OPTIMIZATION OF DRILL GEOMETRY FOR ORTHOPAEDIC SURGERY

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A Master's Thesis

Submitted in partial fulfilment of the requirements

for the award of

The Master of Science Degree of the

Loughborough University of Technology

April 1974

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NOTATION

b	=	breadth of chip
d	=	axial displacement
h	=	relative lip height
i	=	angle of inclination
k	=	$\frac{1}{2}$ drill point angle
r	=	radius at any point on drill lip
t	=	$\frac{1}{2}$ web thickness
v	=	velocity vector
E	=	Young's modulus
H	=	average roughness depth
P	=	any point on lip of drill
R	=	radius at outer corner of drill
V	=	volume
W	=	web thickness after thinning
β	=	web angle = $\sin^{-1} \frac{t}{r}$
γ	=	rake angle
δ	=	helix angle
η	=	chip-flow angle
μ	=	viscous modulus
ρ	=	$\frac{\text{radius at P}}{\text{radius at outer corner}} = \frac{r}{R}$
τ	=	$\frac{\text{half web thickness}}{\text{drill radius at outer corner}} = \frac{t}{R}$
σ	=	stress
ϕ	=	elevation angle

Notation continued

Suffices

1,2	=	different moduli in Kelvin-Voigt model
3	=	prior to cutting
4	=	after cutting
a	=	face
b	=	bone
c	=	collagen
e	=	effective
h	=	hydroxyapatite
j	=	projected
n	=	normal
o	=	at outer corner
p	=	at point P
C	=	chip
D	=	drill

INTRODUCTION

The fixation of fractures represents the great compromise between biological principles and engineering principles (1). Although a fracture may be very soundly and solidly fixed according to engineering principles, bony union will fail if this violates the biological principles of fracture healing. The aim in all methods of fracture fixation is to produce enough immobilization to allow the process of bony healing to proceed without interruption and yet to do as little as possible which will interfere with the outcome of the important biological processes. The purpose then in almost any type of fixation is to produce a fixation of the bone, either by internal or external means, which is sufficient only to maintain its position while the biological process of healing goes on.

To hold a reduction rigidly, the fracture must be converted into a stable unit. Only if this rigidity is maintained during the whole healing process can patients remain free from pain even while exercising muscles and joints (2). The slightest movement at the fracture site will result in joint stiffness produced by pain. The rigidity of internal fixation therefore determines the success of open fracture treatment. For this form of treatment plates and screws are the devices most commonly used. The successful outcome of this method depends on fundamental mechanical principles and failures are usually caused by defective materials or improper

technique of application. The hole into which the screw is placed must be of correct size, not too large so that the threads of the screw or tap cut a thread in the bone insufficiently deep to hold the screw, but not so small as to start a fracture in the bone or cause the screw to break during insertion. The majority of holes drilled preparatory to the insertion of screws are made in the shaft of long bones. These shafts of long bones are in effect tubes, there being a hard outer cortex and a central medullary cavity. The point of entry of the drill is called the near or proximal cortex and the point of exit the far or distal cortex.

Bone as a material, is a specialised type of connective tissue, characterised by the presence of cells with long branching processes (osteocytes) which occupy cavities (lacunae) and fine canals (canaliculi) in a hard dense matrix consisting of bundles of collagenous fibres in an amorphous ground substance (cement) impregnated with calcium phosphate complexes (3). The bone structure may therefore be described as a highly oriented fibre matrix with calcium salts cemented in place to provide rigidity. Bone tissue shows many levels of organisation, the most prominent of which is the lamellar structure resembling a laminated plywood-type matrix.

As of necessity the holes are drilled freehand which is difficult to do even with a drill guide. With an inefficient cutting action there is considerably more effort required by the surgeon and his control over the drilling process is

affected. If the torque on the drill is too great there is a tendency for the drill to jam or even to break in the hole. Should excessive thrust be required the drill may plunge through the far cortex damaging surrounding soft tissue.

With the increased use of internal fixation and the associated difficulties of drilling bone an interesting question arose as to whether the drill geometry could be changed in order to improve drill efficiency. Owing to the nature of the material an empirical approach was made to the drilling problem, fresh pig femurs being used for the specimens because of the impracticability of obtaining human bone.

The features of the drill which affect its performance are the material and its geometry. The materials used for orthopaedic drills are high speed steel, stainless steel and vitallium. The drill shape includes diameter, length, web and flute proportions and type of point grinding. Some of these features are controlled by the drill manufacturers while others can be changed by the user to suit a specific set of conditions. The importance of selecting particular tool shapes for different materials is generally recognised and in engineering operations it is usual to grind the tools to these recommended angles, these angles being the result of much investigation.

From an analysis of drill geometry it can be seen that helix angle, web thickness and point angle are the three quantities

of greatest significance in determining drill performance (51). In recent years there have been developments in drill point geometries, these being the spiral point, the four facet point and the radial or rounded lip point (96), each with its own particular characteristics.

Three types of points were used during this investigation, these being the radial relief, four facet and spiral point ground at angles from 80 - 150 degrees inclusive. The helix angles of the drills used were quick, normal and slow. The effects of both web thickness and point thinning were also considered.

This work endeavours to establish what effect the type of drill point, helix angle and web thickness have on drill performance, the knowledge of which will enable the existing orthopaedic drill to be improved. Drill life was not considered important as the number of holes drilled at any one time would be relatively few and the drill could be resharpened, or replaced at the first indication of dullness or after approximately forty holes (4).

CHAPTER 1 EARLY METHODS OF DRILLING AND INTERNAL FIXATION

The earliest known work on the drilling of bone was in the Neolithic Period when a hole was made in the skull with a terebra-like instrument, either made of obsidian or metal (5). In the 5th century B.C. and during the time of Hippocrates a trephine was available. A button of bone could be removed with the circular saw or several holes made near each other could be joined with a bone cutter so that a piece of bone could be removed. The prehistoric Incas used a tumi, Fig. 1, which could be moved to and fro while pressure was applied against the skull. A longitudinal cut could be made by this technique and by having four linear incisions to the bone at right angles to each other a square piece of bone could be removed from the skull.

This early work was concerned with the drilling of the skull and it is quite likely that these procedures were used for headaches, convulsions, head injury, and mental disorders as well as for religious ceremonial reasons. They were not used for the fixing of broken limbs, this branch of surgery developing many centuries later. Before the use of internal fixation, which necessitates drilling and positioning of the bone, the surgeon often left Nature an impossible task. After many accidents, even when treated by surgeons of skill and experience, a person was reduced to a state of life-long deformity even though Nature has almost unlimited power of adapting living structures to new conditions. With the

advent of internal fixation the surgeon could assist Nature in obtaining a perfect result in the mending of broken bones, when by a little foresight and a perfect reapposition of parts he could make Nature's task so easy that a good result was certain.

The principles underlying internal fixation are firstly the perfect reapposition of parts (6). Bones, joints and muscles are so shaped and so fitted together that they work as parts of a perfect mechanism; the alteration of one part necessitates an alteration to all the parts. Perfect restoration permits the old machinery to be used without any alteration. The second principle applied to the operative treatment of fractures is a surgical one, that is, the gap between the broken ends is treated as if it were an incised wound, edges are brought together, not by sutures but by screws; the aim is bony union by first intention. The principle of rest is secured by fixation derived from screws in place of outward splints and bandages.

The date of the first use of internal fixation is unknown, but as early as 1862 in a book by Gurlt (7), a number of cases were reported in which the freshening and reduction of fractured bone ends as well as the nailing, screwing and wiring of bones were attempted. In this country Lord Lister (born 1827) introduced many improvements in the surgery of bones and joints. Before his day open operations for resetting badly united fractures, or for attempting to secure union in

ununited fractures, or for correcting deformities, were rightly thought to be almost unjustifiable because they were actually compound fractures inflicted by the surgeon and exposed the patients to the risks attendant upon these injuries. When he at last honestly believed he "could operate so as to avoid putrefaction" (8), he felt justified in dealing with a formidable case of this nature. This was in December 1868. The operation was carried out on a patient who had fractured the neck of his femur eighteen months before and consisted of exposing and freshening the ends of the fragments, the patient making a good recovery.

Lister's method of procedure varied according to the particular bone involved. If it were the shaft of the femur, after exposing the seat of the fracture, he stripped off the periosteum and then sawed the bone across, if possible in such a way as to allow one fragment to be locked into the other when the deformity had been corrected. This often necessitated a certain amount of modelling of the fragments after the first sawing, for which purpose he did not hesitate to protrude them freely out of the wound. When this part of the process was complete the bones were drilled and bound together with very stout silver wire which was secured by twisting and hammering down the twisted ends. For fixing ununited fractures of the tibia he often used iron or ivory pegs. They were not rounded and had massive square heads. They were driven obliquely into round holes made by a bradawl

through both fragments and were left projecting through the wound some distance into the dressing. The iron pegs were removed after a number of weeks; those made of ivory usually became so firmly incorporated with the bone that only the distal parts could be taken away by clipping them across with bone pliers. The presence of the pegs was intended to favour the deposit of callus by exciting a mild degree of inflammation.

This way of treating ununited fractures was not so much a new departure as that of exposing and wiring badly united fractures. With badly united fractures the limbs, though deformed, were mostly useful; with ununited fractures they were generally useless, thus the alternative was amputation. Moreover, experience showed that there was comparatively small risk in the open treatment of ununited fractures. The only recent fractures Lister treated by operation were those of the patella and olecranon (9).

For his larger operations in this field he often used ordinary carpenter's and sculptor's tools, appreciating the fine large handles which working men know are essential for delicate manipulation. Among them were huge gouges and chisels and the more delicate sculptor's tools which the hand grasps firmly and without effort. Nickel-plated all-metal instruments had hardly come into fashion. Lister preferred wooden handles. He never thought that metal handles were essential for aseptic security. He used also to point out that, while the tools supplied to mechanics

were often much better, they were always infinitely cheaper than those which surgeons were obliged to put up with.

