4)	
48	B	1138 (165)	1289 (187)	9	35	14 (10)	
	C	1068 (155)	1310 (190)	17	49	35 (26)	
	A	1282 (186)	1565 (227)	3	7	5 (4)	
28	B	1344 (195)	1627 (236)	7	26	8 (6)	
	C	1310 (190)	1586 (230)	11	39	16 (12)	
	P/F-4660 Powder Forged Steels						
38	A	862 (125)	951 (138)	10	23	8 (6)	
	B	827 (120)	924 (134)	17	44	27 (20)	
	C	896 (130)	965 (140)	20	52	47 (35)	
48	A	1103 (160)	1275 (185)	5	14	5 (4)	
	B	1110 (161)	1282 (186)	8	32	11 (8)	
	C	1068 (155)	1310 (190)	15	41	27 (20)	
28	A	1358 (197)	1654 (240)	3	8	5 (4)	
	B	1344 (195)	1654 (240)	6	22	7 (5)	
	C	1310 (190)	1586 (230)	10	30	14 (10)	

* Yield strength determined at 0.2 percent offset

TABLE VIII. Cross reference between wrought and grade C powder forged steels.

Typical Longitudinal Wrought Steel Properties ^a (Wrought properties are significantly higher in the longitudinal than in the transverse direction)					Typical Transverse Powder Forged Steel Properties (Powder forged properties are not significantly different between the longitudinal and transverse direction)					
AISI Corp.	Core Hardness HRC	Yield ^b Strength N/mm ² (ksi)	Tensile Strength N/mm ² (ksi)	Elongation ^c %	Reduction of area %	P/F Comp.	Yield ^b Strength N/mm ² (ksi)	Tensile Strength N/mm ² (ksi)	Elongation ^d %	Reduction of area %
4130	20	814 (118)	938 (136)	20	63	P/F-4620	896 (130)	965 (140)	24	65
	38	1165 (169)	1331 (193)	14	52	P/F-4640	1068 (155)	1310 (190)	17	49
4140	28	772 (112)	889 (129)	20	62	P/F-4620	896 (130)	965 (140)	24	65
	38	1055 (153)	1186 (172)	15	52	P/F-4640	1068 (155)	1310 (190)	17	49
	48	1469 (213)	1655 (240)	10	42	P/F-4660	1310 (190)	1586 (230)	10	30
4340	28	745 (108)	952 (138)	21	56	P/F-4620	896 (130)	965 (140)	24	65
	38	1214 (176)	1303 (189)	13	48	P/F-4660	1068 (155)	1310 (190)	15	41
	48	1524 (221)	1731 (251)	10	41	-	-	-	-	-
8650	28	862 (125)	952 (138)	19	59	P/F-4620	896 (130)	965 (140)	24	65
	38	1158 (163)	1276 (185)	14	48	P/F-4660	1068 (155)	1310 (190)	15	41
	48	1538 (223)	1724 (250)	16	41	-	-	-	-	-
9310	28	703 (102)	945 (137)	19	64	P/F-4620	896 (130)	965 (140)	24	65
	38	1034 (150)	1234 (179)	15	56	P/F-4620	1068 (155)	1310 (190)	20	56

a. Typical properties derived from the following sources:

Alloy Digest, Engineering Alloy Digest, Inc., Upper Montclair, NJ., Various dates.
Aerospace Structural Metals Handbook, Code 1201, 1203, 1209, Battelle Columbus Laboratories,
Columbus, OH, 1963, 1973, 1974.
Metals Handbook, 8th Ed., Vol 1 and 2; 9th Ed., Vol 1 and 4, American Society for Metals,
Metals Park, OH, Various dates.
Source Book on Industrial Alloy and Engineering Data, American Society for Metals,
Metals Park, OH, 1981.

b. Yield strength determined at 0.2 percent offset

c. Elongation determined for 2 in. or 50mm.

d. Elongation determined for 1 in. or 25mm.

APPENDIX A

METHOD FOR DETERMINING THE PRESENCE OF SURFACE FINGER OXIDE
PENETRATION AND OF INTERPARTICLE OXIDE NETWORKS OF LOW ALLOY
POWDER FORGED STEEL PARTS

10 SCOPE

10.1 Scope. This appendix covers a recognized microscopical method for determining surface finger oxide penetration and interparticle oxide networks in low alloy powder forged steel parts. This appendix is a mandatory part of the specification. The information contained herein is intended for compliance with the specification.

