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Abstract

These notes summarize my experience modeling all moving parts of the DARPA diesel engine with Pro/Engineer 8.0. The purpose of the exercise has been to investigate the suitability and effectiveness of the design paradigm of an industrial modeling system.

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1 Introduction

One of the difficulties agile manufacturing has to address is the problem of implementing design paradigms that interface effectively with all steps of the manufacturing process. It is felt that this question is not so much a matter of devising geometric and analytic processing algorithms and infrastructure, but is in essence a problem of proper conceptualization. To approach this problem, a good strategy might be as follows:

1. Assess concretely the role of the design paradigm in the overall process, and identify the linguistic elements of successful design.

2. Implement the successful concepts in an open-ended, object-oriented problem-solving environment that maximally leverages existing infrastructure.

This case study evaluates as a point of reference the state-of-the-art in geometric modeling, using a realistic example, and quantifies what is possible with current tools. The results indicate that there is a strong potential for significant progress.

How long does it take to express an industrial-size design on an industrial-strength modeling system? How long *should* it take? To gain some insight into these questions, the DARPA diesel engine has been modeled in Pro/Engineer, version 8.0, on a Silicon Graphics 340 VGX with 64 MB main memory. The specifications for the engine came from blueprints originally prepared by the Engine Corporation of America.

I explicitly tracked the time spent interacting with the system. In addition, time has been spent reading the blueprints and devising a good sequence of modeling steps. This time has not been tracked explicitly, but an estimate is given later.

The models incorporate all design data of the blueprints except for tolerancing and surface finish specifications. Every effort has been made to implement the blueprints faithfully. However, there were several ambiguities in the drawings or outright mistakes. These have been documented in the session protocols, as well as the interpretation choices I made to correct them. The model files have been deposited with the National Institute of Standards and Technologies.[1]

2 The Modeling Process in Pro/Engineer

Parts are defined in Pro/Engineer as a sequence of features, beginning from a base feature (the *first feature*). Features generate or modify solid geometry (protrusions, cuts, blends, etc.) or add reference quantities (datums). Each feature must be explicitly related to features already constructed, by alignment and/or

[1] Contact Peter Brown, <brown@cme.nist.gov>, for instructions how to access the files.

dimensioning. This entails a parent/child relationship among the features that must be accounted for in modifications and in layering operations. "Rerouting" a feature means changing this relationship.

When constructing a feature, three activities are carried out. First, modifying attributes are chosen that select which variation of the feature construction will be used. For example, we may choose to construct a constant-radius blend of edges, as opposed to constructing a variable-radius blend. Then, the feature is placed; e.g., by selecting the edges to be blended. Finally, the feature is dimensioned, say by choosing the blend radius. For sketched features, placement is mixed in with dimensioning via the alignment operations and the dimensioning scheme.

The basic design cycle alternates feature specification, or modification, with feature generation, or regeneration. When editing the shape, which can be done at any time, features are added, deleted, or modified. In principle one can edit any feature, changing shape, placement and dimensioning. The changes entailed to dependent features are automatically made. General Boolean operations can be performed in assembly mode.

3 Stored Representations

Pro/Engineer stores parametric designs; i.e., the stored text describes how to construct the Brep, not the Brep itself. The file format is low-level and appears to be object code for a virtual geometry computer. The stored representation of the final assembly is approximately 30 mega bytes.

In addition, Pro/Engineer keeps a journal file that records textually all user input. This file, when replayed, regenerates literally every interactive gesture of the recorded session. The trail file can be significantly more compact. For example, the piston bridge trail file is less than one-tenth of the stored part file in size.

Pro/Engineer has a programming interface that gives access to the evaluated Brep and allows interfacing it with, say, a dynamics simulator. Whether similar access is possible at the parametric level of abstraction is unclear.

4 Summary of Modeling Times

Table 1 shows total times for modeling the parts. The parts were modeled one-by-one, in the order in which they appear in the table. Also shown is the final file size Pro created for each part. There is no strong correlation between file size and modeling time: Some simple operations such as mirroring can increase the parts file size significantly. Furthermore, when some operation did not behave as expected, devising a work-around on the spot sometimes took disproportionate amounts of time.

Connecting Rod	3.7 hrs	1,157,591 bytes
Bearing Cap	1.7 hrs	865,115 bytes
Pin plugging oil line	0.1 hrs	48,757 bytes
Piston Head	2.1 hrs	952,668 bytes
Middle Piston Skirt	0.3 hrs	581,287 bytes
Lower Piston Skirt	2.4 hrs	1,064,836 bytes
Piston Bridge	1.9 hrs	1,287,178 bytes
Crankshaft	3.5 hrs	6,381,421 bytes
Total Time	15.7 hrs	12,338,853 bytes

Table 1: Design Times for DARPA Engine Parts, and File Sizes

On one occasion I lost work: The piston bridge was completely modeled in 1.4 hrs, but the part was not stored in the final form and the journal file was incomplete because the file system was full. If Pro gave a warning I did not notice it. I also managed to crash the system on one occasion. Despite these few singularities, Pro/Engineer was a stable system to work with and overall very dependable.

The moving parts were assembled in several stages. First the connecting rod, the bearing cap, and the oil line plug. Here, a dimensioning error in the oil lines was discovered and corrected. Then, the four piston components were assembled. Another modeling error was discovered and corrected. Then, a single copy of all these parts was assembled into a global reference frame locating the three significant axes, one for the main bearing, one for the connecting rod bearing, and one for the piston wrist pin. Finally, these components were reflected on various datum planes of the frame to complete the assembly. In this final stage the modeling time is almost entirely computation time that Pro/Engineer took to compute mirror images and place them. The assembly times are summarized in Table 2.

