TOOL DESIGN
SECOND EDITION

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PREFACE

This textbook was written at the Rochester Institute of Technology as part of its program for developing teaching materials which are practical in nature and closely related to the actual requirements of industry.

General methods of tool design which enable the student to develop ideas into practical specifications for modern manufacturing methods form the basis of this work. An attempt has been made to broaden the base of study as much as possible, and for this reason, topics that may be dealt with in other courses, such as springs, welding, and tolerances, are included in so far as they apply to tool design.

An effort has also been made to apply some of the fundamentals and practices of the science of strength of materials to the actual design of tools. Equations have been set up and formulas derived wherever the development of these is within the capabilities of the student. Many problems have been fully worked out as examples, and students with passing grades in a course in strength of materials will be able to follow them and may be inspired to solve original problems assigned them. All the assigned problems are of a practical nature; many are taken from local industries, and all of them are of the type that young designers are likely to encounter during their first few years in industry.

It is not expected that all students will complete each assignment or solve every problem. On the other hand, it is hoped that some students will be stimulated to continue the study of some of the subjects for which we have laid the foundations. A list of references is given at the end of each chapter.

The material is arranged primarily for a course having lecture-discussion periods with laboratory or drawing time assigned. During these laboratory periods the problems may be assigned individually, with the instructor functioning in the role of chief designer in an industrial organization.

Many photographs are included to give the student an idea of the general nature of the tool to be designed. Thus it is possible for the instructor to advise, to give suggestions for design improvements, to indicate weaknesses and impractical ideas, and to counsel those needing additional assistance.

The authors are grateful to Charles Speidel, of the Eastman Kodak

Company, for his practical suggestions based upon a background of many years of tool and instrument making. They are also greatly indebted to Fred Buehler, of the Rochester Institute of Technology faculty, for his aid in preparing the section on automatic screw machines. Thanks are also due to W. H Armstrong of Pennsylvania State University, J. N. Edmondson of Ohio State University, and other colleagues in the tool engineering field.

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CHAPTER 1

INTRODUCTION

The term tool design has become recognized as meaning the design of special tools for the economical production of large quantities of machine or instrument parts. In order to understand what tool design is, as well as to understand its place in industry, it is necessary to consider a few aspects of modern manufacturing.

First and foremost, there is the need for economy. No matter what the product is or where it is going to be used, the objective of executives, engineers, salesmen, workmen, and all other members of a manufacturing concern is to produce a product of the highest possible quality at the lowest possible selling cost.

Selling Cost of a Product. The selling cost depends on many factors. Some of these, such as the cost of raw materials, interest rates, marketing expenses and so on, do not involve the tool designer directly. In others, such as the correct design of the product, the choice of raw materials, and the selection of manufacturing methods, the tool designer shares the responsibility with other members of the organization. Actual manufacturing costs, however, are the direct concern of the tool designer. He is always endeavoring to lower the factory cost of every article being fabricated. This is accomplished by the design of laborsaving tools and devices, as well as by keeping in mind the problem of the final assembly of the machine. This last point is important, since it would be useless to save money in machining a part only to find that the savings are lost by difficult assembly work.

Manufacturing Costs. Factory costs can be divided into two main groups: (1) investment charges on tools and equipment and (2) direct labor costs. Both must be as low as possible, and both directly influence each other. It is always possible to lower labor costs by investing in tools. Likewise, a saving in investment costs generally means higher labor costs. In all cases, a compromise must be made between these two conflicting requirements, and as much ingenuity and skill as possible should be used to ensure the best tool for the least expenditure.

Direct Labor Costs. These depend on the hourly wage rates, incentive payments, degree of skill needed, and amount of labor required. The last two items are the concern of the tool designer, since it is always possible to reduce the degree of skill needed and the amount of labor required by supplying better tools and equipment. But the new tools cost money, and this investment must be recovered by the economies effected. Each unit produced will have to carry its share of the equipment cost. If very large numbers are needed, the cost of new tools per unit will be very low. If, however, only a few units are needed, the cost of new tools may be prohibitive. Thus in the endeavor to ensure economical manufacturing, the most important factor is the number of identical units required.

