Net-Shape Forged Gears—The State of the Art

Trevor A. Dean and Zhongmin Hu

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Introduction

Traditionally, high-quality gears are cut to shape from forged blanks. Great accuracy can be obtained through shaving and grinding of tooth forms, enhancing the power capacity, life and quietness of geared power transmissions. In the 1950s, a process was developed for forging gears with teeth that requires little or no metal to be removed to achieve final geometry. The initial process development was undertaken in Germany for the manufacture of bevel gears for automobile differentials and was stimulated by the lack of available gear cutting equipment at that time. Later attention has turned to the forging of spur and helical gears, which are more difficult to form due to the radial disposition of their teeth compared with bevel gears. The main driver of these developments, in common with most component manufacturing, is cost. Forming gears rather than cutting them results in increased yield from raw material and also can increase productivity. Forging gears is therefore of greater advantage for large batch quantities, such as required by the automotive industry.

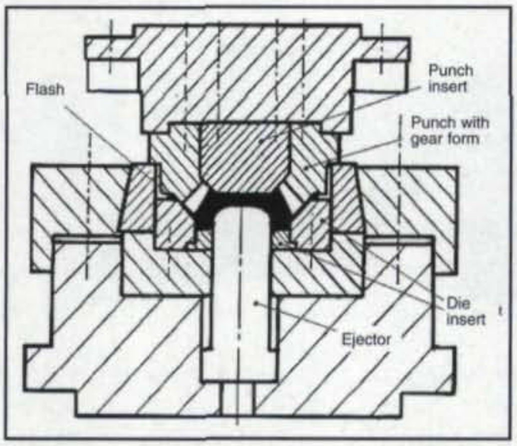


Figure 1—Flash bevel gear die.

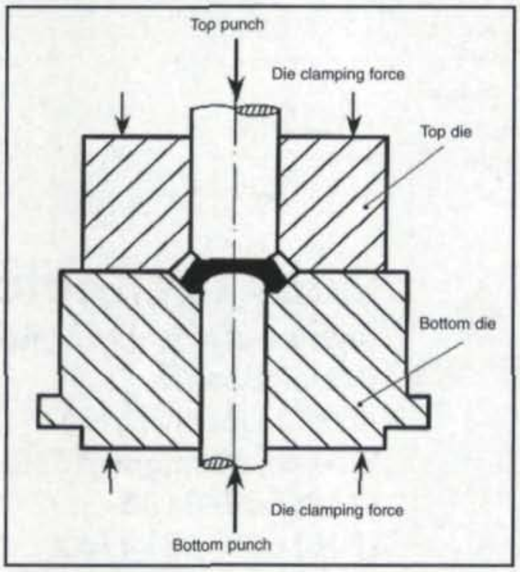


Figure 2—Flashless bevel gear die.

Cold forging (forging with workpieces at room temperature) results in parts with the highest accuracies. Differential bevel gears can be forged cold to finished geometry (net-shape). However, it is normally cheaper to forge them with a small amount of excess metal (near net-shape) and use a simple machining operation on their back faces to bring them to finished size. No machining of teeth is necessary. Depending on overall geometry, some spur and helical gears can be cold extruded with a net-shape tooth form. But, gears that have large diameter-to-width ratios—typical of those used in gearboxes and other power transmitting systems—must be forged in completely closed cavity tools using preheated workpieces. Thus, such gears are at best near net-shape, and considerable efforts are being undertaken to devise a second cold forming operation that will improve their tooth accuracy to net-shape standard. A cutting operation subsequent to forging results in an uneconomic processing route.

It has been shown that forged gears have higher strengths than cut ones, and this offers the opportunity for using them at higher power density ratings. This is attractive where weight is a penalty, such as in automobiles.

Bevel Gears

A commercial process for forging bevel gears using hot workpieces for automobile differential gears was available by the early 1960s (Ref. 1). The accuracy of the tooth form of the as-forged gears was sufficient for the automobiles of that period, but the design of the forging tool resulted in flash being formed (Fig. 1). Also, post-forge machining was required on the back face and the bore of the components. Continual developments of the process have resulted in tool sets with completely enclosed die cavities (Fig. 2). Using these cavities, it is possible to forge net-shape bevel gears. But, most often the bore is finish formed in subsequent operations, not in the forging tool. It may be said with little qualification that the technology for forging radial-and spiral-toothed bevel gears is virtually developed to its ultimate stage of commercial refinement.