20 APPLICABLE DOCUMENTS

20.1 Other publications. The following document forms a part of this appendix to the extent specified herein. Unless otherwise specified, the issue of the document that is adopted by DOD shall be the one in the DODISS cited in the solicitation. Unless otherwise specified, the issue of the document which has not been adopted shall be the issue of the non-government document which is current on the date of the solicitation.

ASTM

ASTM E3-80 Preparation of Metallographic Specimens
(Application for copies should be addressed to ASTM, 1916 Race
Street, Philadelphia, PA 19103.)

30 TEST SPECIMENS

30.1 A metallographic specimen shall be removed from the powder forged steel part to cover each designated critical area. Critical areas shall be defined by the applicable part drawing or the contract or purchase order. Specimens shall be taken from the powder forged steel part in the condition in which it is to be supplied. The polished surface of the specimens shall be parallel to the forging direction.

40 PREPARATION OF SPECIMENS

40.1 In mounting the specimen for grinding and polishing, protection from rounding the edge of the part is essential. In polishing the specimen it is important that a clean polish be obtained and that edge detail of the part not be destroyed. Specimens shall be examined in the as-polished condition, free of the effects of any prior etching (if used). It is recommended that the procedures described in ASTM Method E3-Preparation of Metallographic Specimens be followed. Automated grinding and polishing procedures are recommended.

50 PROCEDURE

50.1 Surface finger oxide penetration.

50.1.1 Surface finger oxides are surface oxides which follow prior particle boundaries into a powder forged steel part from the surface and cannot be removed by physical means such as rotary tumbling. Examples of surface finger oxides are shown in Figure 1.

50.1.2 Scan the perimeter of the metallographic specimen, initially at a magnification of 100X and carefully examine each designated critical area at a higher magnification, e.g., 400X. Measure the maximum depth of penetration of surface finger oxides from the finished part surface in mm for each designated critical area.

50.2 Interparticle oxide networks.

50.2.1 Interparticle oxide networks are continuous or discontinuous oxides which follow prior particle boundaries in powder forged steel parts. Examples of interparticle oxide networks are shown in Figure 2.

50.2.2 Scan the perimeter of the metallographic specimen initially at a magnification of 100X. Carefully examine each designated critical area at a higher magnification, e.g. 400X. Record the presence of any interparticle oxide networks in the designated critical areas. If interparticle oxide networks are present in a critical area, compare them with those found in first article parts.

60 EXPRESSION OF RESULTS

60.1 Surface finger oxide penetration. Report the maximum depth of penetration of surface finger oxides from the finished part surface in mm for each designated critical area.

60.2 Interparticle oxide networks. Report the presence of interparticle oxide networks in each designated critical area. If interparticle oxide networks are present, report if they exceed those found in the first article parts.

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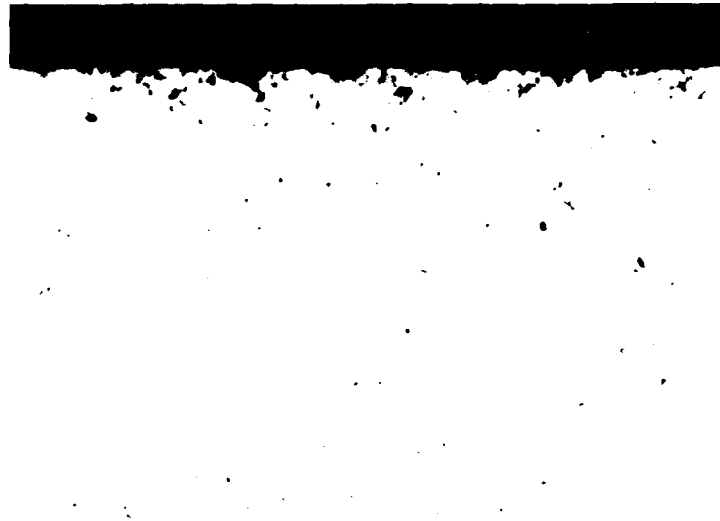
100X