Importance of Numbers. A survey of industry would show that many plants are producing goods for which the demand is limited. Capital goods, such as certain machine tools, locomotives, cranes, and so on, do not become obsolete or wear out very fast. Thus the market is small. Even if the selling price can be reduced, the demand is not increased very much. Consequently, special tools that can operate on only one particular machine part are too expensive to use. All production must be on versatile machine tools, even though the direct labor costs will be high. Tool designers are employed in plants producing special machines, but the field is limited. They cannot effect a large saving by the design of specialized tools.

On the other hand, plants manufacturing goods for which a very large potential market exists are always able to lower manufacturing costs by the use of special tools. The special tools, if well designed, will reduce the amount of labor and lessen the degree of skill required to produce the goods. The cost of the new tools may be very high, and if the model of the product is changed, they may be rendered valueless long before they are worn out; but while they are in operation, their first cost can be recovered from the very small charges on each unit.

Thus large numbers result in lower prices, and lower prices for certain products enable more people to purchase them. This sales increase allows a further decrease in manufacturing costs per unit. Under these conditions the possibility of the tool designer's making a large contribution to the success of the company is very great. Products for which a large potential market exists include automobiles, refrigerators, typewriters, electric motors, hand tools, radio receivers, and cameras. All these and many others can be sold in ever-increasing numbers if the price can be reduced to a point at which the public is willing and able to pay.

Tool Profit and Loss. When considering the "tooling up" for a given production, the question arises as to how large the batch must be in order to pay for the cost of planning, special tooling, and setting up the equipment. Another way of expressing the question is "How soon will these tools pay back the money spent on them?"

Of course, no definite or certain answer can be given, and in all cases management must assume a risk. Markets may not be as expected, or interest rates and taxes may be increased, but this is no reason for neglecting an analysis of all the costs and earnings involved, with a view to giving the tool designer an estimate of how much his tools should cost; that is, whether he should design expensive tools with high production rates or low-cost tools of limited output.

Several formulas have been developed by J. W. Roe for the determination of the probable profit on proposed new tooling. One of these is

$$N = \frac{CG + S}{a(1 + t)}$$

where N = minimum number of pieces that should be made per year
C = dollar cost of jig or fixture including design, drafting, and overhead if designed in the plant or price if purchased
G = annual total allowance for interest, taxes, depreciation, repairs, and storage, %
S = yearly cost of setting up tools and machine
a = dollar saving in labor costs per unit
t = percentage of overhead on labor saved

NOTE: The larger the values of C, G, and S, the larger the number of parts needed. The larger the values of a and t, the smaller the number required.

Example: Assume that 170 workpieces are needed per year and that it costs \$10 to set the tools up for a run. It is estimated that a new jig will save \$0.60 per workpiece and that the overhead charged to direct labor is 50 per cent of the labor costs. Overhead costs are 6 per cent for interest, 4 per cent for fixed charges, taxes, insurance, and rent, 50 per cent for depreciation, and 10 per cent for repairs, all adding up to a total of 70 per cent. How much should be spent on the new tool?

Solution:

$$N = \frac{CG + S}{a(1 + t)}$$

$$170 = \frac{0.7C + 10}{0.60 \times 1.5}$$

$$C = \$204$$

This is the amount that should be spent on the new tool of which about \$68, or 33 per cent, should be spent on design. The actual percentage of the total cost varies with different companies, and there is no established rule. In general, the cost of designing jigs and fixtures is about 33 per cent of the total cost of the tool, that of die sets about 25 per cent, and for gages 15 per cent. In studying these values, it should be remembered that most die-set designs have fewer details than jig and fixture designs of equal manufacturing costs and that gages require close tolerances that raise manufacturing costs in comparison to design costs. Furthermore, if more than one tool of identical design is needed, the percentage of design cost to manufacturing cost will be lowered.