Spur and Helical Gears

Extruded gear forms. Essentially two types of forming processes may be used to form these gears. If the aspect ratio (width/diameter) is large, they can be formed by extrusion. Typical extruded part types are the starter motor pinion and the helical shaft gear shown in Figure 3. Depending on the composition of the workpiece steel, these parts may be extruded at room temperature (cold formed). This results in high accuracy, and the tooth forms usually do not have to be finish machined. A gear of lower aspect ratio, which has been cold extruded, is shown in Figure 4. A considerable amount of metal has to be machined from the end faces, which have been distorted during extrusion. The loss of metal in machining these faces will be a consideration in judging the economic viability of extrusion.

Obviously, the distortion arising in extrusion of gears of even lower aspect ratios would render the process uneconomical because the amount of metal to be removed would be too high a proportion of the total. For this reason, such gears are forged in cavities in the manner of bevels. However, due to the fact that the teeth of spur and helical gears radiate normally to the axis of symmetry, they are more difficult to forge than bevel gears.

Forging machines & tooling. Forged gear technology is directed to high-volume production, and the forging machine most suitable for this is a mechanical press. However, virtually any forging machine with controllable stroke, load or energy, having accurate guidance, can be used if economic considerations allow.

Several forms of tooling designs are usable for gear forging, and the best choice depends on the geometry of the particular gear to be forged. A simple design that has been used to undertake early experiments at the University of Birmingham, in England, is shown in Figure 5 (Ref. 2). Essentially, it consists of a die insert with a female form of the gear teeth to be forged in its bore. A gear-shaped ejector, which can slide along the gear teeth, closes the bottom of the die cavity. The periphery of the punch, which is attached to the slide of the forging machine, is gear shaped so that the punch can slide in the cavity and close its upper end. The load cell shown is used for experimental purposes only and is not likely to be found in commercial situations. A gear is forged by placing a cylindrical billet on the ejector in the cavity and squeezing it sideways into the teeth of the insert under the force of the downward moving punch. When the punch has moved upwards, the forging is removed from the cavity by forcing the ejector upwards. This design can be used only for spur gears, as the necessary rotation of the punch to enable it to mate with a helical die insert is not practicable. An alternative tool design that is suitable for a wide range of spur and helical gear shapes is shown in Figure 6. The important features of this design that differ from the previous one are as follows:

The die insert is supported on light springs and can move vertically, guided by an external cylinder. The punch does not enter the die insert but contacts it on its top face. Thus, as the punch moves downwards, it closes the top end of the die cavity and pushes the insert downwards.

The diameter of the ejector is the same as the

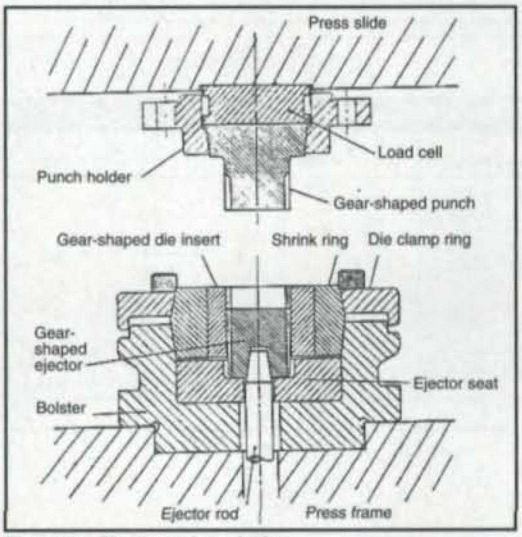


Figure 5—Simple tool set design.

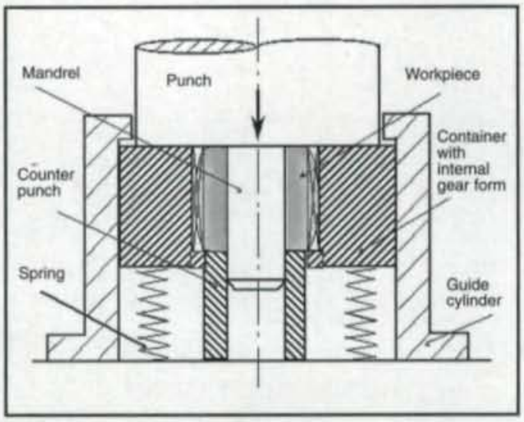


Figure 6—Gear forging tool set with spring container.