Mirrored parts are not updated automatically. The two oil holes in the crank shaft that were added later were not propagated in the assembly. In consequence, the three other crankshafts had to be regenerated.

5 What Pro/Engineer Did Well

Modeling the engine was in many ways a natural activity for Pro/Engineer's design interface. The graphical definitions and shape editing operations are very efficient and well thought-out. This interface provides flexibility and direct

Connecting Rod Subassembly	0.4 hrs
Piston Subassembly	0.5 hrs
Engine Assembly	1.5 hrs
Total Time	2.4 hrs

Table 2: Assembly Times for DARPA Engine Parts

manipulation without sacrificing precision.

With few exceptions, the shape elements could be expressed easily and dimensioned in precisely the same way as specified on the blueprints. In particular, sketching things in a rough, but topologically correct way, and then dimensioning them to the required values was very straightforward. As the project continued, it became increasingly easier to adapt the modeling process to Pro's style and capabilities.

The most useful detail aspects of the interface were the explicit dimensioning scheme and the dimension representation when editing geometric shape. The "mirror" operation, and the various modalities of selecting shape elements (query select, select by menu, select by number) were also extremely useful. Not all operations utilize the full range of selection modalities, a deficit that should be easy to remedy in future system releases. The same applies to the very useful "make datum" operation that again is not available in some placement steps.

6 Where Pro/Engineer Had Problems

Pro/Engineer is counter-intuitive in the sense that the attribute sequencing is difficult to grasp for new users. Reading the manuals was definitely a must. This initial difficulty did not persist long, however. There were repeatedly problems when creating groups and patterning them. For examples see the construction logs of the piston head and the crank shaft. These problems are probably due to bugs.

Although Pro/Engineer does have Booleans in assembly mode, these operations are not explicitly available in parts mode. As the project progressed, I missed the Booleans less and less, except for some revolved cuts needed for the piston bridge and the lower piston skirt. A revolved cut cannot be ended at a reference surface, yet this capability is needed for those parts. It should be simple to add.

Pro/Engineer can perform extruded cuts that stop at the next positive surface ("thru next" attribute). In some situations, Pro does not detect the end correctly. One example are the oil passages in the connecting rod. The lateral passages will not stop at the central passage if the holes have equal diameter. The problem could be rooted in numerical precision or in the detection algorithm. Similarly, there is a problem if the cut begins with an edge on the exit surface as is the case in the piston head. Of course, one can work around this and create "blind" holes beginning at suitably placed datums.

While Pro/Engineer mirrors several features at once in parts mode, only single parts can be mirrored in assembly mode. The reason seems to be that mirrored parts are named and stored explicitly, but it would be useful to replicate or mirror subassemblies in their entirety. Note that the geometry of the mirrored part is not fully editable and no datum planes are available. Regenerating a mirrored part updates it from the reference part and incorporates the changes made to the original part after the mirror operation.

Since the elaboration of geometric constraints can be a very expensive computation, the constraint solver must have restricted capabilities, and this is the case here. The restrictions of the constraint solver seem to be relatively minor and only rarely were difficult to work around. An example is the cut at the lower outside of the lower piston skirt whose profile consists of three circular arcs. The sketcher would not regenerate this cross section, proclaiming it ambiguous, underdimensioned, or overconstrained depending on how it was drawn. Eventually I performed only a partial cut and completed it by feature mirroring.

Overall, the numerical precision of the system has been quite satisfactory although not exeptional. No attempt has been made to evaluate Pro/Engineer in this respect.

7 Conclusions

The total modeling time spent on this project has been under 20 hours, counting only the interaction with Pro/Engineer. Additional time was required to read the blueprints and plan a strategy for expressing the parts design on the system. This additional time is estimated at no more than another 40 hours. These figures clearly demonstrate that a good user interface makes a crucial contribution to raising the productivity of design tools.

When considering the entire manufacturing process, considerations would have to be given to other aspects of the user interface. For example, are the features defined in a way that makes subsequent manufacturing steps simpler, or are the features only of geometric significance? Such questions should be evaluated in a similar manner, for example using Pro/Engineer's other functionalities such as their FEM, sheet-metal, project, and manufacturing modules. The results of the present study should give grounds for much optimism here.

Manufaturing is a vast subject, and mechanical parts have widely-ranging shapes. I would not claim that the design paradigm of Pro/Engineer is well-suited in every case. For example, turbine-blade design may well require different design concepts and gestures. However, this experiment has clearly demonstrated that research into effective user-interfaces is important and has very substantial pay-offs. In fact, a good user-interface maximally leverages the underlying infrastructure.

A Appendix: The Session Protocols

The verbatim session protocols follow. Each session entry begins with the session date and the length of the session, in hours. The protocols are grouped by parts with a code identifying the defining blueprint. The parts and the final assembly are shown in the figures at the end of this report. The postscript files were produced by Pro/Engineer directly from the models.