Economic Lot Sizes. After the special tools are made, another problem confronts the production manager and, to a certain extent, the tool designer. This is the economic size of a manufacturing batch for a given set of tools and market. The chief factor here is the cost of tooling up, that is, dismantling the old production line, putting the old tools in storage, bringing out the new jigs and fixtures, and rearranging machines and conveyor systems. To this must be added the clerical labor to issue the orders and the loss of time while the factory production is zero.

Considering these items, the first consideration would be to order as large a lot as possible and to store the surplus until it could be sold. But storage under modern conditions is very expensive, and a point is reached where, for a given market, the cost of storage plus interest offsets the gain due to a large production run.

The designer's interest in this is to reduce, as far as possible, the cost of tooling up. This is not easy, but much can be done by avoiding unnecessary weight in jigs and fixtures, by utilizing machines already in the production line, and by following established procedures as much as possible.

Various methods for the determination of economic lot sizes have been developed. Some of these consist of the tabulation of estimated values and the plotting of total costs against the number of lots. The lowest point on the curve gives the most economical production. Many formulas have also been developed; one by Camp[1] is

$$Q = \left(\frac{20RS}{C}\right)^{1/2}$$

where Q = order quantity
R = numbers absorbed by market each year
S = setup cost per run, dollars
C = total cost per workpiece, dollars, with 10 per cent interest rate to cover investment in parts and storage

Example: Records show that a plant can sell 15,000 pistons per year and that the cost of setting up for a run (apart from tool or machine costs) is \$300. If it costs \$4 to make each piston when all charges except selling and advertising are considered, how many pieces should each lot contain in order to have the lowest over-all cost?

Solution:

$$Q = \left(\frac{20RS}{C}\right)^{1/2} = \left(\frac{20 \times 15{,}000 \times 300}{4}\right)^{1/2} = 4743$$

[1] Alford, L. P., and J. R. Bangs, "Production Handbook," The Ronald Press Company, New York, 1945.

This indicates the economic size of the lot, but for practical purposes and for convenience in ordering, this figure should be rounded out to 5000, which would make three runs per year and simplify the scheduling procedure.

Designing and Supplying Factory Tools. There are many different types of tooling-up methods, and we cannot study all of them thoroughly here. Only a general view of the part the tool designer plays in modern industry can be presented.

Most tooling-up programs start when a new product or a new model of a product is to be manufactured. However, tooling-up programs are often undertaken with a view to providing new tools for a product that has been steadily increasing its sales for some seasons. The increased sales justify the expense of the new tools. In addition tool designers are often called upon to redesign tools that are not quite satisfactory in service or to improve tools where operators, foremen, and others offer worthwhile suggestions.

Specifying Tools. When the design of a product is released by the engineering department, blueprints of all parts are sent to the tool-design department. The tool engineers and the factory executives then begin the study of the manufacturing program. The tool engineers must be familiar with the equipment and resources of the factory. They must learn the approximate number of units to be made, and they must be able to estimate the amount of money that is available for investment in new tools. The sales department is the principal source of the first piece of information, and the general manager has the final decision as to expenditures. Sometimes the general manager requests an estimate of the proposed cost of the new tools, which he approves or modifies; or he may tell the tool engineers how much they are allowed to spend.

After careful consideration has been given to these items, the tool engineers start to line up the machine tools and to break down the manufacturing process into individual operations. Each part is carefully examined. An experimental model may be available, or they may work from blueprints.

Redesign for Economical Manufacture. The part will have been designed by *product engineers*. These will be primarily responsible for the proper functioning of the part. They should, however, have given some consideration to economical manufacture. But since they are not so closely connected with detailed shop processes as the tool engineers, they may have overlooked a few possibilities. Consequently the tool engineers first consider the redesign of the part for easier production. Under no circumstances are they allowed to make any changes themselves, but they should offer suggestions to the engineering department. In case of conflicts as to economy of production versus correct functioning of the part, the engineering department always makes the final decision.