It was not long before other surgeons began to follow Lister's example, one of them being Sir William Arbuthnot Lane (born 1856) who was at that time an assistant surgeon at Guy's Hospital. Lane was concerned at the poor results being obtained by the ^{then} present method of treatment of fractures of the fibula and tibia and in a paper (10) in 1885 he criticised these methods. In December 1893 a man aged 34 had sustained a fracture of the leg two inches above the ankle joint. Attempts by all the conventional methods of manipulation and traction failed to reappose the fractured ends. Lane therefore resolved, "to treat the bones as one would the broken leg of a table or chair." The operation (osteo-synthesis, Albin Lambotte named it) was carried out on 8th January 1894; the broken ends of the tibia were exposed, but required both ingenuity, patience, and force to bring them into perfect apposition. Two screws were inserted across the oblique line of the fracture to keep the fragments in place. A week later, on 15th January, two similar cases were admitted to his wards and were treated in the same manner.

Three months later, at a meeting of the Clinical Society of London held on 13th April 1894 (11), Arbuthnot Lane announced his new method of treatment in a brief paper which he entitled, "A Method of Treating Simple Oblique Fractures of the Tibia and Fibula, more Efficient than those in Common Use".

At that meeting he not only described a new method of treating fractures, but he enunciated an altogether new surgical standard.

About this time another surgeon, Elie Lambotte of Belgium, had, unknown to Lane, treated oblique fractures of the tibia in 1888, 1889, 1890 by direct operation, planned on the same lines as those which had appealed independently to Lane. Each man had met the same problem, and solved it in a similar way.

The German surgeon Fritz Koenig recognised the importance of internal fixation and published his first concept in a paper in 1902.

The operative treatment of simple fractures was met with the most violent and virulent opposition for many years. This continued until the meeting of the British Medical Association in London in 1910 when Lane had the honour of opening the discussion, "On the Operative Treatment of Simple Fractures". Following this a Committee was appointed by the Council of the British Medical Association in response to a recommendation to that effect by the Section of Surgery. The reference to the Committee was, "To report on the ultimate results obtained in the treatment of fractures with or without operation", using the following methods, (a) by manipulation and immobilisation by means of splints: (b) by direct operation; (c) by massage and mobilisation. The verdict,

which appeared in 1912, was distinctly in favour of Arbuthnot Lane's operative method. A few years later this method of treatment was also accepted in Germany.

Today's methods of fracture treatment aim at complete restoration of all functions of the injured limb, with rapid ossification of the fracture after it has been properly reduced, and, on the other hand, the integrity of the surrounding soft parts. Open reduction by itself, without appropriate internal fixation, should not be attempted in any case where conservative treatment may be expected to produce union of the fracture in a satisfactory alignment. Here the risk of opening a closed fracture without proceeding to internal fixation would be unjustifiable (2).

CHAPTER 2 BONE

2.1 Classification of Bone

Bone may be classified in the following manner (12). (13).

Long bones, such as the humerus, radius, ulna, femur, tibia and fibula. They form the longest bones in the arms or legs and must therefore be strong supporting structures. Each bone has a shaft composed of a cylindrical rod of compact bone (the diaphysis) with a projection at each end of the shaft (the epiphyses) composed mainly of cancellous bone with a thin outer casing of compact bone, see Fig. 2.

Short bones and irregular bones. Examples of short bones are the metacarples, metatarsals and phalanges of the irregular bones, the vertebrae, spheroid, ethmoid, mandible bones. These are composed mainly of cancellous bone with a thin covering of compact bone.

Flat bones. The scapula and cranial bones. These can be so thin that they are translucent. Others, however, consist of a layer of cancellous bone between two plates of compact bone.

2.2 Composition of Bone

Each long bone in the body consists of the following parts (14):

- (a) diaphysis (b) epiphyses (c) articular cartilage
- (d) medullary cavity (e) endostium (f) periosteum.

(a) The diaphysis is the main shaft portion of the long bone, the thick compact bone and the hollow cylindrical shape offer great strength with minimum weight.

(b) The epiphyses are the extremities of the long bones. Their bulbous shape provides space for muscle attachment near the joint. Lightness despite size is achieved by construction of porous cancellous bone with only an outer layer of compact bone. Arrangement of the lamellae corresponding to the lines of stress gives added strength to the epiphyses.

(c) The articular cartilage is the thin layer of hyaline cartilage covering the articular surface of each epiphysis. Resiliency of this material cushions jars or blows.

(d) The medullary cavity, running the length of the diaphysis, contains yellow or fatty bone marrow in adults.

(e) The endostium is the membrane that lines the medullary cavity and Haversian canals. It is composed of cells that become active osteoblasts as needed.

(f) The periosteum is a dense white fibrous membrane that covers bone except at joint surfaces where articular cartilage forms the covering. Many of the fibres of the periosteum penetrate the underlying bone to weld two structures to each other. (The penetrating fibres are called Sharpey's fibres). Muscle fibres interlace with periosteal fibres to anchor muscles firmly to the bone. The inner layer of the periosteum

of growing bones contains osteoblasts (bone-forming cells). Because of its bone-forming cells and blood vessels, the periosteum is necessary for bone growth and repair and for its nutrition and therefore for survival of its cells.

2.3 Description of Typical Long Bone

A typical long bone is shown in cross section in Fig. 3. Such a bone is composed of two basic types of bone, compact (lamellar) bone and spongy (cancellous) bone. Compact bone makes up the entire wall (cortex) of the central portion (diaphysis) as well as the outer portion of the flared ends (metaphyses) of the bone. The interior of the metaphyses is composed of spongy bone which in turn is built up of a collection of plates and bars called trabeculae that are analogous to the solid portions of a sponge. In this cancellous bone red marrow is present. The outer surface of the bone is covered by a membrane called the periosteum.

At microscopic level all compact bone and the trabeculae of spongy bone are composed of osteones (also known as Haversian systems) as shown in Fig. 4 and Fig. 5. An osteone is a tubular structure about 10 - 20 mm in length with an outer diameter of about 250 μm . It surrounds a passage known as a Haversian canal which is about 70 μm in diameter (15). The canals contain capillaries that feed the living portion of bone and which receive the blood from the Volkmann canals which run diagonally or at right angles to the Haversian

system. The axes of the osteones are aligned with the direction of average compressive stress. Each osteone is composed of several layers (lamellae) of collagen fibres. In each lamella the collagen fibres are parallel and spiral about the axis of the osteone. The direction of the spiral is reversed in each adjacent lamella, Fig. 5. The osteones also contain spaces called lacunae which house bone cells that are known as osteocytes. The lacunae are situated at the interface between adjacent lamellae and are connected to the Haversian canal by tiny passages (canaliculi). There are about 20,000 lacunae per cubic millimetre of bone.

The collagen fibres of which the lamellae of the osteones are composed are parallel and are observed to comprise bundles of very much finer fibrils which have cross striations that are in register across adjacent fibres. These cross striations are about $.064\mu\text{m}$ apart (16).

Hydroxyapatite crystals are deposited around the periphery of the collagen fibres between each pair of striations. The individual fibres vary in diameter depending upon the type and age of bone, where the bone has been taken from and the method of preparation and measurement. Viewed at electron microscopic level Kraus (17), gives the thickness of the collagen fibres as $.3 - .5\mu\text{m}$ thick with hydroxyapatite crystals $.008 \times .015 \times .05\mu\text{m}$ in size. Welch (18) gives the thickness of the collagen fibres as $.02 - .2\mu\text{m}$ diameter with hydroxyapatite crystals $.004 \times .004 \times .04\mu\text{m}$.

2.4 Chemical Composition of Bone

Bone is a remarkable and complex substance. It functions as both a structural and as a dynamical chemical system which supplies certain ionic species necessary to the metabolic function of the body. The bone matrix contains an organic component and an inorganic component, the latter of which accounts for approximately two thirds of the weight of the bone (19). Water is also present, mainly in association with the collagen and the cement substance.

Most of the inorganic component is collagen (90 - 96%) (17). The remainder of the organic component is known as "cement substance" and consists mainly of mucopolysaccharides (20) (19). Bone collagen is the substance which yields glue when bone is boiled. It is a crystalline, non-living substance that is present in all body tissues and is made up of amino acids, glycine, proline, hydroxyproline and glutamic acid. Bone collagen has the unique ability to mineralize and it is this feature which is felt to be attributable to the presence of the ground substances chondroitin sulphate and hyaluronate, that distinguishes it from the collagen that is found in other body tissues.

Bone mineral is the inorganic phase of bone. The major subphase of the bone mineral is hydroxyapatite (20), together with citrates, carbonates, magnesium, calcium and trace elements. Hydroxyapatite is not a compound; it is a

crystalline lattice structure that contains calcium, phosphate and hydroxyl ions (17), (16), (19), (21). These crystals are very small and are referred to in section 2.3.

2.5 Strength of Human Bone

The earliest mention of the mechanical significance of bone form was made by Galileo (1638), but its strength and other physical properties were not extensively studied until the latter half of the nineteenth century (22). Many people have since tried to determine the intrinsic strength of bone and to evaluate it as a structural material, though it is known that soft tissues play an important role in preventing fractures in accidents. The density, size and shapes of bones are also important when trying to assess the stresses the skeleton can safely resist.

Most of the early work up to 1957 on the mechanical testing of bone has been reviewed by Evans (22). A summary of the work since then has been compiled by J. C. Wall, S. Chatterji and J. W. Jeffery (23), who considered the reasons why previous work on the material strength of bone had given differing results.

Evans and Lebow (24) 1951, found no correlation of tensile or shear properties of bone with age but Ko (25) 1953, however, found that the ultimate tensile strength of wet femoral compact bone is greatest in bone from people 20 - 29 years of age and least in people 60 - 79 years of age . Age

changes in the ultimate percentage elongation of this bone show that it is greatest in persons 10 - 19 years of age and least in persons 60 - 79 years old . A graph and details showing how strength varies with age are given in Figs. 6 & 7.

Dempster & Liddicoat (26) 1952, showed that cubes of bone subjected to compression, longitudinally, radially and tangentially to their original position in the shaft are much weaker by about 63 - 65% in radial and tangential strength than in longitudinal strength. The ultimate tensile strength of bone as tested cross grain is less than its compressive strength as tested cross grain.