A.1 Connecting Rod Components

```
Connecting rod; OP-07-03-01-001:

 3/14/92   1.5: Base feature at thickness of middle section.
Difficulties:  error in round spec of I-cutout
Interpretation of round for crank shaft reinforcement
inconsistent with draft angle cross section of slot
as well as with view E
Elect to construct reinforcement at matching draft
angle without base blend.  One could alternatively
reduce the outer diameter and fit a blend, or one
could reorder the slot and protrusion features.

 3/16/92   0.5: Elect to retract top extrusion by 0.02, so that it
can be blended to rod's midpart.

 3/17/92   1.5: Layered features.  In creating lubrication channels,
Pro's "thru-next" feature creation algorithm will not
stop when channel diameters are equal.  Feeders changed
to 0.1404R.  Side view of OP-07-03-01-001 suggests that
side cut of top part by 0.5R reaches front surface.
In this model it does not.  Pro unable to add 0.125R
round against top also.

 3/21/92   0.1: Added last oil channel and created layer 4.

 4/ 8/92   0.1: Changed diameter of oil channels, added inside chamfer
on bearing surface edge.
```

Connecting rod bearing cap; OP-07-03-01-002:

3/18/92 1.0: Base shape built by three extrusions across the bearing surface, and extrusions for the bolt holes. Then several cuts. Bolt support structure extruded "blind" instead of "thru-next". Because of this mistake, an additional cut has been made to remove excess material inside bearing surface.

3/18/92 0.5: Chamfers and blends added. Pro has trouble with complex terrace blending at left bolt support structure. Blends at bottom inside of both bolt protrusion cuts show that the blends are created sequentially.

3/26/92 0.2: Added hole for pin aligning bearing shells, along with datum planes and a cut to accommodate pin head.

Plug for lateral oil channel:

3/21/92 0.0: As fast as clicking allows, less than 5 minutes.

4/ 8/92 0.0: Changed diameter for adjusted dimensions in connecting rod.

A.2 Piston Components

Piston head; OP-07-05-00-001:

3/19/92 0.25: Piston head base feature. Chose to begin with a default datum plane arrangement whose common intersection should later serve in assembling the piston.

3/19/92 0.25: Basic rib extrusion added plus rib cuts. Difficulties in patternizing the cut radially. Pro refuses to go past 4th instantiation.

3/20/92 0.30: Patterned 3 cuts, mirrored to get the remaining ones. Organized cuts into layer 1. Elected to model the diagonal cut without imitating the cutting device, as a clean cut.

3/21/92 1.00: Tried to construct depression on cylinder head. Scheme tried unsuccessfully: Cut first the deep end as feature of revolution with vertical axis. Next, make a transition cut, 12 deg revolution of same cross section but with horizontal axis on top surface. Finally, cut an extruded feature with same cross section toward outsdide. Pro cannot properly cut this way. Tried various attribute variations unsuccessfully.

3/22/92 0.30: Made slanted cut beginning at the outside as blind cut. Accuracy problems due to shallow angle (12 deg). Higher accuracy could be obtained by a blended cut. Top view differs from blueprints possibly because of this.

Piston middle skirt; OP-07-05-00-013/XVII:

3/22/92 0.30: Began with default datum planes to position part wrt center of piston bridge. Lost time calculating radius of top groove incorrectly. A very simple part.

Piston lower skirt; OP-07-05-00-003:

3/24/92 0.75: Time lost with default precision settings of Pro. Blue prints do not fully dimension the peak of the diameter taper.

3/25/92 1.00: Bottom skirt cut. Several strategies tried. Pro has problems mirroring features that involve placement through silhouette alignment. Final strategy used: Chamfer the 30 cut a full 360, fill the excess cut so created with an extrusion from the bottom up. Remove excess fill with spherical cut. Pro needs an operation that allows "thru-next" for revolved features, otherwise their feature generation won't map to NC easily.

3/28/92 0.50: Added rounded cut to outside lower part. Several strategies used because Pro does not like to make three circles each tangent to the other, without worrying about conflicting constraints. Final cut a quarter plus two mirroring.

4/ 7/92 0.15: Deleted wrong pin hole and recreated it in the right place. Note that corrected part automatically appears in assembly.

Piston Bridge; OP-07-05-00-002:

3/28/92 1.40 Created half part, mirrored, then added holes and cut on symmetry plane. Either blueprints are inaccurately drawn or Pro has precision problems: holes on symmetry plane do not completely avoid exterior groove.
The part should have gone faster, but I made several mistakes. Recovery in Pro is nice. Many errors are fixed by redefining feature, including cross sections, placement scheme, and attributes. In the worst case, the feature is deleted and then correctly rebuilt.

4/ 1/92 0.50 Discovered that the final object was nort stored. Recovered work from incomplete trail file and added missing features to complete bridge.
Blueprints appear to indicate that center hole is larger than 0.25". But hole is not explicitlt dimensioned, so left it at 0.25.

A.3 Crankshaft

Crankshaft; OP-07-02-00-001:

4/ 6/92 1.00: Crank shaft created by a sequence of 180 revolutions. Each section is created from the center outwards, revolved around appropriate axis. Base feature is default datum planes. Specific issue with interpreting the fillets of excentric shaft sections. Drawing would indicate a slanted or variable-radius fillet that is, however, not specified. Chosen interpretation is to create a fixed-radius blends, against a larger disk, that is then trimmed with a final cut around the excentric disks.
Created half of the main bearing. Problem in mirroring the required cut of the excenter in the bearing sahaft. Changed attributes from "thru all" to "blind".

4/ 7/92 2.00: Added all remaining features except oil holes. Pro has difficulties placing bolt holes with sketched cross section (!) Holes eventually created as revolved cuts. No problem patterning them radially. Groove cuts at crank ends also a problem as Pro gets confused about its dimensioning. Final sequence: Place axis of revolution, sketch circular cut and three center lines to dimension it, regenerate. Now trim circle, losing center placement (!), add tangent lines and align ends; redimension center; regenerate.