An example of a redesign for less expensive manufacture is shown in Figs. 1·1 and 1·2. Figure 1·1 shows a design of a connector for two rubber hoses fastened to a frame. The unit is quite satisfactory as to performance, but it is expensive to manufacture. Piece *A* is turned down from bar stock 1⅜ in. in diameter, seven holes are drilled, and three are tapped. In addition three screws are required, each of which must be handled

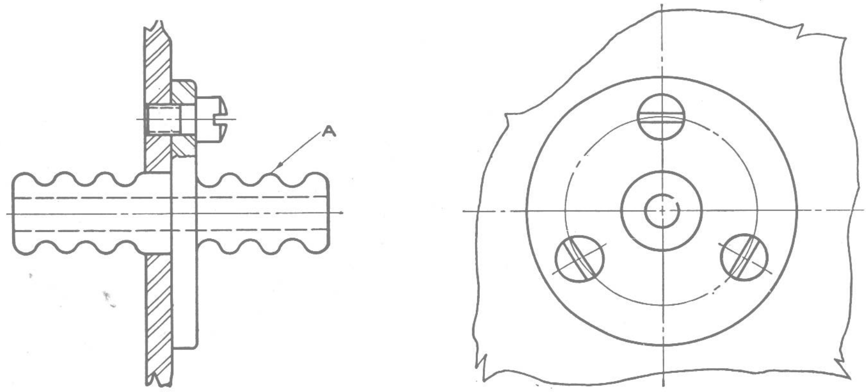

FIG. 1·1. Original connector.

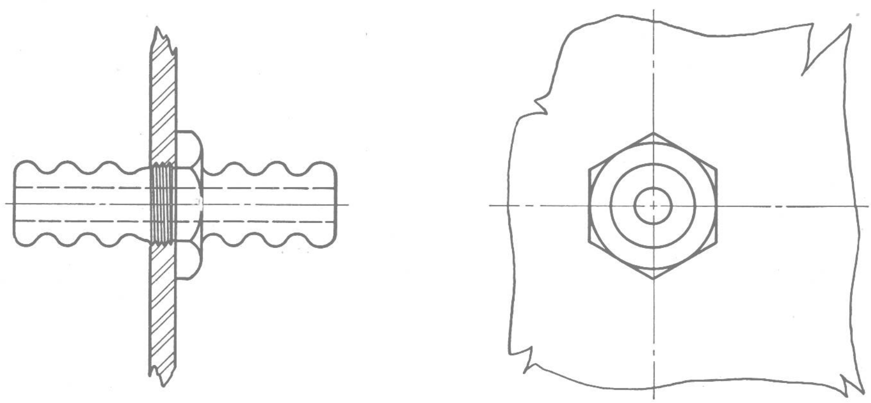

FIG. 1·2. Redesigned connector.

separately at assembly. Figure 1·2 shows the same connector redesigned for economical manufacturing. The stock size is reduced, ⅝-in. hexagon stock being specified. Only one hole has to be drilled and tapped. Furthermore the assembling is less time-consuming. It is obvious that both designs are equally satisfactory in service. The saving due to this redesign was estimated at 50 per cent.

Another example of redesign for less expensive manufacture is the small bracket shown in Fig. 1·3, which was originally designed as a casting. Since these were to be manufactured in lots of 10,000, the tool engineers,

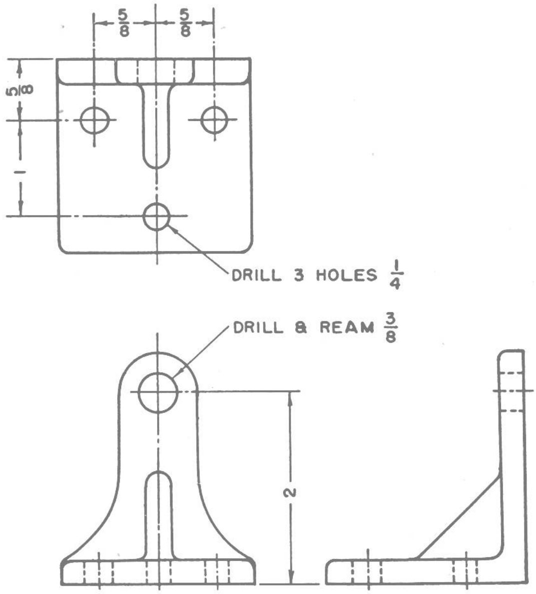

FIG. 1·3. Cast bracket.