Dempster & Coleman (27) 1961, and Amtmann (28) 1968, found that in compression tests on the human femur the weakest bone sample strength has about 66% of the hardest bone sample strength depending upon the particular region of the femoral shaft from which the bone was taken.

The ultimate tensile strength of wet bone from the middle of the femoral shaft is greater than that of bone from the upper or lower part of the shaft (24) (25). Ko states that bone from the medial side of the femoral shaft has a greater tensile strength than that from other sides of the shaft, but Evans and Sedlin (24) (29), said that the lateral quadrant of the shaft has the highest ultimate tensile strength. Bone from the middle third and the medial side of the femoral shaft showed a slightly greater ultimate elongation than did specimens from other regions of the bone.

From these results it can be seen that bone is a compact anisotropic material and as many of the tests carried out on bone were not originally designed for this type of material, the laws that apply to homogenous material should have been used with caution (29). This may account for some of the exceedingly large scatter shown by the bone strength tests, but there are also many other factors to be considered as shown on page 16. Variable conditions of testing also make comparison of results extremely difficult, some bones are tested wet, others dry, and some in a controlled humid atmosphere.

Stech (30) 1966, explained the anisotropy of bone using a simple model which consisted of a cube with a number of circular holes running through it in one direction. By adjustment of the hole size and direction of loading he evaluated shear, compressive and tensile strength, comparing this to how bone would behave when loaded in a similar manner.

The results of 25 years research in the Department of Anatomy, The Kyota Prefectural University of Medicine, Japan, on the strength of biological materials have been published by Yamada (31) 1970. In this study all the materials used were fresh and unembalmed from one ethnic group using the same testing techniques and equipment. Care was taken to see that the materials were mechanically stable before testing (i.e. the state in which stable or constant strength values are obtained).

1. Individual	Sex
Age
Height and weight
Race
Agility prior to death
Cause of death
2. Bone	Particular bone, e.g. femur
Right or left limb
Dimensions
Time between death and removal
Nature, e.g. osteoporotic
Chemical composition
Bulk density
Hydroxyapatite crystal size
3. Storage	Medium, e.g. formol, freezing
Time stored
Freezing rate
4. Removal of
small sample	Method, e.g. saw, grinding machine
Temperature during machining
Location from which taken
Axis of sample
5. Test piece	Size
Shape
Collagen fibre orientation
Cortical or cancellous bone
6. Test	Condition of test piece, e.g. wet
Type of grip
Type of testing machine
Rate of deformation
Purity of stress
Time lag between death and test

Factors which may influence the physical properties
of bone (23)

In order to reach the mechanically stabilized state, intact organs from which the test specimens were made, were removed from the cadavers, put in a physiological saline solution and stored in a refrigerator overnight or longer. The mechanical stabilization is caused mainly by the saturation with water plus the disappearance of rigor mortis for smooth and skeletal muscles.

A summary of the research done by Yamada and his group on the strength of compact bone in both tension and compression is given below, together with the mechanical properties of wet femoral compact bone over an age range of 20 - 29 years and 60 - 69 years.

The stress strain curves for wet compact bone in tension are shown in Fig. 8 although some authors have a different ranking to these. The proportional limit for both wet and air-dried compact bone ranges from 55 - 65% of the ultimate tensile strength, while the elastic limit for both wet and air-dried compact bone corresponds to 80% of its ultimate tensile strength. The percentage of elastic recovery for both wet and air-dried compact bone, immediately after removal of stress and just before rupture, is 84%; including the elastic after-effect it is 92%.

The creep limit corresponds to 65% of the ultimate strength in both wet and air-dried compact bone. The maximum creeping time is 24 hours and the elongation at creeping

rupture is 1.6 times the ultimate elongation in a normal test.

During compression tests it was found that the elastic limit corresponded to 75% and 70% of the ultimate for wet and air-dried compact bone respectively. The percentage of elastic recovery for wet compact bone immediately after removal of stress and just before rupture is 88%; with the elastic after-effect it is 93%. Corresponding values of 75% and 90% respectively were found for air-dried bone. The creep limit is 70% of the ultimate strength for both wet and air-dried compact bone, the maximum creeping time being 15 hours for wet and 30 hours for air-dried bone. The contraction at creeping rupture is 1.2 times the ultimate contraction in a normal test for wet and 1.8 times for air-dried compact bone.

A list of the mechanical properties is shown overleaf.

Mechanical Properties	Age Group	
	20 - 29 yrs.	60 - 69 yrs.
Ultimate tensile strength MN/m ²	128.4	86.5
Ultimate percentage elongation	1.44	1.26
Ultimate compressive strength MN/m ²	166.5	146.0
Ultimate percentage contraction	1.9	1.8
Ultimate bending strength MN/m ²	173.7	139.0
Ultimate specific deflection	.075	.053
Ultimate torsional strength MN/m ²	57.3	48.6
Ultimate distortion	.028	.027
Modulus of elasticity (torsion) GN/m ²	3.44	2.94
Modulus of elasticity (tension) GN/m ²	17.30	-
Modulus of elasticity (compression) GN/m ²	10.39	-

Sedlin and Hirsch (29) 1966, have carried out a number of investigations in order to outline a standard procedure for the storage, preparation and testing of bone samples. A summary of the main findings is given below.

1. Values for physical properties calculated utilizing standard formulae were used as a basis of comparison of specimens that were prepared and loaded in identical fashion.

2. More than 500 specimens from mid-femoral diaphysis from 20 subjects were tested either in bending, tension or compression.

3. It was found that:

(a) There was no significant effect of temperature on maximum stress and energy absorbed to failure in the range between 21°C and 37°C. The modulus of elasticity may be slightly increased. Total deflection to failure is increased at 37°C.

(b) Air drying alters the physical properties in less than one hour in the majority of instances.

(c) Freezing of specimens prior to testing increases the strength of specimens insignificantly, but does not change any other property.

(d) Fixation in formalin does not appear to alter the modulus of elasticity of small samples.

- (e) There is no difference in physical properties that can be attributed to size of specimen in the size ranges tested.
 - (f) When bending bone as a beam with central load and unfixed end supports, the modulus of elasticity can be significantly changed by varying the distance between supports.
 - (g) The cross-section dimensions of specimens should be measured before testing whenever possible.
 - (h) Repeated loading of the same specimen does not alter the modulus of elasticity if loads of the order of 35 per cent of the breaking strength are used and one minute or more is allowed for recovery.
 - (i) Specimens obtained from the lateral quadrant of the mid-femoral diaphysis are stronger and those from the posterior quadrant are weaker with anterior and medial quadrants intermediate on average.
 - (j) Determination of the volume of Haversian canals in the specimen does not account for the bulk of the variation in the physical properties in individual specimens.
 - (k) Significant differences exist in the physical properties of bone from different individuals that are not accounted for by age.
 - (1) A high correlation is present between the maximum stress in bending and the modulus of elasticity in bending.
4. Bending tests of small samples of cortical bone appear to be reliable in the demonstration of differences in physical properties between individuals.

During all these tests the specimens were worked in the fresh state or stored at -20°C in Ringer's solution until they could be handled. When they were being worked on they were kept in Ringer's solution at room temperature and kept there at all times when not actually being handled.

Ko (25) 1953, found no significant change in the tensile strength of human compact bone stored in a physiological saline solution at room temperature for several months.

Hazama (32) 1956, reported the same for the torsion^a strength of human compact bone.

An extensive survey on the biomechanical characteristics of bone has been done by Swanson (20), collecting the results of numerous research workers. From the values obtained, and making the best possible assessment of their accuracies, Swanson suggests the following as representing the tensile properties of wet bone from the middle third of a fresh adult human femur loaded parallel to the axis of the femur:

Young's modulus	16.7 GN/m ²
Yield stress	69 MN/m ²
Stress at fracture	98 MN/m ²
Strain at fracture	.015

To determine the deflection and stresses in a bone specimen subjected to short term static loading of limited intensity, it may be sufficient to characterise the bone as a linearly elastic material. For higher intensity loads it is necessary

to account for non-linear time independent material effects. If, however, the changes in stresses and deformation under loading conditions of long duration are to be studied, then the viscoelastic properties of the material must be taken into consideration.

Most of the current research in the analysis of bone behaviour centres around its classification as a viscoelastic solid. In addition to its strain rate sensitivity which was demonstrated by McElhaney (3) 1966, human compact bone also possesses additional characteristics that are typical of viscoelastic solids. These are instantaneous elasticity, strain retardation and stress relaxation (17). Sedlin (33) 1965, considered rheological models which might represent the stress-strain-time variations observed in mechanical tests. As a result of his observations he proposed the three-element viscoelastic model for bone shown in Fig. 9. This consists of a Kelvin-Voight model of viscous modulus μ and elastic modulus E_1 , in series with an elastic component of modulus E_2 . Since the values of μ , E_1 and E_2 are not presently available, he did not give any numerical values to the properties of this model.

Laird and Kingsbury (34) 1973, investigating the dynamic viscoelastic material properties of bone concluded that although the three element model may be valid for the quasistatic case it did not truly represent the bone material over the range of frequencies they tested.

Frankel and Burstein (35) 1970, after considering various models and results, state that biological tissues exhibit viscoelastic behaviour to varying degrees and that studies of the mechanical behaviour of living tissues must take into account this complex phenomenon.

Vincentelli and Evans (36) 1971, studied the relation between ultimate tensile stress, strain and modulus of elasticity to the collagen fibre orientation and degree of calcification of cortical bone taken from adult human tibias.

After the mechanical properties of the specimens had been determined, cross sections were taken as near to the fracture as possible in order to find the type of osteone present. The osteones were classified into three main types, light, dark and intermediate according to their appearance in polarised light. In light osteones the majority of the collagen fibres spiral around the long axis of the osteone at an angle almost perpendicular to it. In the dark osteones the orientation of the majority of the fibres is more nearly parallel to the long axis of the osteone. In the intermediate osteones collagen fibres with both types of orientation are more evenly distributed in the osteone.