4/ 9/92 0.50: Added forgotten oil holes. Procedure: create horizontal datum axis through the end points of both holes on the crank, create datum points by their intersection with the surface, create vertical datum axes through the points. Create two datum planes defining the axes of both holes. Create two datum planes perpendicular to hole axes, and offset by 0.75 from datum points to be clear of surface. Place radial holes "thru next" from these planes.

A.4 Assembly

Connecting Rod Assembly:

4/ 7/92 0.25: Assemble rod and bearing cap. Also, try to assemble oil plug -- but diameter appears to be wrong. Also regenerate connecting rod without any suppressed features because Pro seems unable to resume features from assembly mode.

4/ 8/92 0.15: Added oil plug to assembly. Regeneration fairly slow. Several trials to get positioning just so.

Piston Assembly:

4/ 7/92 0.50 Assembled all four piston parts. Lower skirt placed several times in error. Much time spent waiting for Pro to get things done. Lower piston skirt appears to have the pin hole incorrectly placed, which caused the previous placement errors.

Engine Assembly:

4/ 8/92 1.00: Constructed a reference frame for assembly, put together crankshaft, connecting rod subassembly, piston subassembly. Directory structure had to be flattened: While Pro can access parts in subassembly, the stored assembly description does not record the full access path, so it cannot recreate the assembly.
Much time goes to wait for regeneration to complete.
Second crankshaft and connecting rod subassembly created by

mirroring. The inability to mirror entire subassemblies is a deficit of Pro's capabilities.
Main issue: selectively turn off visibility without need to worry about feature sequencing and interdependence.

0.25: Mirrored the four piston components and one connecting rod. All time goes to waiting for generation to finish.

0.25: Mirrored remaining parts: 2 crankshafts, one connecting rod, two bearing caps. Oil channel plug for connecting rods has not been mirrored.