Figure 3—Extrusion-forged gear forms.

Figure 4—Through-extruded spur gear.

Dr. Trevor A. Dean

is emeritus professor of manufacturing engineering at the University of Birmingham, located in England. He also is leader of the metal forming group in the university's school of manufacturing and mechanical engineering. The group works on aspects of precision-forming engineering components. A mechanical engineer, Dean has worked on the forming of near-net and net-shape gears for more than 20 years and has published more than 140 papers on the subject.

Dr. Zhongmin Hu

is a research scientist in the University of Birmingham's School of Manufacturing and Mechanical Engineering, in the school's metal forming group. A mechanical engineer, he works on the net-shape forging of gears, aerofoil blades and other components. His main research work is in finite element analysis, friction and lubrication, and surface topography of forging products.

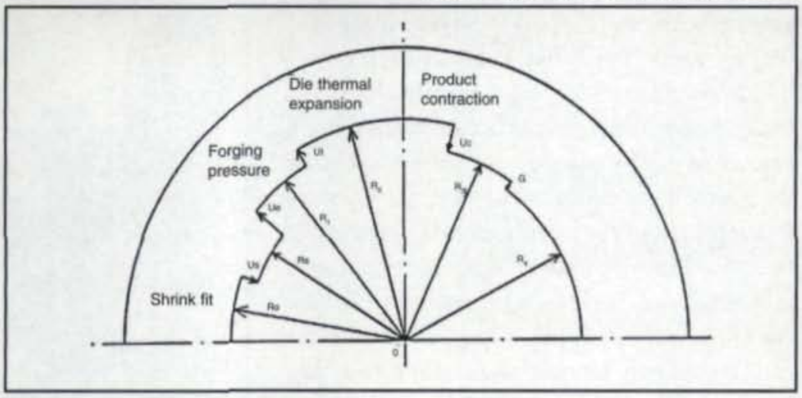


Figure 7—Correction factor in dies.

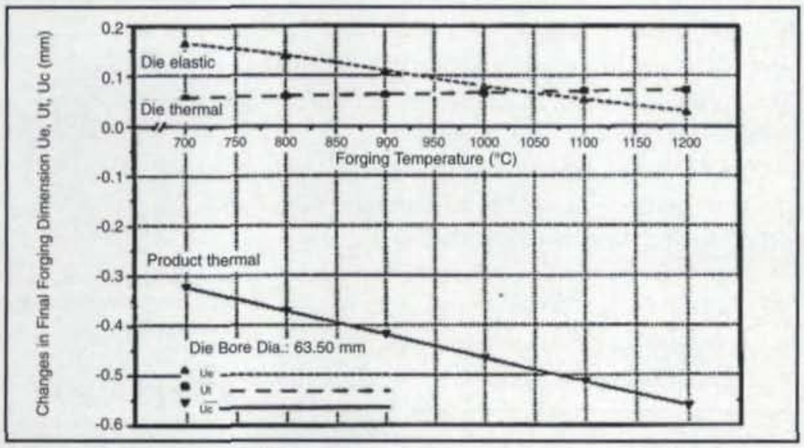
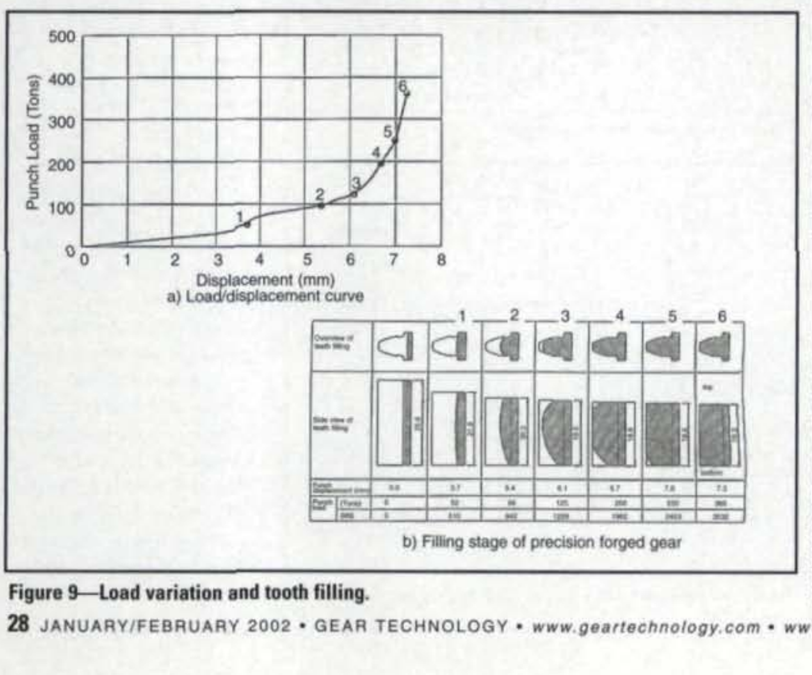


Figure 8—Temperature variations.