The percentage of the cross sectional area formed by the different histological variables was now found with respect to the original break area and a corrected break area, the latter being the intact cross section minus the area of the

Haversian canals, Volkmann's canals and resorption spaces. The corrected break area was the one used in the final analysis of the histological composition of the cross sections since, except for the lacunae and the canaliculi, it represents the area of bone subject to stress during the mechanical testing.

When the relation between the mechanical properties of the specimens and the orientation of the collagen fibres in the various histological components in the section was analysed, a high positive correlation was found between the percentage of the break area formed by the dark osteones and the ultimate tensile strength and the percentage elongation of the specimen. Ultimate tensile strength and percentage elongation had a high negative correlation with light osteones present. Osteones of long bones usually have their long axes coinciding with that of the shaft of the bone; this also applies to the majority of collagen fibre bundles in the osteones that appear dark in polarised light. Consequently, these osteones are in a better mechanical position to resist tensile stress and strain in the direction of the shaft of the bone than are osteones whose collagen fibre bundles are predominantly oriented at a large angle to the long axis of the osteone and the bone. Thus the greater the number of dark osteones in a given volume of bone the higher is its tensile strength. Conversely, the greater the number of light or intermediate osteones in the bone the lower its tensile strength. The

authors found no significant correlation between the modulus of elasticity and any of the histological variables.

2.6 Temperature Effects on Bone

The effects of temperature on the deformation of bone when stressed parallel to the collagen fibres were examined by Bonfield and Li (37) 1968. This was done in order to determine the elastic strain, the anelastic strain which was recoverable with time after unloading, and the plastic strain. A model of the deformation was proposed in which the bone was considered as an idealised composite of hydroxyapatite and collagen. The temperatures used ranged from -58°C to 90°C , the specimens being strained at a constant rate to a given stress. This procedure was repeated for a number of stresses up to a maximum of 32.4 MN/m^2 .

Two distinct stages were noted in the temperature dependence of the deformation of the bone. In the -58°C to 25°C range a residual plastic strain was measured after the recovery of the anelastic strain, with equilibrium obtained after 15 minutes, whereas in the 50°C to 90°C range the specimens contracted to a length smaller than the original and equilibrium was still not established after 72 hours.

From their observations the value of Young's modulus for bone could now be calculated and it was seen that there was a linear dependence of Young's modulus of bone on temperature within the range -58°C to 25°C , the value increasing as the temperature was reduced.

Using the composite model the variation in Young's modulus of bone within the range -58°C to 25°C was now analysed. Knowing that Young's modulus for collagen is temperature dependent and that of hydroxyapatite temperature independent and that the applied stress is distributed between them in the ratio of their relative volumes and elastic moduli

$$\sigma_h/\sigma_c = E_h V_h / E_c V_c \quad \dots\dots(1)$$

Assuming equal values of Poissons ratio the Young's modulus of bone (E_b) is given by

$$E_b = E_h V_h + E_c V_c \quad \dots\dots(2)$$

From equation (2) it can be concluded that the increase in Young's modulus of bone as the temperature is decreased is a reflection of a change in the elastic behaviour of collagen, the hydroxyapatite remaining stable. On this basis, the values of E_c can be derived from equation (2) as a function of temperature. From equation (1) it can be seen that a decrease in the ratio E_h/E_c results in the collagen supporting a larger proportion of the applied load.

The model of deformation was complicated at temperatures in the interval from 50°C to 90°C by the non-equilibrium recovery process. The bone did not deform as a coherent composite. Such a transition cannot be explained solely by the reorientation of the structure of the collagen, but must also reflect a weakening of the bonds between the collagen and hydroxyapatite and therefore an irreversible change in the structure.

2.7 Strength of Pig Bone

Oda (38) 1955, carried out research to find the strength of pig bone and some of his results are shown graphically in Fig. 10. The properties of pig femora are given below:

Wet bone

Ultimate tensile strength	$86.24 \pm 1.47 \text{ MN/m}^2$
Ultimate percentage elongation	$.68 \pm .010$
Modulus of Elasticity	14.60 GN/m^2
Ultimate compressive strength	$98 \pm .68 \text{ KN/m}^2$
Ultimate percentage contraction	$1.9 \pm .020$
Modulus of Elasticity	4.80 GN/m^2

Air-dried bone

Ultimate tensile strength	$102.9 \pm 1.08 \text{ MN/m}^2$
Ultimate percentage elongation	$.61 \pm .010$
Modulus of Elasticity	18.32 GN/m^2
Ultimate compressive strength	139.2 KN/m^2
Ultimate percentage contraction	$2.0 \pm .02$
Modulus of Elasticity	6.07 GN/m^2

Tensile properties of compact pig bone:

The proportional limit for wet bone corresponds to about 55 - 65% of its ultimate tensile strength, the same as for wet human compact bone. The elastic limit which is greater than the proportional limit corresponds to about 80% of the ultimate strength in wet compact bone. The relationship

of the elastic limit to the proportional limit is similar to that of man. The percentage of elastic recovery for wet compact bone immediately after removal of stress and just before rupture is 64%. With the elastic after-effect this is 89%. The creep limit corresponds to 65% of the ultimate strength, this is similar to man, the maximum creeping time being 10 hours. The elongation at creeping rupture is 1.1 times that in a normal test.

Compressive properties of pig bone:

The elastic limit is approximately 65% of the ultimate strength for wet and 60% for the air-dried compact bone. The percentage of elastic recovery for wet compact bone immediately after removal of stress and just before rupture is 67%, including the elastic after-effect it is 83%. The creep limit corresponds to 70% of the ultimate strength for both wet and air-dried compact bone, this being similar to man, the maximum creeping time being about 20 hours. The contraction at creeping rupture is 1.7 times the ultimate contraction for both wet and air-dried compact bone in a normal test.

It can be safely concluded that compact bone is an anisotropic, nonhomogeneous, viscoelastic solid, its properties being influenced by many factors. In vivo the behaviour of bone is complicated by the fact that it has the capacity to grow and to repair itself. It also grows in response to the loads that are applied to it; altogether it is a very remarkable material.

CHAPTER 3 REVIEW OF PREVIOUS WORK ON DRILL PERFORMANCE

3.1 The Drilling of Metal

It is intended in this section to review briefly some of the work carried out over the last twenty years on the drilling of metals in order to study the effects of changing the various features of the drill and drilling conditions. Twist drill nomenclature and definitions are shown in the Appendix.

Shaw and Cook (51) 1954, analysed drill point geometry and it was evident that helix angle, web thickness and point angle were the three quantities of greatest significance, Fig. 16, in determining drill performance. From this it was shown that an increase in web thickness has an insignificant influence at the periphery of the drill. The main effect was a strengthening of the cutting edge near the point. An increase in point angle also has a much smaller influence at the periphery than at the centre of the drill. This is true of the effective rake angle which increases with increase in point angle. Unlike the two previous quantities, the helix angle has the greatest effect near the periphery. An increase in helix angle causes a large increase in the normal and effective rake angles, but correspondingly less support all along the cutting edge.

Using a drill dynamometer for a variety of drills operating under a wide range of conditions the results obtained verified the changes expected when varying the geometry of the drill

point, the conclusions being:

- (1) both torque and thrust decreased with increase in helix angle;
- (2) thinning the point of the drill had no effect upon the torque and caused only a small decrease in thrust;
- (3) increasing the point angle gave a decrease in torque but an increase in thrust;
- (4) a pilot hole halved the thrust on the drill but had an insignificant effect on torque;
- (5) the torque on the drill varied as the square of the drill diameter;
- (6) as the drill wore so the torque increased, the thrust remaining constant.

Oxford, Jr. (52) 1955, carried out an investigation into the mechanics of the actual cutting operation which takes place along the cutting edges and under the chisel edge of a twist drill. In order to explore the cutting action of the twist drill it was necessary to devise an experimental technique which would permit examination of the drill chips in the process of formation. This was achieved by the use of a quick-stop apparatus that stopped the relative motion between the drill and the workpiece and "froze" the action at any particular time. To prevent excessive rounding of the edges during metallographic polishing the chips were given a hard coating of electroplated nickel before sectioning. After

plating the holes in the specimens were moulded full of transparent thermoplastic which permitted a visual check of the orientation of the section being taken along planes crossing the chips in the desired direction.

The chip formation mechanism along the cutting edges (lips) of a twist drill appeared to be basically the same as for any other metal cutting operation, a marked similarity being observed between these and the planing and milling chips shown by Ernst (53) and Merchant and Zlatin (54).

The action which occurs under the chisel edge of a twist drill is quite complex and photomicrographs of sections normal to the chisel edge of the drill resemble the cutting action of a tool with a very high negative rake angle of about minus 56 degrees. At the very centre of the drill the only tool velocity is that of the feed in the axial direction and it was observed that the deformation in the centre resembled that caused by an indenting punch. Direct visual observations as well as plane sections through the workpieces using a high power stereomicroscope were used to study the action under the chisel edge and as far as can be determined there was an actual chip formed by the chisel edge. When this chip fills the space between the drill clearance surface and the bottom of the hole it is wiped or extruded towards the cutting edges of the drill, forced into the flute space of the drill and carried off adhered to the apex of the generally conical chip produced by the flute cutting edges. In some cases part, or

all, of the chisel edge chip turned over the edge of the flute and was ejected as a highly deformed ribbon-like chip.

In connection with the study of chip formation, it was necessary to determine the direction of chip flow so that the chip sections could be oriented properly. To measure chip flow angle, the prepared specimens were sectioned on a plane parallel to the cutting edge and parallel to the drill axis. The section plane was ground carefully to the centre or slightly beyond so that the point of the cutting edge could be seen when viewed normal to the section plane. The measuring of the specimen was carried out on a toolmaker's microscope, with the point of the cutting edge lying in a plane normal to the optical axis of the instrument. With this arrangement it was possible to read directly the chip flow angle at any point along the cutting edge. Since the dimensions of the drill are known it is possible to find the actual radius of the point where the measurements were taken. The angular measurements were made right at the point of the cutting edge and were accurate and repeatable to within 2 degrees.