Figure 1: Connecting Rod

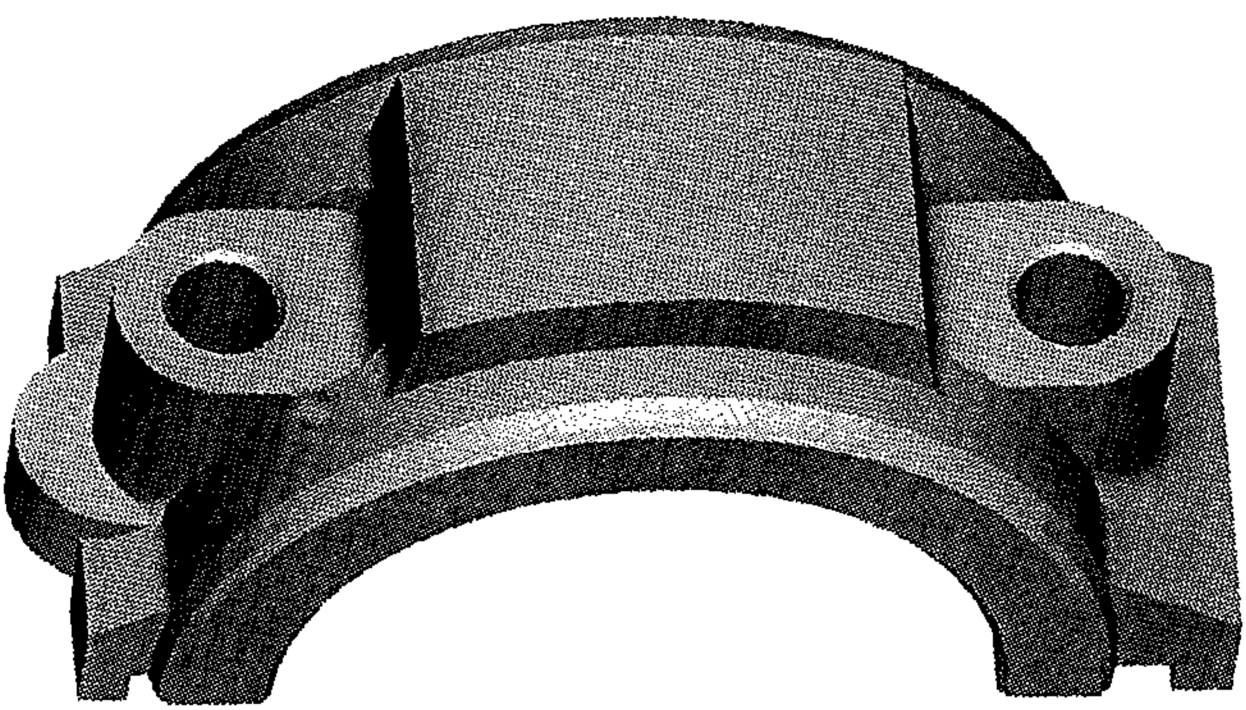

Figure 2: Bearing Cap

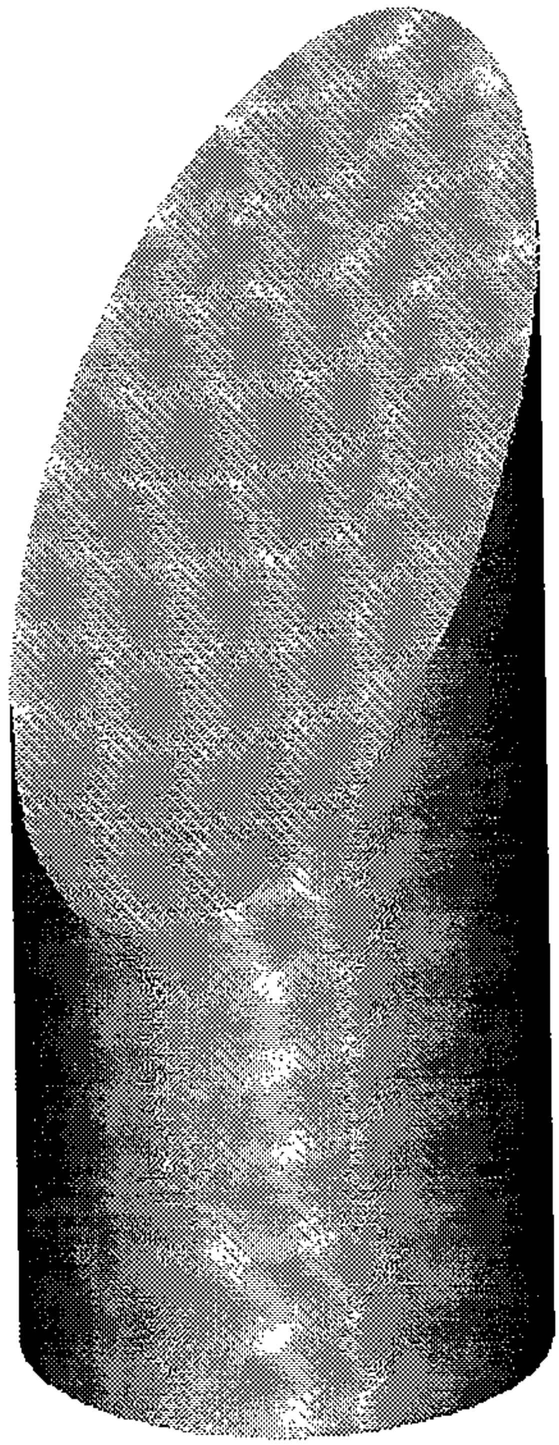