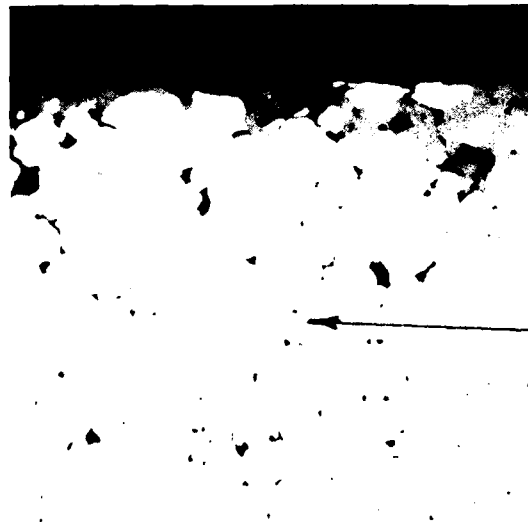
400X

Figure 1. Example of surface finger oxide penetration extending inward from the powder forged part surface. Shown more clearly at high magnification.

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100X



Surface finger
oxide

Interparticle
oxide network

400X

Figure 2. Example of interparticle oxide networks within a powder forged part. Shown more clearly at high magnification.

APPENDIX B

METHOD FOR DETERMINING THE POROSITY AND INCLUSION CONTENT OF
CRITICAL AREAS OF LOW ALLOY POWDER FORGED STEEL PARTS

10 SCOPE

10.1 Scope. This appendix covers a recognized microscopical method for determining the porosity and inclusion content of critical areas of low alloy powder forged steel parts. This appendix is a mandatory part of the specification.

20 APPLICABLE DOCUMENTS

20.1 Other publications. The following documents form a part of this appendix to the extent specified herein. Unless otherwise specified, the issue of the document that is adopted by DOD shall be the one in the DODISS cited in the solicitation. Unless otherwise specified, the issue of the document which has not been adopted shall be the issue of the non-government document which is current on the date of the solicitation.

ASTM

ASTM E3-80 Preparation of Metallographic Specimens

ASTM E562-83 Determining Volume Fraction by Systematic Manual Point Count

ASTM E768-80 Preparing and Evaluating Specimens for Automatic Inclusion Assessment of Steel

(Application for copies should be addressed to ASTM, 1916 Race Street, Philadelphia, PA 19103).

30 TEST SPECIMENS

30.1 A metallographic specimen or specimens should be removed from the powder forged steel part to cover each designated critical area, austenitized and quenched. Critical areas shall be defined by the applicable part drawing or the contract or purchase order. The polished surface of the specimens shall be parallel to the direction of forging.

40 PREPARATION OF SPECIMENS

40.1 In polishing the specimens, it is highly important that a clean polish be obtained and that inclusions not be pitted, dragged or obscured. It is recommended that the procedures described in ASTM Method E3-Preparation of Metallographic Specimens and E768-Preparing and Evaluating Specimens for Automatic Inclusion Assessment of Steel be followed. Automated grinding and polishing procedures are preferred when available. Specimens shall be examined in the as-polished condition, free of the effects of any prior etching. (If used).

50 PROCEDURE

50.1 Superimpose a grid of between 100 and 250 point count upon the microscope viewing screen for a portion of a designated critical area of the specimen. Select a magnification such that the size of the porosity or inclusions are approximately one-half of the spacing between grid points. Count and record the number of grid points falling upon porosity or inclusion particles within the field of view. (Note: Any grid point which falls on the porosity or inclusion boundary shall be counted as one-half. To avoid bias, questionable points shall be counted as one-half). Count successive equally spaced fields of view within the critical area until at least 6000 grid points have been superimposed on the area without overlapping. If 6000 grid points cannot be superimposed within the designated critical area, the specimen shall be repolished and the counting continued until the required grid points have been superimposed. The total number of grid points falling on porosity plus inclusions for all fields counted shall be divided by the total number of grid points superimposed to determine the surface area percentage of porosity plus inclusions.

60 EXPRESSION OF RESULTS

60.1 The area percentage of porosity plus inclusions shall be reported to the nearest 0.05 percent for each designated critical area of the part.

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APPENDIX C

METHOD FOR DETERMINING THE NONMETALLIC INCLUSION LEVEL OF LOW ALLOY POWDER FORGED STEEL PARTS

10 SCOPE

10.1 Scope. This appendix covers a recognized microscopical method for determining the nonmetallic inclusion level of low alloy powder forged steel parts. This appendix is a mandatory part of the specification. The information contained herein is intended for compliance with the specification.