Steel and titanium alloys were the materials used for the cutting tests, and the chip flow angles measured experimentally using different point angles were related to effective rake angle along the cutting edges using a new derivation of the normal rake angle for a twist drill.

Following their previous papers Shaw and Oxford (55) 1957, approached the problem of computing the torque and thrust on

a drill by dimensional reasoning and the rules of cutting force development in two dimensional cutting. General equations were derived for drill torque and thrust and were found to be in good agreement with experimental data obtained by use of a drill dynamometer. A variety of work material was drilled in order to verify these equations. The web thickness was found to influence thrust and torque significantly, but the influence of the drill helix angle was found to be relatively unimportant, providing that chip jamming does not occur. If this is encountered both torque and thrust rise greatly, usually causing overheating and drill failure.

A detailed investigation was carried out by Galloway (56) 1957, on drill performance. The general experimental procedure involved close control of the drill, drilling machine, cutting fluid and material machined, while the selected variables such as relief angle, point angle, helix angle and point thinning were varied, drill life and quality of hole being measured.

The effect of factors such as drill shape were considered in relation to the penetration rate, which, together with drill life, forms the basis of workshop decisions concerning production rates and drilling costs. Torque and thrust were plotted continuously for every hole drilled and observations made for drill wear and cutting noise throughout tests.

Results showed that for each material there was a different range of point angle which gave the longest drill life,

together with an optimum nominal relief angle. Various methods of point thinning were tried and a number of these were shown to improve drill life. The materials used were cast iron, steel and titanium alloy.

Reducing the point angle lowered the thrust in drills over 1/16 in. (1.588 mm) diameter. Torque increased with a reduction in point angle except in titanium alloy. When the relief angle was varied from 4 to 20 degrees it had little effect on the cutting forces, but the addition of a 30 to 40 degrees clearance behind a 12 degrees relief on the first 5 degrees of flank reduced thrust by about 10 per cent. The amount of clearance should be limited to maintain the strength of the chisel edge.

The torque and thrust was found to decrease as helix angle increased. Although lower torque and thrust reduce power consumption and deflection, the helix angle must frequently be determined by other considerations when machining metal.

The webs of commercial drills normally increase in thickness towards the shank to stiffen the drill, but this has the disadvantage that the thrust increases as the drill is reduced in length by successive grinding operations. Various methods of point thinning were used in an attempt to reduce thrust but none of them reduced thrust sufficiently in cast iron and steel En 12 to justify thinning the points of thin web drills (web thickness/diameter ratio - .11). Point thinning of

shortened drills having a thick web at the point (web thickness/diameter ratio - .21) reduced thrust by 40 - 60 per cent, although in some cases this seriously weakened the drill point.

Cowie, Pegler and Wight (58) 1957, studied the effects of point angle and relief angle on drill performance when drilling low carbon steel En 3A and medium carbon steel En 10 with 5/8 in. (15.88 mm) diameter 18-4-1 high speed steel drills. Both the drill and the work material were carefully controlled, as well as the drill geometry.

The test criterion was drill life per regrind expressed as the number of holes drilled before drill failure. The drill was considered to have failed when any part of the outer corner, cutting edge or chisel edge began to collapse. Drilling torque and thrust were continuously recorded throughout the tests. During drilling soluble cutting oil was applied at a constant rate, at a temperature of $24^{\circ}\text{C} \pm 1^{\circ}\text{C}$. Having chosen a suitable cutting speed and feed for each material based on the results of preliminary tests 'Blind' holes were drilled to 1 1/8 in. (28.58 mm) depth of full diameter.

When drilling En 3A there was no marked difference in drill life between drills ground to point angles of 100 to 120 degrees but drill life decreased as the point angle increased over 120 degrees. The most economical drill life was obtained with a relief angle within the range of 10 to 14 degrees. Change in point angle had little effect on thrust but torque

decreased as the point angle increased from 100 to 140 degrees. Relief angle had little effect on torque but thrust decreased as relief angle was increased from 4 to 20 degrees.

The drilling of En 10 required a different drill geometry in order to obtain maximum performance. Drill life increased when the point angle was increased from 80 to 90 degrees and decreased as the point angle was increased from 100 to 120 degrees. The best drill life was obtained when the relief angle was within the range 11 to 15 degrees. Thrust increased and torque decreased when the point angle was increased from 80 to 120 degrees. Relief angle had no marked effect on torque but thrust decreased when the relief angle increased from 4 to 20 degrees.

With these two sets of results it was now possible to suggest a common drill with a point angle of between 100 and 105 degrees and a relief angle of 12 ± 2 degrees if mixed batches of low and medium carbon steels were to be drilled. This would eliminate the need for two separate sets of drills.

Later Cowie and Pegler (59) 1958, did an extensive series of tests to determine the effects of changes in point angle and relief angle on drill performance when drilling a range of non-ferrous materials. Point angle and relief angle were selected as the variables because the chip thickness would be affected by a change in the length of the drill lip and in particular are two drill features that can be varied by the drill user.

The drilling test results showed that there was a point angle and relief angle for each material which gave maximum tool life.

From previous work by Boston et al. (60) it would appear that reduction in chip thickness would improve tool performance. This could be achieved by increasing the drill point angle to a stage where structural weakness of the drill point would impose limitations. Failure, however, was caused by wear and not structural collapse indicating some limiting factor other than structural weakness had been reached. In an attempt to determine the limiting factors a study was made of the changes in the "fundamental" cutting angles caused by altering the drill point angle.

It was evident from the results of the analysis of the drill point geometry that drill life was affected not only by changes in chip thickness but also by the effective rake angle.

A mathematical analysis was also made of changes in relief angle along the cutting edge and it was concluded that the relief angle is more important than just providing clearance on the drill. The ability to take a given amount of wear and to withstand the cutting forces acting on it are also necessary.

The helix angle of the drill directly controls the effective rake angle and as this varies with point angle so does the efficiency of the drill. A grinding operation could be carried out on the rake faces in order to modify the effective rake but it was recommended that when drilling materials which require

tools with a high rake angle, quick helix angle drills should be used. Similarly with materials on which it is normal to use tools ground to low rakes, drills with slow helix angles should be selected.

In view of the limitations of the conventional drill, research studies were undertaken by Haggerty (61) 1961, aimed at the elimination of the chisel edge. As a result of this research a new "spiral point" was developed. Fig 18.

Because of the more effective cutting action at the centre and larger chip space, there was found to be a 15 to 34% reduction in the thrust force when machining steels. The values of torque for the spiral point drill were found to be approximately equal to those for the conventional drill because of the small influence of the chisel edge on this component; the average torque for the spiral point drill being 4% lower than that of the chisel point drill.

One effect of the self centring action of the spiral point was to eliminate the bellmouth condition which is produced with chisel point drills. The amount of hole oversize is also affected by the centring action of the drill point. A series of comparative tests for oversize of holes was made with ten chisel point and ten spiral point drills in each of four different sizes. Three holes were drilled with each drill making a total of thirty holes for every size and point geometry tested. The average values of hole oversize and

spread of values were noted and considerable improvement in both hole oversize and spread was obtained with the spiral point drills.

Comparative life tests were also conducted with spiral point and chisel point drills in the laboratory under numerous conditions. In all these tests the end point in drill life was determined when a rapid increase in cutting forces occurred. The resulting values from these tests indicate that, on this basis, the average drill life when using spiral point drills was in all cases as that of the chisel point drills and in many cases better.

Work undertaken at P.E.R.A. by Moore, Pegler and Shadrack (62) 1961, compared the performance of spiral point and conventional point drills, when drilling cast iron and alloy steel, their general conclusions being that there were few major differences between spiral point and conventional point drills on the limited basis of comparison chosen for the investigation.

The advantages of the spiral point drill were:

- (a) lower thrust force, the difference in drilling torque being negligible,
- (b) greater consistency of drill life when drilling cast iron,
- (c) the probability of about 20% greater drill life at the low cutting speed/high feed rate combination used, although the life of the spiral point drills was only about half that of conventional point drills when using a high cutting speed/low feed rate ratio.

The authors also carried out work (63) to obtain factual information on the effect of selected types of point thinning on drill performance. Graphs were obtained that enabled a drill user to decide when the point should be thinned or relieved and also the minimum length of chisel edge that should remain after thinning. Various methods of point relief and thinning were suggested and it was found that drill life after thinning was increased considerably between regrinds. Point thinning of both conventional and thick web drills appreciably reduced the thrust, but only reduced the torque in the case of the thick web drill. The effect on hole size of errors in drill manufacture (when the flutes are not of the same shape or of unequal depth) could be considerably reduced by controlled point thinning. Conversely, if the thinning is not accurately controlled the symmetry of an accurately made drill could be seriously affected and oversize holes produced. Fig. 19.

Pal, Bhattacharyya and Sen (64) 1965, developed a theoretical method for calculating torque when drilling ductile materials, proceeding from the initial properties of the work material, geometry of the drill and cutting conditions. The complex nature of the extrusion process at the region under the chisel edge compelled the authors to restrict their theoretical analysis to cases with a pilot hole in the workpiece.

Abuladze's shear stress formula was used to correlate the nominal shear stress with the standard mechanical properties of the work material. In order to verify the derived equation

for drilling torque a series of tests was carried out on low carbon steel, using a range of standard drills, three different feed rates being employed. The torque was measured by strain gauges mounted on a torque tube, the gauges being suitably instrumented. In order that the results would not be affected the drills were carefully checked for wear throughout the period of the tests, the results of which showed close agreement between the theoretical and experimental values except in the region of the chisel edge.

Waller (65) 1966, devised special equipment and techniques to evaluate drill performance. Two special purpose machines were designed for automatic drill life testing, both having automatic feed and work indexing. For comparison purposes drill life was expressed as the number of holes for a given set of test conditions, the drills being taken to total failure. Tests to evaluate the tendency of the chips to clog the flutes were developed, the point of clogging being recognised by a sudden increase in torque recorded on a dynamometer, the comparison of clogging performance being measured by the depth of hole that could be drilled prior to clogging. A toughness or "misalignment test" was used that gave comparative figures of the resistance to breakage of various drills; this is particularly useful for drills below $\frac{1}{4}$ in. (6.35 mm) diameter, and is an important property to the drill user.