mindful of the economy of the action of punch presses, suggested a redesign to a stamped part, as shown in Fig. 1·4. A question arose as to whether the stamped bracket would be sufficiently rigid without a rib, but after careful study the product designers were satisfied that the stamping would function satisfactorily.

An estimate of the costs is as follows: For the casting, the tool costs are

Pattern	$12	
Milling fixture	26	
Drill jig	22	
Total		$60

Production costs are estimated as

Foundry cost (including material)	$575	
Milling	425	
Drilling	300	
Surface finishing	200	
Total		$1500
Total cost of 10,000 parts		$1560

For making the stamping, two press operations are necessary, and the tools would cost:

Compound blanking and piercing die set	$150	
Forming die	80	
Total		$230

Production costs are estimated as

Stock	$ 72	
Blanking and piercing	135	
Forming	105	
Surface finishing	100	
Total		$412
Total cost of 10,000 parts		$642

The estimated saving by redesign is therefore $918.

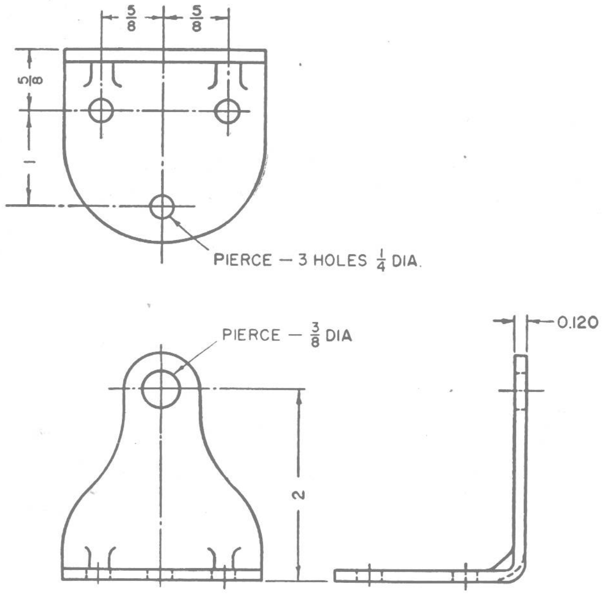

FIG. 1·4. Stamped bracket.

Redesign to Reduce Scrap. Sometimes the tool designer can effect an economy of manufacture by reducing the amount of material that is scrapped.

Example: A circular flange 150 in. outside diameter (OD) and 120 in. inside diameter (ID) was to be flame-cut from 3/8-in. flat plate.

As originally specified, the scrap would have been 16,138 sq in. or 1572 lb per flange. At a price of 7 cents per pound this would cost $110. However, instead of cutting a complete circle from a single plate, the tool designer proposed to cut the flange in nine pieces from three plates, as shown in Fig. 1·5. The scrap would then be only 1750 sq in., and the cost $11.90 per flange. If the cost of welding is estimated at 2 cents per inch, the cost per flange would be $9 \times 15 \times 2 =$ $2.70, and allowing 40 cents for the extra flame cuts, we have a net saving of $95.

This same value can be obtained by subtracting the total cost of the three small plates from the cost of the large plate.

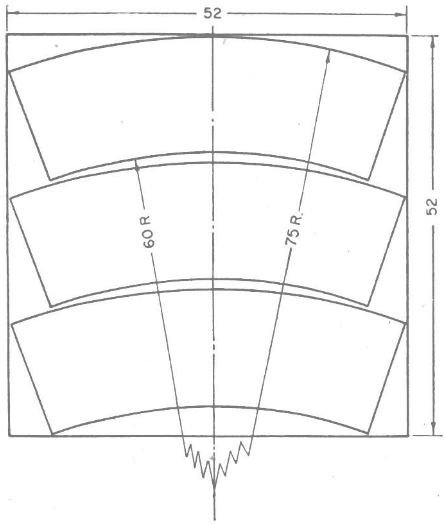

FIG. 1·5. Flanged section.