Table 1—Typical Accuracy of Forged Parts.

Comparison Item	Hot Forging	Warm Forging		Cold Forging
Temperature Range	1,000 ~ 1,250°C	Over Ac_1	Below Ac_1	Room Temp.
Decarbonized Layer (mm)	0.3 ~ 0.4	0.10 ~ 0.25	0.1	0
Roughness (Ra)	> 100 µm	> 50 µm	> 20 µm	> 10 µm
Draft	< 7°	< 1°	< 1°	= 0°
Accuracy (µm)	±0.5 ~ ±1.0	±0.05 ~ ±0.2	±0.05 ~ ±0.15	±0.005 ~ ±0.1
Thickness (mm)	±0.50 ~ ±1.5	±0.20 ~ ±0.40	±0.10 ~ ±0.25	±0.10 ~ ±0.20
Eccentricity (mm)	0.5 ~ 1.5	0.10 ~ 0.70	0.10 ~ 0.40	0.05 ~ 0.25



a) Load/displacement curve

b) Filling stage of precision forged gear

Figure 9—Load variation and tooth filling.

root diameter of the gear teeth, allowing it to be a simple cylindrical shape.

A mandrel is mounted on the punch, enabling hollow workpieces to be used. Thus, only a small amount of metal has to be removed to finish the bores.

There are eighteen different practical configurations of the four elements of the tool set—punch, insert, ejector and mandrel—which may be used on a press with one moving slide (Ref. 3). Each has advantages and disadvantages, and the best design depends on the overall geometry of the gear to be produced.

Factors affecting accuracy. The dimensional accuracy of a forging is affected by tooling and the process by basically three factors shown diagrammatically in Figure 7:

Most die cavities are made by EDM, and to compensate for spark gap and/or wire thickness, an allowance, G, on nominal dimensions is made.

Elastic expansion of the die, U_e, is caused by forging pressures.

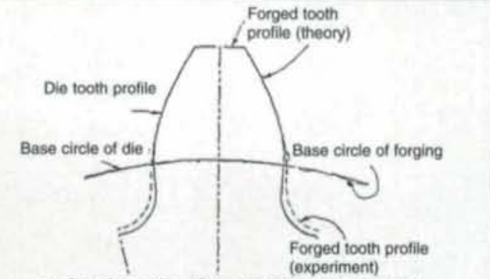
Thermal expansion of the die, U_t, occurs as it is preheated to reduce thermal shock when forging is being undertaken at elevated temperature.

Post-forging thermal contraction, U_c, of a forging made at elevated temperature occurs after it is removed from the die.

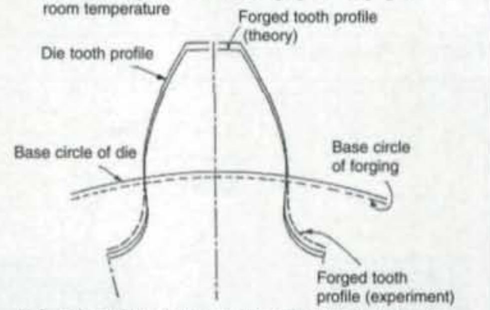
The relative magnitudes of die thermal and die elastic effects can be seen by referring to Figure 8, which shows values obtained for a steel forging of nominal diameter 63.5 mm, forged in steel dies, and which are qualitatively applicable to all sizes of forging. It can be seen that as the temperature of the forging is increased, the elastic expansion of the die decreases. This is because the strength of the workpiece metal reduces as temperature is increased and stresses on the die wall are reduced. Also, it may be seen that the higher the forging temperature, the greater is the increase in forged dimension due to the thermal expansion of the die. This is due to the greater amount of heat transferred from hot workpiece to die at higher forging temperatures. The greatest absolute effect, and also the effect that varies most with change in forging temperature, is the thermal contraction of the forging. From this figure, it can be deduced that dimensional consistency can be achieved only if workpiece temperature and forging stresses are closely controlled. As forging stresses are related to billet size, temperature and tool lubrication, the whole production process—from incoming raw material to release of forging from the die—must be executed with utmost control if dimensional consistency is to be achieved. In an ideal situation, if thermal distortion could be predicted and controlled, preheating billets alone would not affect accuracy. However, practical limitations on temperature control and the sensitivity of dimensions to temperature leads to the situation that accuracy decreases as forging temperature increases. Thus, unheated (cold) forging is the technology that enables the greatest accuracies and the most consistent dimensions to be achieved in forging production. Accuracies typical of cold-, hot- and warm-forged components are given in Table 1.