Figure 3: Oil Pin

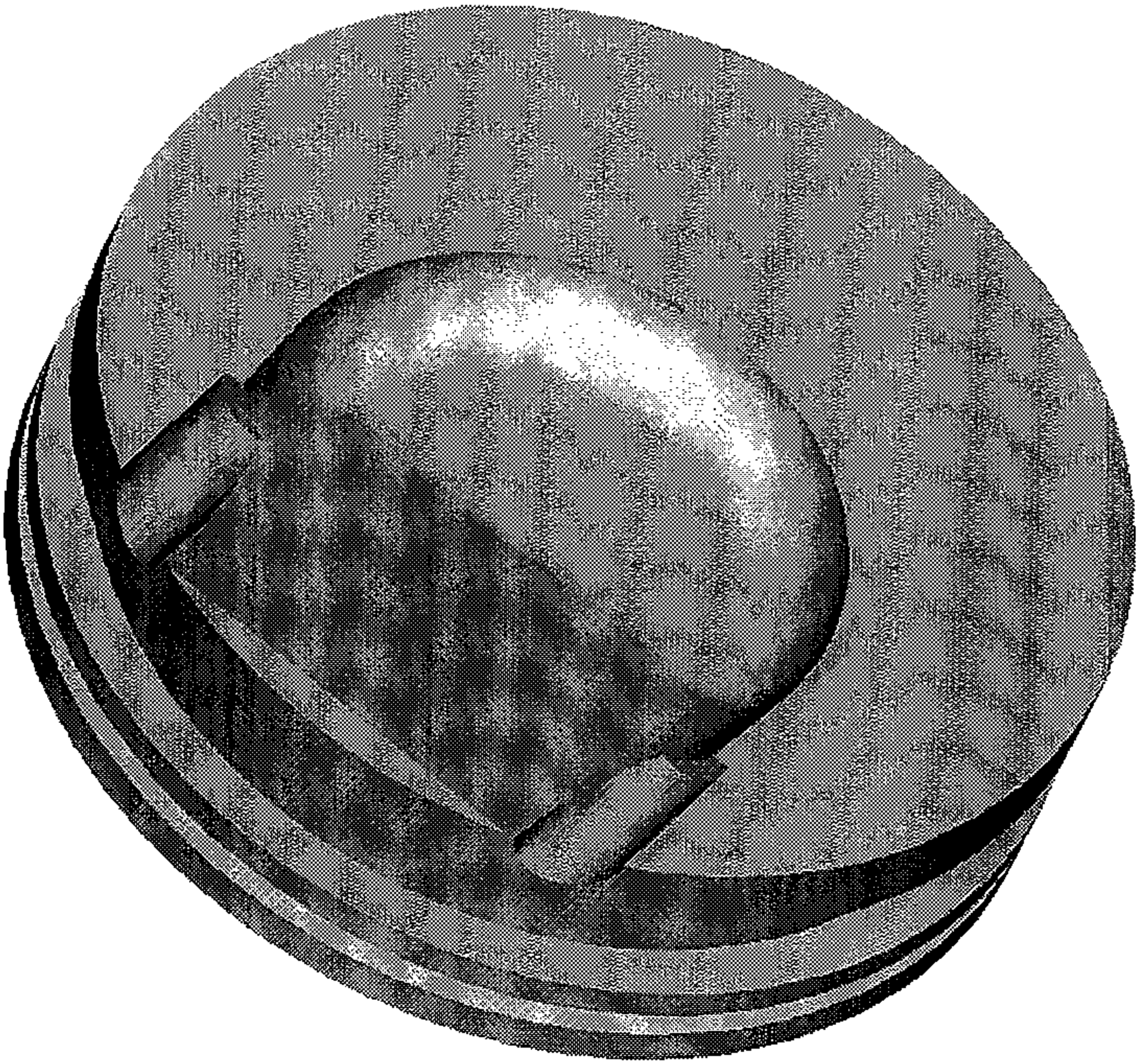

Figure 4: Piston Head

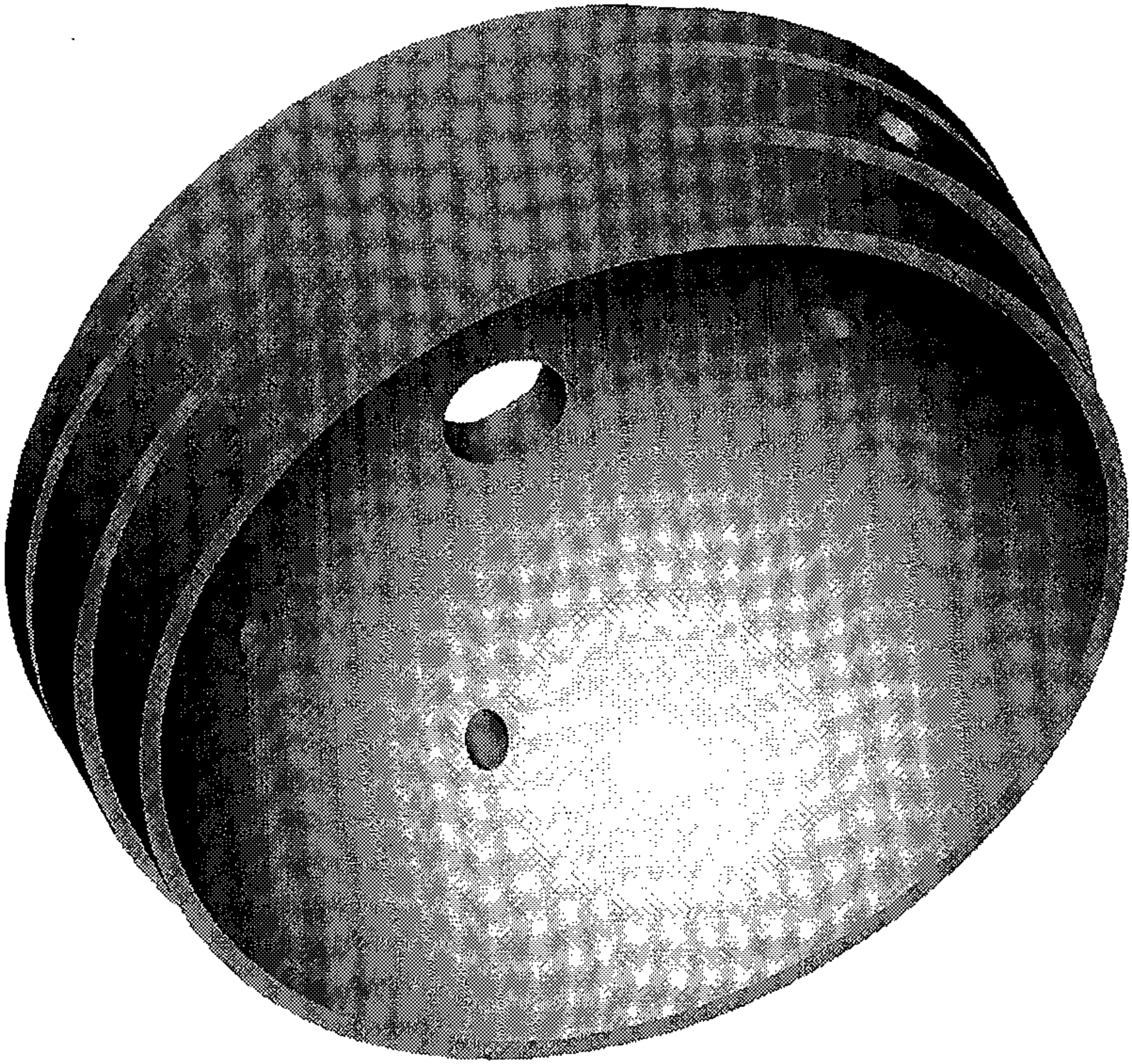