Machine-tool Selection. The machine tool is selected on the basis of lowest cost to manufacture. The first consideration should always be given to a machine already in the plant, since the fixed charges, such as interest, taxes, maintenance, and so on, against an old machine are less than those of a new machine. Also an old machine may be taken from idleness, which is always a long step toward economical manufacturing. But it may happen that all the machines in the plant are unsuitable for the particular process under consideration. Or perhaps a new machine tool has recently been put on the market which has an improved performance over similar older machines. Consideration should be given to this aspect. A new machine may cost less to operate, but its initial cost may offset the savings. Only careful judgment can make the decision, which always must be considered on the merits of each individual case.

Operations Sheets. Once the machine tools are selected, the individual operations are listed. An operation consists of all the work that can be done at one setup. A typical operation sheet is given in Table 1·1 for the workpiece shown in Fig. 1·6. A study of this will show that operations are not always made consecutively on the same machine but are made in the order that will reduce the number of required motions to a minimum. The tool engineer is always trying to reduce the number of operations by skillful planning. For example, he endeavors to design dies for multiple operation rather than to allow the operations to be performed on a number of punch presses.

The Tool Designer's Task. Once the operations are listed, the name of the machine, a description of a given operation, and a blueprint of the part to be made are given to the tool designer. The task of the designer is to provide drawings of a tool or set of tools to make the workpiece. He will be told the number of parts required, and he will have his experiences of the factory facilities available. If large numbers are required, then an expensive tool may be justified. If only a few parts will be needed, then the tool must be inexpensive. In all cases the tool must be made as economically as possible for the required service. The tool should be easy and safe to operate; it should also look practical and attractive, but it certainly should not have unnecessarily elaborate trimmings or needless complexity. This latter point is very important, since even experienced designers sometimes may let their enthusiasm for fine mechanisms lead them to develop excellent tools that are not practical from the standpoint of cost. Of course, striving to obtain economy may be overdone, and unsatisfactory tools produced. It is a question of good judgment based on experience. In order to complete his task the tool designer must produce a complete set of drawings showing (1) an assembly drawing, (2) if

TABLE 1·1. MACHINE-TOOL LINE-UP FOR PRODUCTION OF CONNECTING ROD (FIG. 1·6)

No.	Machine	Operation
1	Bench	Inspect forging
2	Snagging grinder	Remove flash by grinding
3	Duplex miller	Straddle mill-boss faces at *A*
4	Drill press	Drill bearing-cap bolt holes at *B*
5	Drill press	Spot-face bearing-cap bolt holes at *B*
6	Milling machine	Slit crank boss at *C*
7	Drill press	Drill and CSK oil hole at *D*
8	Surface grinder	Grind mating faces of cap and rod at *C*
9	Milling machine	Mill face for bolt at *E*
10	Bench	Assemble rod and cap
11	Drill press	Rough-drill wrist-pin hole in boss
12	Two-spindle horizontal boring mill	Bore twist-pin and crank-pin holes simultaneously
13	Universal reaming fixture (hand)	Ream wrist-pin and crank-pin holes
14	Surface grinder	Finish-grind boss faces at *A*
15	Magnaflux	Inspect

the design is complex, one or more subassemblies, (3) a detail drawing of each part, (4) a complete list of parts needed to make the tool. These are handed to the toolmakers, whose task it is to make the tools.