In a later work by Bera and Bhattacharyya (66) 1967, an improved theoretical model for calculating torque and thrust when drilling a ductile material was derived. The torque was estimated by considering the actual variation of the chip thickness along the cutting edge of the drill and applying a suitable angle relationship. Further, by applying the theory of wedge indentation the indenting component of the thrust force at the chisel edge zone was also estimated. From their work they found that the comparison between theoretical estimated values and experimental test results showed close agreement.

Because aluminium is a very soft material a special fishtail point drill was developed by Zaima, Yuki and Kamo (67) 1967, to obtain efficient drilling of this material in plate form. In order to test the effectiveness of the drills the accuracy of the drilled holes was investigated with respect to inlet and outlet diameters, the torque and thrust being measured when using different drill shapes with (a) a constant feeding speed, (b) a constant feeding force.

Billau and Heginbotham (68) 1968, established a method of control of general drill factors in order to make drill testing and evaluation of results more predictable. Close control of the drill, drill mounting, drilling machine and material specification was observed. The "screech" test method of deciding drill failure was found to be unsatisfactory and wasteful, therefore a wear band was measured on a specially

prepared drill lip clearance. Having established a reliable method of measuring drill wear a statistical analysis was made of the results of the drill tests in order to determine the effects and interaction of the variables upon drill life. An estimated reliable drill life was also found.

Williams and Trigger (69) 1968, used a photographic technique to study the formation of the chip in the region of the chisel edge. The material chosen was acrylic plastic because the chip formation could be observed from the bottom of the hole. A computer programme was written to compute the major angles for a standard 3/8 in. (9.525 mm) diameter drill and a 3/8 in. (9.525 mm) diameter 20 degrees modified helix drill, dramatic changes being observed in the face rake angle and the effective rake angle when using a constant helix.

Photographs showed that a drill accurately ground on the face to increase the axial rake close to the chisel edge will produce better chip flow. Comparison of results when drilling malleable iron using standard drills and modified drills with constant helix angles indicated that drilling conditions were clearly better from the standpoint of torque, thrust, chip formation, tool life and hole size when using 20 degrees modified helix drills.

Two researchers, Wilson and Weintraut (70) 1968, carried out trials designed to determine spiral point drill capabilities. Test pieces were of oil-quenched steel and the performance of drills ground on a Cincinnati Spira-point drill

grinder were compared with conventional, chisel point drills. The drills were $\frac{1}{4}$ in., $\frac{1}{2}$ in. and $\frac{3}{4}$ in. (6.35 mm, 12.70 mm, and 19.05 mm) diameter. In the course of the investigation a number of tests was undertaken with spiral and chisel point drills sharpened to point angles of 118, 130 and 140 degrees. These tests suggested that the 130 degrees angle is the most satisfactory for the spiral point, although scatter of data with this point angle was wide. Other findings include longer drill life, lower torque and thrust, and better holes with the spiral point drill. Limitations were imposed by the necessity for a more exacting drill specification, greater losses in efficiency when the point breaks down and reduced drilling capabilities when flutes become overloaded.

During the machining of aluminium plate Zaima, Yuki and Shimizu (71) 1968, noted that when using conventional drills, a strain figure of polygonal shape (having an odd number of vertices) was formed in the countersink during the early stage of drilling. This strain figure swivelled with the rotation of the drill during the process of countersinking and is called the "walking phenomenon of drill". At the drilling stage when the drill margin was in contact with the material face, the vertices of the strain figure gave a rotating scar to some depth of the hole wall, this being called "rifling phenomenon" which caused a lowering of drilling accuracy. Fifteen standard 10 mm diameter drills were used, each with 29 degrees helix angle. Point angles of 110, 118, 130, 140

and 150 degrees combined with lip clearance angles of 12, 14 and 17 degrees, the chisel edge angles ranged from 123 to 167 degrees. Drilling tests were made on nine different types of aluminium alloy plates and a relation was obtained between the walking phenomenon and drilling conditions or materials.

From their observations the authors concluded that the swivelling speed of the polygon depended upon the dimensions of the drill and conditions of drilling. The speed was higher with larger chisel edge angles or higher drilling speeds. In general, it was high for hard materials and became lower for soft materials if the chips were not fully removed. It was thought possible to determine the drilling machineability for any material by the swivelling speed of the strain figure.

Venkataraman and Parker (72) 1968, investigated the drilling of ultra high strength steels using a drill of special design, the geometry of which had been established using a three dimensional mathematical model and computer programme. The cutting action was confined to the lips of the drill, the chisel edge region remaining clear by drilling a pilot hole in the specimen. Using a rectangular blade of material it was possible to incorporate various cutting angles which ultimately led to two cutting lips similar to those of a standard twist drill. A special blade holder was designed to satisfy the following requirements:

- (i) to simulate the cutting action of a standard drill,

- (ii) to facilitate easy mounting of blades with known geometry,
- (iii) to give a good clamping arrangement to take the heavy cutting forces encountered while drilling ultra high speed steel.

The material chosen for the blade was tungsten carbide and this was subsequently ground to shape using a diamond wheel.

Close agreement was found between the calculated and measured values of drill geometry to justify the use of a three dimensional analysis for the determination of the variation of geometry along the drill lips. When certain basic parameters of the drill are known it is possible to determine the variation of geometry for a range of angles, thus minimising the otherwise involved and lengthy measurements.

Using the three dimensional mathematical model developed previously (72) Venkataraman (73) 1968, was able to simulate the drill lip on a shaper tool, the chisel edge not being considered in this case. High speed steel was chosen for the tool material and a velocity clearance of 6 degrees was used on the simulated tool.

The tool was fixed on a shaping machine and the specimen mounted on a three component milling dynamometer. Tests were carried out at three speeds corresponding to the cutting speed at inner, mean and outer radius of the drill. Chips obtained from these tests were compared with chips obtained from a

drilling test with a drill of corresponding geometry and because of their similarities it was concluded that the cutting action of the simulated shape tool resembled that of a corresponding drill. Using this analysis the complex cutting action of a drill could be studied.

DeVries (74) 1968, summarised the measurement techniques used by research workers to study the temperatures in drilling.

The principal experimental methods used were:

1. The tool-work thermocouple method.
2. Methods employing standard thermocouples.
3. Methods using thermal-sensitive paints.
4. Indirect temperature measurement techniques.
5. The Garter Spring thermocouple method.

A description was given of each of the above methods together with a discussion of the experimental results obtained and a summary of their advantages and limitations.

Methods have been used to measure the torque and thrust when drilling but until this investigation by Naureckas and Gabrick (75) 1969, there had been no way to measure how the total torque and thrust were distributed along the cutting edge itself. Photoelastic techniques were used to analyse the various stress patterns produced in the workpiece, the assumption being that the stress in the workpiece would be representative of the stress on the cutting edge of the drill.

A built-up model was placed in a special jig, a low cutting speed being used in order that the stress pattern could be followed. At one diameter in depth the drill was stopped and the cutting edge was placed at right angles to the axis of the polariscope. Thrust was now applied to the drill and the stress distribution due to the thrust was recorded photographically. The procedure was repeated with drills of different shapes until a drill with even stress distribution along the cutting edge was developed. Under actual drilling conditions the drill life was increased considerably with this new shape which has now been patented.

Williams (76) 1969, considered the effect of the feed velocity on the cutting geometry of a twist drill and equations were derived for calculating the dynamic cutting geometry of the chisel edge from a known static geometry. For this investigation the author used a bevel ground drill which is similar to the four facet point, this not only simplifies the analysis of the geometry but also provides more control of all the geometric parameters.

The results of this investigation showed that the feed velocity had little effect on the cutting geometry of the main cutting edges. The dynamic geometry, however, was very different from the static geometry of the chisel edge and should be used in future studies of this drill feature.

Using a similar drill geometry Williams later (77) 1970, with the aid of models studied the effect of the chisel edge on the

torque and thrust when drilling. From this research predictions were made as to the shape of the wear zone about the chisel edge and equations derived for calculating the torque and thrust developed by the chisel edge, given the geometry of the drill point, the cutting conditions and a shear stress factor for the work material.

De Beer (78) (79) 1970, investigated the effect of web thickness on the rigidity, torque and thrust when drilling steel. When the normal twist drill web geometry was altered by reducing the web thickness a corresponding reduction in rigidity was observed. The combination of torque and thrust during drilling determines the deformation of the drill and a reduction in web thickness affects both of these. The thrust was reduced in one case by as much as 40% with a 14% reduction in torque when a standard 14 mm drill web was reduced to .62 mm. Tests, however, showed that it appeared unnecessary to go to very thin webs as below a web thickness of 1 mm a further thinning of the web had very little effect on the cutting forces. This may be explained by the fact that the effect on thrust is proportional to the area of the web cross section. The reduction in web thickness did not appear to impair drill life because the rigidity and drill load were changed at the same time and their effects counteracted each other. This was verified by a series of practical tests.

Fujii, DeVries and Wu (80) 1970, analysed the design and grinding parameters of a twist drill in order that a high

speed digital computer could be used to further analyse the drill geometry and aid design. The design parameters include the drill diameter, point angle, helix angle and web thickness. The grinding parameters include the point angle and, by assuming conical grinding, the nominal relief angle at the outer corner, the cone semiangle and the X co-ordinate of the cone vertex. The investigation assumed a drill with a straight cutting edge and no drill margin (land). The drill flute and flank shapes were first analysed in a plane perpendicular to the drill axis and the influence of the design parameters on the flute contour was also studied. Drill point cross sections in planes inclined to the drill axis were also analysed to describe the drill point geometry, including the face rake and nominal relief angles. A computer programme was developed which enabled drill point cross sections to be designed in planes perpendicular to the drill axis, using the above parameters. When the computer designed drill was compared with a true drill they were almost identical.