Figure 5: Middle Piston Skirt

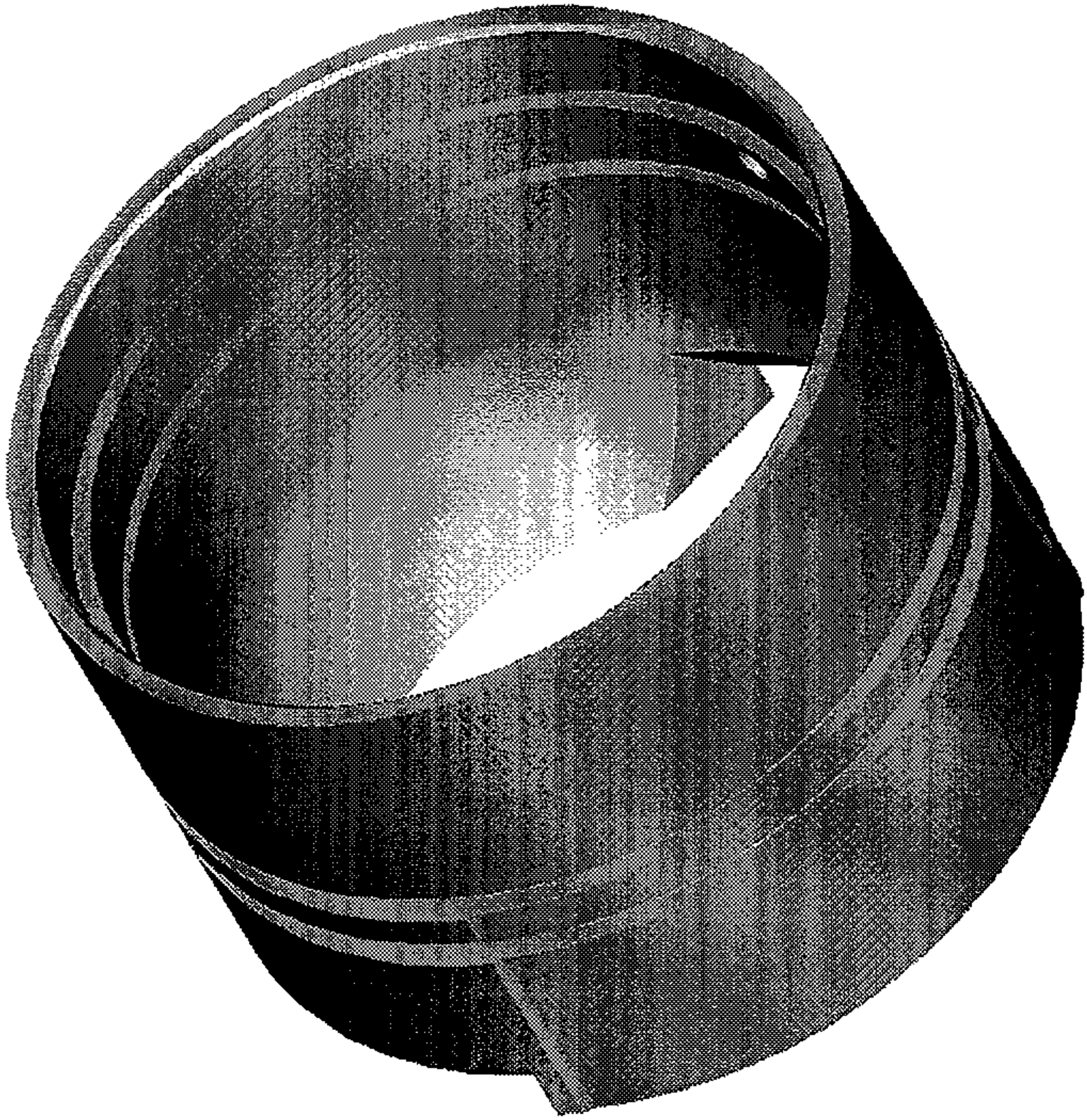

Figure 6: Lower Piston Skirt

Figure 7: Piston Bridge