The Professional Requirements of a Tool Designer. The tool designer must first know manufacturing procedures. He must be able to visualize exactly how the workpiece is to be made. He should be competent to judge the merits of different methods. For example, the tool designer should be able to determine whether a workpiece should be made on a shaper or a milling machine, or whether another workpiece should be a stamping or a die casting. The product designer in the engineering department will also have a share in making decisions relative to the advantages of a particular stamping to a corresponding die casting, and

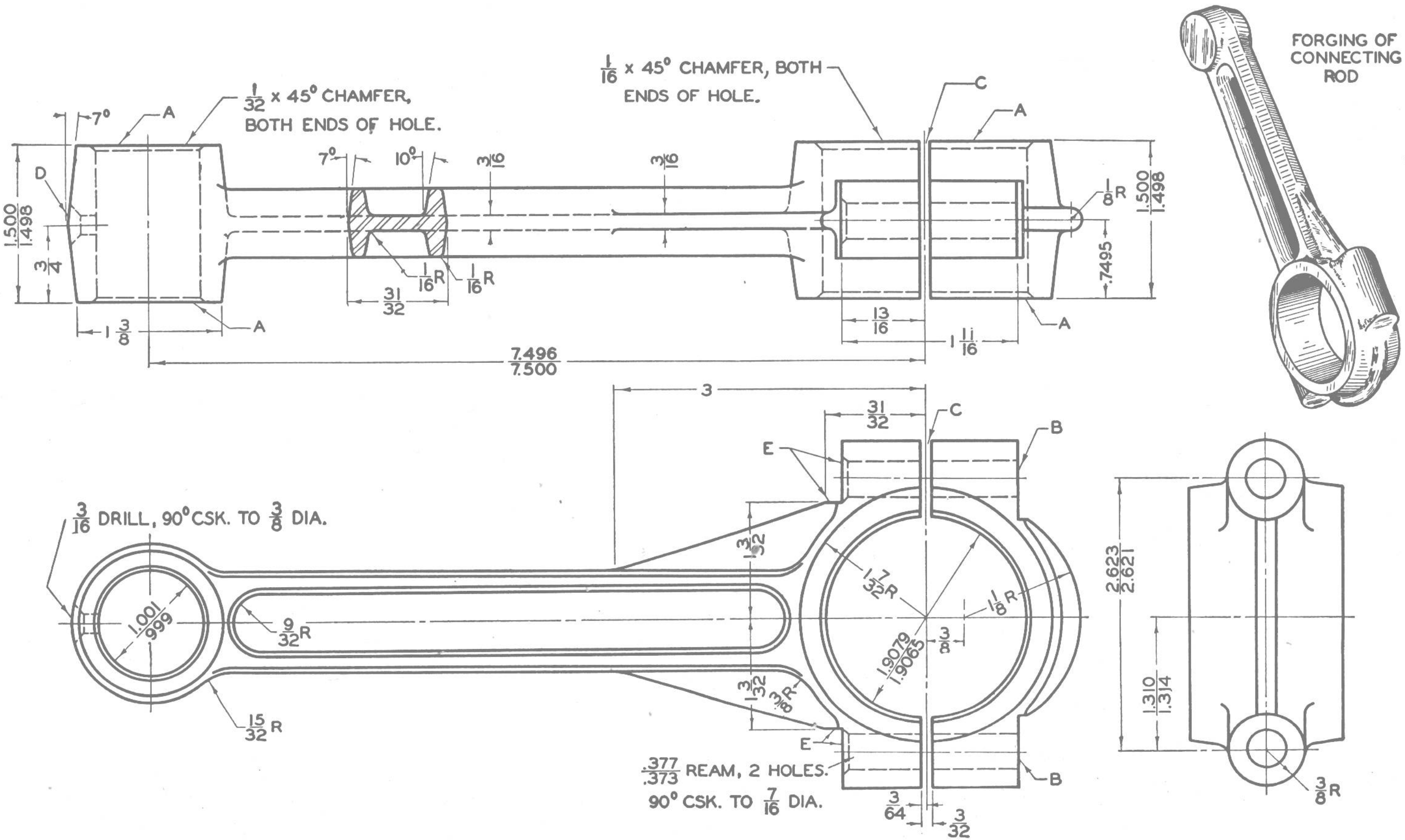

Fig. 1·6. Connecting-rod dimensions.