20.1 Other publications. The following documents form a part of this appendix to the extent specified herein. Unless otherwise specified, the issue of the document that is adopted by DOD shall be the one in the DODISS cited in the solicitation. Unless otherwise specified, the issue of the document which has not been adopted shall be the issue of the non-government document which is current on the date of the solicitation.

ASTM

ASTM E3-80 Preparation of Metallographic Specimens

ASTM E768-80 Preparing and Evaluating Specimens for
Inclusion Assessment of Steel

(Application for copies should be addressed to ASTM, 1916 Race Street, Philadelphia, PA 19103.)

30 TEST SPECIMENS

30.1 A metallographic specimen should be removed from the powder forged steel part, austenitized and quenched. The polished surface of the specimen to be measured shall be not less than 350 square mm (0.54 square inch) in area. Multiple sections are permitted in order to obtain the necessary area for measurement on small parts. The polished surface should be parallel to the direction of forging, or as specified in the contract or purchase order, and should represent the core region of the part.

40 PREPARATION OF SPECIMENS

40.1 In polishing the specimens, it is highly important that a clean polish be obtained and that the inclusions not be pitted, dragged or obscured. It is recommended that the procedure described in ASTM Method E3-Preparation of Metallographic Specimens and E768-Preparing and Evaluating Specimens for Automatic Inclusion Assessment of Steel be followed. Automated grinding and polishing procedures are recommended. Specimens shall be examined in the as-polished condition, free of the effects of any prior etching (if used).

50 PROCEDURE

50.1 Survey at least 350 square mm (0.54 square in.) of the surface of the polished specimen at a magnification of 100X. Detected inclusions shall be sized on the basis of near neighbor separation. Features within 3mm of one another at 100X magnification (within 30 μ m (0.03mm) of one another on the specimen) are considered to be part of the same inclusion. For individual features below 0.03mm in length, three such features within 0.03mm of one another are required to constitute an inclusion aggregate. An individual feature less than 0.03mm in length will be added to an inclusion larger than 0.03mm, provided both features are within 0.03mm of one another. Examples are given in Figures 1 and 2. Measure and record the number of inclusion particles that are greater than 3mm in length (30 μ m on specimen) and greater than 10mm in length (100 μ m on specimen) and greater than 15mm in length (150 μ m on specimen) at 100X magnification.

60 EXPRESSION OF RESULTS

60.1 Report the number of non-metallic inclusions per 100 square mm that are (a) greater than 30 μ m (b) greater than 100 μ m and (c) greater than 150 μ m in length.

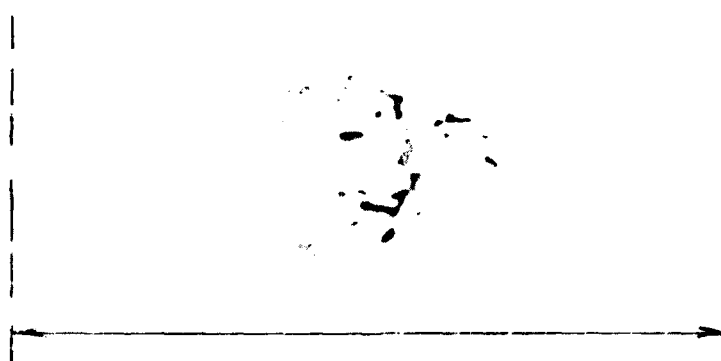


Figure 1. Example of a spotty oxide inclusion. Total length of inclusion to be recorded as indicated. 500X (The higher magnification is shown for illustrative purposes only.)