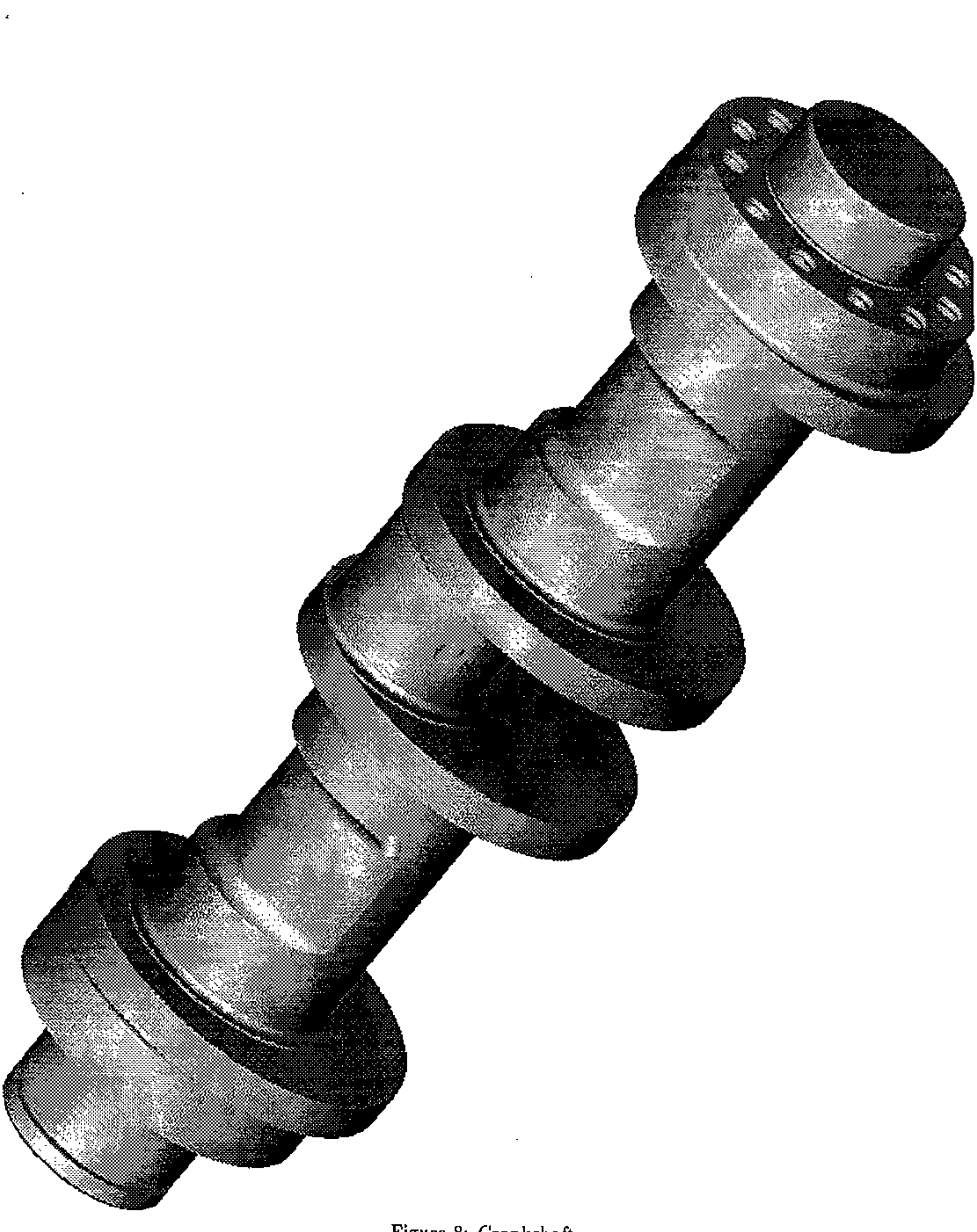

Figure 8: Crankshaft

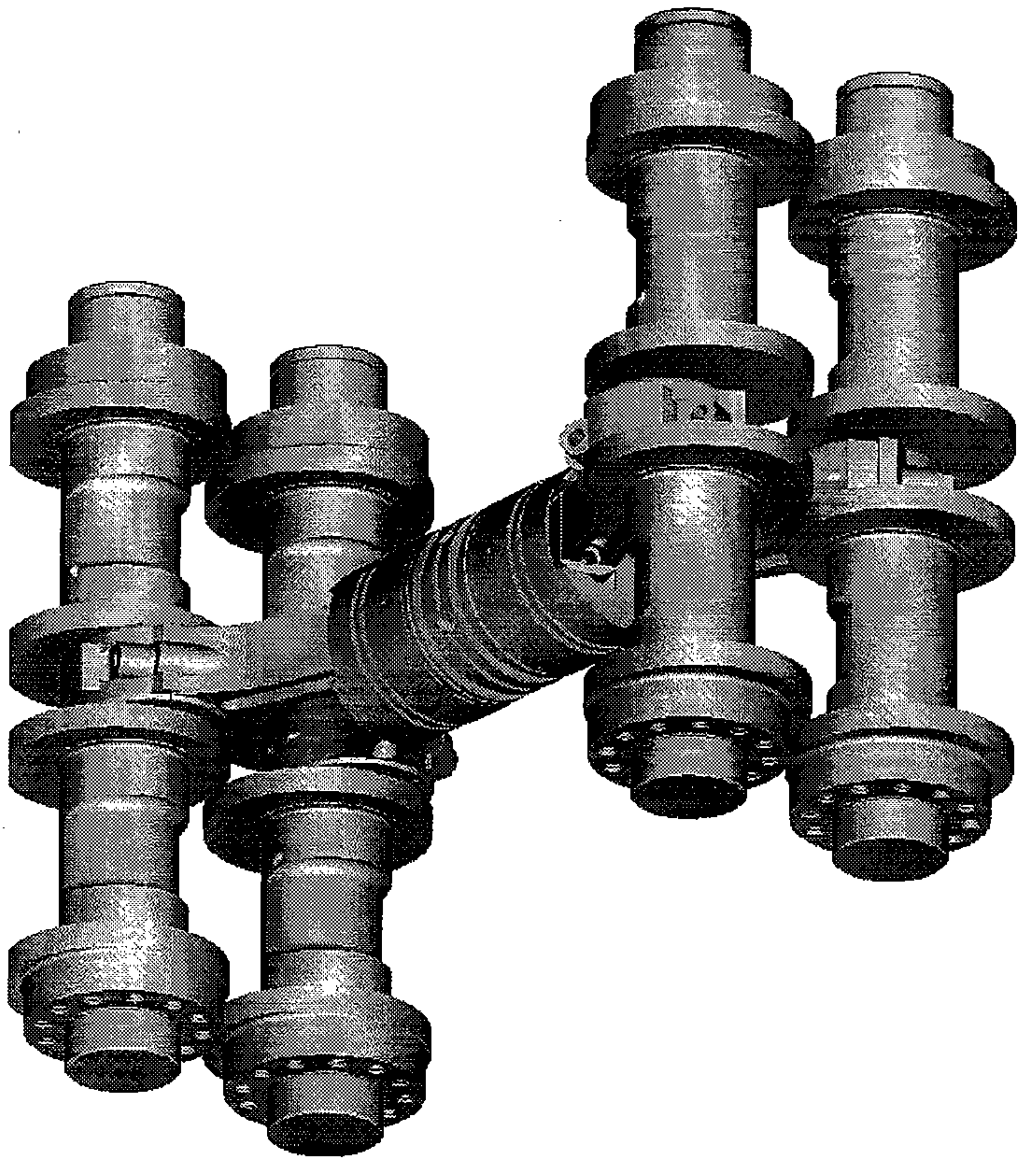

Figure 9: Engine Assembly