To reduce elastic distortion of the die, loads and stresses must be kept as low as possible. Figure 9 shows the load associated with a given level of tooth filling during a forging operation. A noticeable increase in load arises when the workpiece reaches the roots of the teeth in the die cavity (Point 1). When the metal reaches the tips of the teeth in the die cavity, the load increase with ram displacement is very rapid and increases dramatically as the corners are filled. As the corners of gear teeth are usually chamfered, it is possible not to forge them fully. In the case of the example shown, a load reduction of about 50% could be achieved. Mathematical treatment of the distortions arising in tooling described above enables computer-based predictive programs to be developed so that corrections to cavity geometries may be introduced during manufacture so that the teeth of forged gears may be close to the specified shape. Figure 10 (Ref. 4) shows the variation in forged tooth profile that arises with changing workpiece temperature as predicted in theory and obtained experimentally, for a 13-tooth gear with 5.08 module and 20° pressure angle. Figure 10a shows that at room temperature, theoretical forged and die tooth profiles are closely matched above the base circle, and the forged base circle corresponds closely to that of the die. The tooth forged at 1,000° C (Fig. 10b) is smaller than that of the die, as is the base circle diameter. The differences between theoretical and experimental profiles between base and root circles is because the computer program was not arranged to allow for undercutting of the teeth that was machined into the die.

Forged gears. Net-shape processing routes for both spur and helical gears are under considerable investigation by a number of institutions. Obviously, whether or not a gear form is net-shape depends on the quality standard specified by the customer. But, as it appears that forged gears are likely to be commercially viable when made in large batch quantities, the standards being aimed for are those of automotive manufacturers. For use in gearboxes, ISO standard grade 5 is



a) Superimposition of the experimentally obtained profile of a forged tooth on theoretical profiles of the corresponding die and final forging, for forging at room temperature



b) Superimposition of the experimentally obtained profile of a forged tooth on theoretical profiles of the corresponding die and final forging, for forging at 1,000°C temperature

Figure 10—Theoretical and actual tooth profile.

Figure 11—Three gears being investigated.

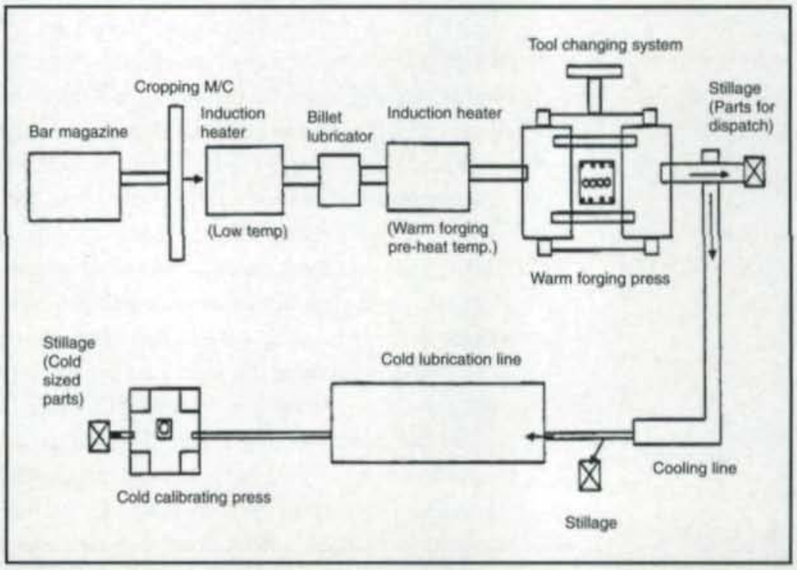


Figure 12—Equipment layout for warm/cold forging.