The conventional chisel edge of a drill was modified by Bhattacharyya, Chatterjee and Ham (81) 1971, to form a pair of cutting edges. This was achieved by grinding small slots at the chisel edge of the drills with suitable setting and orientation angles in order to increase the normal and effective rake angles, thereby converting the extruding action into a cutting action. An optimum value of setting was found to exist for a drill of a given diameter and helix angle, and

experimental results showed that the thrust could be reduced by nearly 50% although the torque was not appreciably affected. These modified drills were unsuitable for ductile materials such as mild steel because the modification weakened the chisel edge and the work material clogged and welded inside the narrow slots. The application of this is therefore limited to soft and brittle materials such as cast iron.

A three dimensional photoelastic technique to study the stresses along the cutting edge of a twist drill was used by Law, DeVries and Wu (82) 1971. For this a three inch diameter drill model was made of Castolite which was stress frozen under simulated drilling conditions and seven segments were sliced perpendicular to and along the cutting edge for subsequent photoelastic analysis. From the fringe patterns produced it appeared that the stresses increased in intensity toward the cutting edge within a particular slice and they also increased along the drill cutting edge towards the outer corner. The maximum shear stress gradually increased from the chisel edge until a maximum value was reached at three quarters of the distance along the cutting edge. This decreased slightly towards the drill periphery. An interesting similarity was observed between the maximum shear stress distribution and a previously determined temperature distribution along the drill cutting edge as shown in their previous paper (83).

3.2 The Drilling of Plastics

The early forties saw rapid developments in the manufacture of plastics. Industry found these synthetic materials were valuable replacements for metals that were difficult to obtain, particularly in cases where lightness in weight, dielectric strength, corrosion resistance and ease of production had to be considered.

Although plastics are outstanding because they can be moulded or formed to finished shape, there are often many machining operations to be performed on them such as turning, milling, drilling, etc., in order to meet tolerances closer than those obtainable by moulding. Also machining may be necessary to supplement moulding operations.

Drilling is often performed on plastic mouldings or laminated parts. Because their properties differ from those of metals many difficulties not encountered in the drilling of metals, such as gumming, burning in the drilled hole, cracks around the hole edge, or the growth of cracks after drilling, can occur in the drilling of plastics.

During September 1943 an article published by many leading American manufacturers gave recommendations for the forming and machining of plastics (98). A similar survey of the current practice at that time was made by Low (99) 1944, whose article, of a general nature, suggested that for holes below 3/16 in. (4.763 mm) diameter a standard high speed steel drill

with a slight negative rake ground on the cutting lips could be used, although special drills gave better results. For holes larger than 3/16 in. (4.763 mm) diameter special drills should always be used. These have highly polished flutes, maximum chip clearance, slow helix for pierced holes, fast helix for blind holes, with a 55 degrees point ground for thin sections and a 90 degrees point for thick sections. A slight radius should be ground at the edge of the lip which helps to maintain hole size. High speed steel drills are recommended. Dubbing the lip of the drill and giving it plenty of clearance will tend to prevent grabbing and splitting. Drills should not be forced and if kept sharp only slight pressure will be necessary. These findings were confirmed many years later (100) The author states that these materials had a tendency to bind on the drill and close in when the drill was removed. It was advisable, therefore, where tolerances are close, to drill a few thousandths of an inch larger than the size required.

The general conditions affecting the drilling of plastics were outlined by Kobayashi (101) 1967, emphasis being placed on the quality of the drilled hole. Elastic deformation during drilling and elastic recovery afterwards are rather large in plastics and will affect the wear of relief surfaces of the drill and the frictional heat generated between these surfaces and the work material. Because of the nature of the material the author found the drilled surface tended to expand inward into the hole, which further increased the friction between

the drill and the work material; this close clearance made the chips hard to eject as the hole became deeper. Chips melted by the heat welded easily to the drill. This also affected the hole's appearance. Gumming of the inner surface of the hole was most severe when drills with a small helix angle were used, because these drills interfered with the removal of the chips.

The appearance of the drilled hole will also vary with drilling conditions. When the depth of cut is small and the cutting speed is high the heat generated during drilling becomes excessive, resulting in either gumming in thermoplastics or burning in thermosets, thus destroying the dimensional accuracy of the hole.

Torque on the drill increased rapidly until the outside edges of the drill began to cut. There was then a further increase because of friction between the edges of the drill and hole. As the point broke through the material the torque decreased but did not return to the original value because of the friction between the drill and the hole due to elastic recovery and thermal expansion. Torque remaining after cutting will affect the temperature rise on the inner surface of the hole. Thrust increased rapidly when the chisel edge of the drill reached the surface of the work and remained almost constant as the hole became deeper. Torque was found to decrease slightly and thrust was found to increase with increased point angle, Fig. 15.

Using drills with three different helix angles it was found that the ejection of chips was easier with a large helix angle and a rapid increase in torque occurred at a deeper hole depth.

When drilling cast polyester resin under the same drilling conditions cracks around the hole edges increased with increased helix angle, because the actual rake angle had increased. The cracks also became larger with increasing point angle and rate of feed, this being the result of increased chip thickness.

Kobayashi reviews the various drilling methods for individual plastics, the types of chips produced and the appearance of the drilled hole, the optimum drilling condition for each plastic having been determined experimentally.

3.2.1 Drilling of Thermoplastics

In general drills having wide, highly polished or chromium plated flutes with narrow lands and large helix angles are used for thermoplastics (102). This enables the chips to be expelled efficiently without overheating and gumming. The drill point should have an included angle from 60 - 90 degrees and a lip clearance from 12 - 18 degrees. The drills must be sharpened frequently and carefully to keep the correct drill geometry.

The speeds used in drilling will depend upon the type of material and size and depth of holes. In general speeds will decrease with increase in hole size and hardness of material. The speed should be the greatest that will not cause burning or gumming

and the feed should be slow and uniform to produce a smooth hole of uniform diameter. Chips should be removed by frequently withdrawing the drill from the hole.

The following are the requirements for drilling specific thermoplastics:

Acrylics (102). Continuous spiral chips indicate proper drilling techniques when working with acrylics (100). Because of the transparency of acrylics it is usually necessary that the inside of the drilled hole has a high finish. Although the standard type metal drills are satisfactory they have a tendency to grab in large or deep holes. Better results are obtained with a sharp drill having a slow spiral with highly polished flutes, an included lip angle of 70 degrees and a lip clearance angle of 4 to 8 degrees. Improved results can be obtained by drilling a pilot hole in acrylic and filling with wax (100). When the finished hole is drilled the wax facilitates chip removal and enables a clear deep cut.

Nylon (102) (100). Nylon can be drilled satisfactorily with conventional twist drills, but more rapidly with twist drills designed for plastics, having deep flutes, highly polished to facilitate removal of chips. It may be necessary to use a drill .002 to .004 in. (.051 to .102 mm) oversize because of the resiliency of nylon and the heat generated during the drilling process.

Cellulose acetate and acetate butyrate (102). The specially designed drills are preferred for this material as the type used for metal needs much slower speeds and feeds to give a clean hole and prevent the material from gumming.

Polystyrene (102). Carbide tipped straight fluted drills with about 8 degrees negative rake have been found most efficient. If carbide tips are not available drills of high speed steel of point angle 70 degrees and clearance angle of 10 - 15 degrees can be used. A slow helix is best for such work.

The drilling of thermoplastic materials was the subject of research by Hoffman (103) 1971, the performance being judged by the following criteria:

- (a) chip formation,
- (b) cutting temperatures,
- (c) surface quality,
- (d) hole accuracy,
- (e) tool wear.

The shape and condition of the chips were used to assess surface quality and cutting temperature, the chip formation being influenced by drill geometry and cutting conditions. Temperatures showed a tendency to increase with decreased feed and increased cutting speed; this could be reduced considerably by the use of cutting fluids. There were considerable variations in surface finish but under suitable conditions an average roughness depth of $H = 4 \mu\text{m}$ could be

reached. The measured accuracy of all drillings was within the tolerance area of IT12, but this could be reduced using one particular drill to IT9. (.007 to .0016 in on dia. for a 0.5 in hole)

No measurable wear on the drills could be found when drilling unfilled basic materials but wear was found when drilling glass fibre and graphite filled Polyamide. It was also found that if the drill flutes were enlarged to improve chip flow, the drill tended to oscillate, this causing surface flaws. Polishing of the flutes made no measurable improvement to results.

The difficulties which occur in drilling thermoplastics are most often of a thermic nature, and the cooling of the drill with emulsion or compressed air applied externally was unsatisfactory. The most successful results were obtained by cooling the drill with emulsion through internal oil channels. From these experiments the following values were recommended for drilling certain types of thermoplastic materials:
point angle 90 - 120 degrees, radial relief angle 10 - 15 degrees, helix angle 27 degrees.

3.2.2 Drilling of Thermosetting plastics

To drill holes in thermosetting plastics standard high speed steel drills with deep flutes can be used (102). Drill points should be ground to an included angle of 70 - 90 degrees and have a lip clearance or relief made by grinding the back away to 1/16 in. (1.588 mm) wide which reduces friction between drill

and work and gives clearance for the chips. Backing off the cutting lip (rake angle) prevents the grabbing which occurs with a drill with a normal point, and will prevent chipping of the hole when the drill breaks through the underside of the work.

A high speed steel or carbide tipped drill with a thin web, steep helix and polished flutes is also recommended (100). For holes to be tapped later, drills one or two sizes larger than is usually recommended for metals should be used. A powdery chip indicates the feed is too slow. An overly fast speed results in a tearing action. Correct feed rate produces definite, separate chips and a smooth hole.

CHAPTER 4 THE DRILLING OF BONE

4.1 Surgical Drill Criteria

The criteria which should be met by a twist drill for bone surgery are varied and in some respects conflicting.

Sneath (39) summarised the requirements as follows:

- (a) start accurately without "walking" despite an angled approach to the bone surface,
- (b) not jam or require a high torque to complete the breakthrough,
- (c) produce a linear hole of accurate size,
- (d) be able to clear the debris adequately,
- (e) advance at a satisfactory rate with an end load of between ten and twenty Newtons.
- (f) be able to cut satisfactorily at speeds from 100 rev/min to 2000 rev/min,
- (g) generate minimum heat,
- (h) be able to be reground accurately and economically by machine.