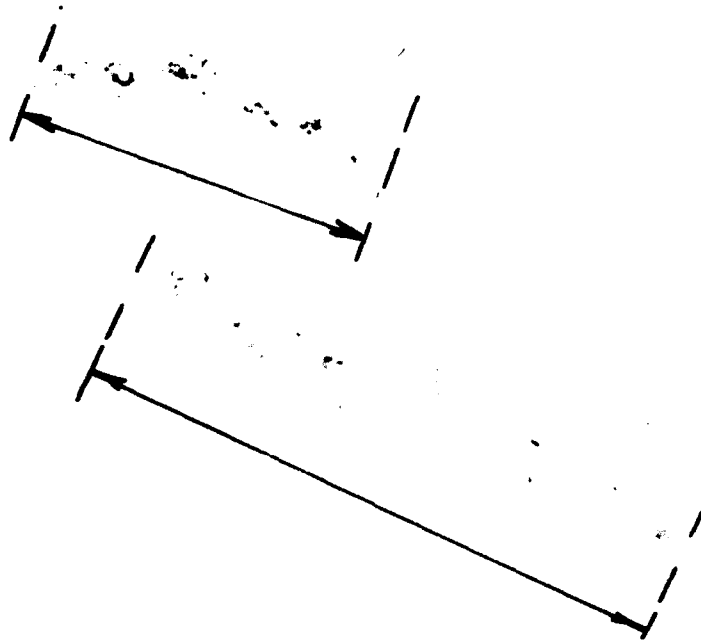


Figure 2. Example of discontinuous sulfide inclusions. Total length of inclusions to be recorded as indicated. 500X (The higher magnification is shown for illustrative purposes only.)

APPENDIX D

METHOD FOR DETERMINING UNALLOYED IRON CONTAMINATION OF
LOW ALLOY POWDER FORGED STEEL PARTS

10 SCOPE

10.1 Scope. This appendix covers a recognized microscopical method for determining the area percentage of unalloyed iron contamination in low alloy powder forged steel parts. This appendix is a mandatory part of the specification. The information contained herein is intended for compliance with the specification.

20 APPLICABLE DOCUMENTS

20.1 Other publications. The following documents form a part of this appendix to the extent specified herein. Unless otherwise specified, the issue of the document that is adopted by DOD shall be the one in the DODISS cited in the solicitation. Unless otherwise specified, the issue of the document which has not been adopted shall be the issue of the non-government document which is current on the date of the solicitation.

ASTM

ASTM E3-80 Preparation of Metallographic Specimens
(Application for copies should be addressed to ASTM, 1916 Race Street, Philadelphia, PA 19103.)

30 TEST SPECIMENS

30.1 A metallographic specimen not greater than 9mm (0.35 in.) in thickness should be removed from the powder forged steel part, austenitized and quenched. This is to ensure complete transformation to martensite in the low alloy areas. The polished surface of the specimen should be not less than 350 square mm (0.54 square inch) in area. Multiple sections are permitted in order to obtain the necessary area for measurement on small parts. The polished surface shall be parallel to the direction of forging or as specified in the contract or purchase order, and shall represent the core region of the part.

40 PREPARATION OF SPECIMENS

40.1 In polishing the specimens, it is highly important that a clean polish be obtained and that the unalloyed iron area not be dragged or obscured. It is recommended that the procedures described in ASTM Method E3-Preparation of Metallographic Specimens be followed. Automated grinding and polishing procedures are recommended.

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40.2 The polished specimen shall be lightly etched with a 2 percent Nital solution.

40.2.1 Etching Compositions:

40.2.1.1 2% Nital - 2ml Nitric acid, 98ml ethyl alcohol.

40.3 The polished and lightly etched specimen shall next be etched with an aqueous solution of sodium thiosulfate and potassium metabisulfite.

40.3.1 Etchant Composition:

40.3.1.1 3gm potassium metabisulfite, 10gm sodium thiosulfate and 100ml H_2O .

40.3.2 The etching time will depend on alloy type and carbon content. The greater the alloy content, the slower the etching rate; the greater the carbon content, the faster the etching rate.

40.3.3 A good contrast should be developed between the low alloy material and the iron contaminant. The iron contaminant will become darkened and the low alloy material will remain light. Other low alloy steel contaminants may also etch, but should be significantly lighter than the iron.

50 PROCEDURE

50.1 Superimpose a grid of between 100 and 250 point count upon a 100X magnified image (that is, a field of view) of the polished and etched specimen. Count and record the number of grid points falling upon iron contaminant particles. (Note: Any grid point which falls on the particle boundary should be counted as one-half. To avoid bias, questionable points should be counted as one-half) Counting successive discrete fields should be continued until at least 2500 grid points have been superimposed upon the specimen. The total number of points falling on iron particles for all fields counted shall be divided by the total number of grid points superimposed to determine the surface area percentage of iron contamination.

60 EXPRESSION OF RESULTS

60.1 The percentage of surface area iron contamination shall be reported to the nearest 0.1 percent.

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Commander
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