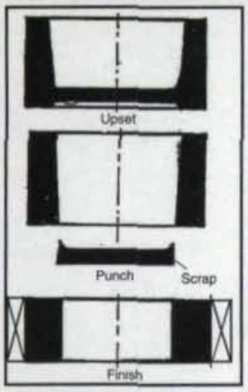


Figure 13—Forging stages of a gear.

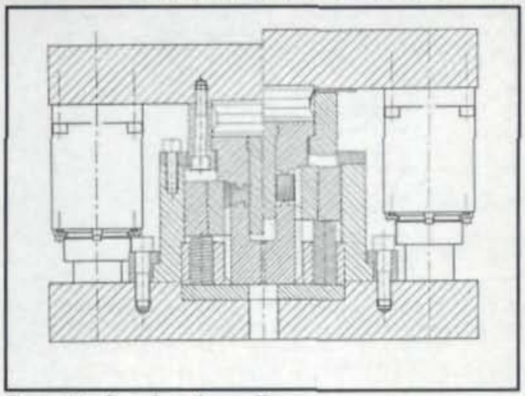


Figure 14—Drawing of gear die.

Figure 15—Photo of gear forging die.

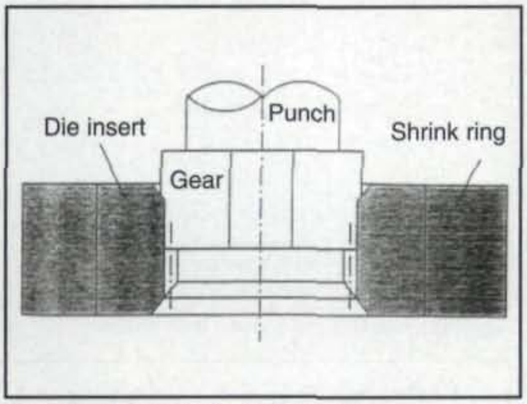


Figure 16—Schematic of gear ironing die.

Table 2—Effect of Ironing on Gears.

	Finishing Die		Induction Hardened			
Feature			**As forged**		**Ironed**	
	Left Hand	Right Hand	LH	RH	LH	RH
Pressure Angle (°)	0.12	0.10	0.73	0.58	0.19	0.16
Involute (μm)	15	13	57	46	27	22
Tooth Trace (μm)	8	5	105	94	93	66
Max. Cum Pitch (μm)	38	25	180	163	113	101
Adj. Pitch (μm)	12	9	73	28	21	16
Tooth Thickness (μm)	31	12	468	285	55	46
Runout (μm)	32		96		62	

required, except for the reverse idler gear, which may be ISO standard grade 10. Currently, investigations are underway at the University of Birmingham with the aim of developing commercial processing routes for the three gears shown in Figure 11. It is envisioned that a shop floor set up similar to that shown in Figure 12 will be utilized. Billets are sawed or sheared from rolled bars with circular cross-section, weighed, heated to about 100° C and coated in a water-based graphite lubricant. They are then heated in a second induction heater to a preheat temperature appropriate to the size, shape and alloy of the gear. That temperature will normally be in the region of 900° C, which is within the warm forging range. The billets are then forged on the first press in three operations: upsetting (squeezing them in a cylindrical die cavity), to produce a prescribed diameter and a central web; piercing of the web to produce a central hole; and finish forging in a die with appropriate peripheral tooth form. The operations are shown diagrammatically in Figure 13. The resultant forging is a near net-shape gear and is oversized by between 0.1 mm and 0.2 mm on all surfaces. The gears are cooled, cleaned and coated with a lubricant suitable for cold forging. They are then passed through an ironing die to bring them to specified dimensions. It is the cold-finishing operation that is still the subject of intensive research activity.

A drawing of the tool set used at the University of Birmingham is shown in Figure 14. Figure 15 is a photograph of the tool set mounted on a crank press. A schematic of the ironing die is given in Figure 16. Some preliminary results from a gear-ironing operation are given in Table 2. The improvements brought about by ironing are obvious, but the quality of the ironed gear is less than ISO grade 5. One of the reasons for this is that the quality of the ironing die was not high enough.

Concluding Remarks

The technology for net-shape forging of spur and helical gears is now well established.

The major remaining task is to develop a forming technique by which teeth of high accuracy may be produced with good productivity and at acceptable costs.

Acknowledgments

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