Earlier Bechtol (40) had made similar recommendations. These were:

- (a) the drill should not "walk" on the surface of the bone,
- (b) the drill should not catch as it emerges from the cortical surface of the bone,
- (c) produce a hole of accurate size.

Of necessity, drilling has to be freehand and the distance which the drill travels after completion of the hole depends on the surgeon. The less this distance is, the less the unnecessary tissue damage and risk to vital structures.

Sneath (39) gives this distance as being proportional to the end load necessary to advance the drill. Therefore the lower the end load compatible with a satisfactory rate of drilling, the more accurate will be the surgeon's control over the drill's direction and distance of travel. This control of end load was also emphasised by Garden (41) as it is essential that the drill does not plunge through the far cortex and damage surrounding tissue.

Sneath assumed that heat production in the bone was proportional to end load and any excessive heat produced would char the organic matter of the bone, blocking the drill flutes and preventing debris removal. This assumption conflicts with the work done by Matthews and Hirsch (4).

Although it is recommended that the drill should be accurately reground by machine after every surgical operation, in many hospitals there are no sharpening facilities. This, together with the high initial cost of the drill, results in the surgeon often being presented with a drill in poor condition.

4.2 Drill Symmetry and Hole Accuracy

The grinding of a point on a drill will not necessarily, in itself, give optimum drill performance. The point geometry

must be concentric with the drill axis and the drill body itself must be symmetrical.

Experiments were carried out by Galloway (56) 1957, in order to obtain basic data needed to improve drilling techniques in a number of engineering factories. Special attention was given to the elements of the drill which could be controlled by the drill user, and their effect on the accuracy of the drilling operation.

A common error in drill grinding was found to be lack of drill point symmetry, particularly where one lip of the drill cuts in advance of the other. This caused a displacement of the chisel edge from the centre of the drill, and the drill tended to rotate about this new centre. The mean hole oversize increased linearly with the relative lip height, being less with a smaller point angle. As a result of the relative lip height h , the chisel edge is displaced from the drill axis by an amount $d = \frac{1}{2}h \tan k$ where $k =$ half point angle.

With a large relative lip height and the tendency to displace the general axis of the drill from the axis of rotation towards a position where the resultant forces on the lips are in balance, the cutting conditions at the two lips are different and premature failure of the drill occurred.

With the advent of high production rates Haggerty (84) 1960, carried out research to determine the effect of point grind symmetry and the effect of web centrality and flute spacing

on drill performance. This was done for both spiral point and chisel point drill geometries.

He first investigated the effect of the point being ground off centre, this producing different drill lip heights. With one cutting edge taking a bigger chip than the other, there will be an unbalance of cutting forces between the two, the drill tending to deflect away from the cutting edge on which the largest force acts, the uneven chip formation and deflection of drill causing oversize holes.

The effect of web eccentricity and flute spacing also affects the point geometry. Unlike the previous test where the difference in lip height remains constant along the main cutting edge, in this case the relative lip height varies along the cutting edge because of the web eccentricity. Here again it was found that the hole oversize for both drill point geometries is directly related to the amount of web eccentricity of the drill.

A study was also conducted as to the effect of web eccentricity on drill life and it was shown that with both chisel point and spiral point drills, increasing web eccentricity decreases drill life.

Landberg (85) 1961, assessing the performance of high speed drilling under laboratory and workshop conditions found that drills with unequal lip height had a far shorter life than those accurately ground. The accurately ground drills also

gave a more accurate hole. A conclusion was reached that many of the drills used in the workshops were incorrectly ground and that better supervision of the grinding and checking operation was necessary.

Using newly developed force measuring devices Spur (86) 1961, investigated the effect of radial force vectors and their variation during one revolution of the drill. An out of balance rotary radial force of constant magnitude causes static bending stress of the drill, with simultaneous dynamic stressing of the workpiece, there is a concentric increase in hole diameter and thus the dimensional accuracy of the drilled hole is influenced unfavourably.

The factors affecting the rotary radial forces are generally caused by some factors related to the tool and were quoted as follows:

- (1) Dissimilar lip length.
- (2) Dissimilar drill point angles.
- (3) Dissimilar clearance angles.
- (4) Non-symmetric web at the point.
- (5) Non-symmetric flutes.
- (6) Dissimilar cutting edge sharpness.
- (7) Out of truth.

Some of these errors in the drill are the product of faulty drill grinding.

A rotary radial force of variable magnitude is a radially directed force vector rotating with the twist drill and

which alters its magnitude periodically or non-periodically during one revolution. The presence of a rotary radial force of variable magnitude is caused by variations of the cutting force which are produced by:

- (1) Unhomogeneity of the material.
- (2) Jamming of chips.
- (3) Non-uniform cooling and lubrication action.

A fixed radial force in a constant direction can also occur. This causes off centre drilling of the hole in a preferred direction.

The influence on the radial force of difference in lengths of lips with equal drill point angles, and of different drill point angles with equal lengths of lip, has been investigated. On the basis of the data obtained it is possible to find for a given limitation of the theoretical hole oversize the admissible error in drill point geometry; the data thus obtained can be used as a basis for drill sharpening.

4.3 Development of the Orthopaedic Drill

An early record of the drills and screws used in orthopaedic surgery was made by Lane (11) 1914. The holes were made with a drill corresponding in size to the screw which was going to be used except where the bone was softer than normal when a smaller drill was used. These drills were of the flat type as used by carpenters. The screws were ordinary "wood screws"

of the trade except that the thread was cut up to the head, there being consequently no barrel. This was to enable the screws to hold the proximal layer of the compact bone only, the screw not entering or gripping the distal cortex, except in the case of a young child. The use of a hand drill, although occasionally expending much energy, was recommended. This gave the surgeon a clearer idea of the density of the bone and enabled him to form a better opinion as to what gauge and length of screw he should employ. The screws and drills were made up into three gauges for convenience, these being 3, 5 and 7 with lengths varying from $3/8$ in. to $7/8$ in. (9.525 to 22.225 mm).

Considerable interest was shown in 1957 by orthopaedic surgeons in the potential advantages of the spiral point drill in bone surgery. Experiments conducted by Ernst and Haggerty (88) in drilling fresh beef bone indicated that the self-centring features of the spiral point geometry drill were particularly helpful in preventing slipping of the drill point when entering the slippery round surface of the bone. Using a spiral point drill with an included angle of 72 degrees it was found possible to enter bone without difficulty at an angle of about 45 degrees to the surface. A surgical drill formed with a 72 degrees spiral point shape was first used in an actual hip pinning operation at Drake Memorial Hospital, Cincinnati, in December 1957. It has since been used successfully in several similar operations.

The work of Bechtol, Ferguson and Laing (40) 1959, has had a major influence on the design of surgical drills. In consultation with the Greenfield Tap and Die Company regarding the specific problems encountered in drilling bones, the following criteria were considered important in the design of an orthopaedic drill, and suitable design recommendations were made.

(1) The drill should not "walk" on the surface of the bone when the hole is first started. This allows the drill to be placed accurately in the centre of a hole in a metal plate, and will prevent it from moving to the side of the hole as the drilling commences. This prevents the drill from damaging the metal plate and also accurately centres the screw. This quality was considered more important after the drill had penetrated the first cortex of the bone and was entering the second cortex. This is because the drill is now firmly held in the near cortex and any walking of the drill point to one side may cause the drill to break.

(2) The authors state that since bone is similar to plastic material and a 90 degrees drill point angle is used to prevent the chipping of this substance, a 90 degrees point angle should be used for the drilling of bone. Another advantage claimed is that it allows the drill point to make contact with the second cortex of the bone at a greater angle than the 118 degrees point which is standard in metal drills.

(3) The cutting face of the drill should have zero rake. This is claimed to prevent the drill from catching as it emerges from the cortical surface of the bone and driving the drill ahead to chip out a piece. The drill also remains sharp longer.

(4) The sharp edges of the spiral flutes should be dulled, so that any wobble of the drill in the process of drilling the hole will minimise the reaming of the hole to a larger size. Tests carried out in the laboratory showed that even with the bone clamped in a vice and the drill hole made with a hand drill as carefully as possible the hole was always 2 or 3 gauge sizes larger than the drill which was used.

(5) The drill should be made of a substance which cannot be corroded in the process of sterilising in an autoclave and should not be brittle. Both vitallium and stainless steel were considered satisfactory for drill material.

The above recommendations are endorsed by the Swiss Association for the Study of the Problems of Internal Fixation (Arbeitsgemeinschaft für Osteosynthesefragen) and are designated by A.S.I.F. or AO.

The majority of twist drills used in bone surgery today are similar to the standard chisel pointed twist drills used in drilling metal, the modifications being the reduction of the point angle to 90 degrees and the removal of the cutting lands as recommended by Bechtol et al. In order to avoid corrosion of

the screws and plates they are usually made of the same material as the screw, which is stainless steel or cobalt chrome alloy.

Sneath (39) 1965, who was dissatisfied with the existing orthopaedic drill, carried out research in order to find the optimum drill conditions. For this work he used two groups of drills, one half of each group was ground to four facet shape and half of these had no cutting lands. The second group had spiral point shape and half of these had no cutting lands. Varying point angles of 60 - 160 degrees were ground on each set of drills with a 15 degrees clearance angle. These drills, together with a number of standard drills, were assessed, firstly by freehand drilling of a number of beef bones using various types of motive power. Secondly the drills were tested for their rate of progression through beef bone when the end load and drill speed were kept constant.

This experiment was later repeated using human bone (42), the assumption being that the most efficient drill would penetrate a given thickness in the shortest time. During this research the performance of the drills was judged by the criteria stated previously.

In order to measure the rate of penetration the twist drill to be tested was rotated at constant speed in a lathe chuck, the bone to be drilled being pressed against this by a constant load. The rate at which this material, clamped in a special

holder which in turn was fastened to the test equipment, advanced on to the drill was equal to the rate at which a shutter and aperture passed between a solar cell and a light source supplied by a stabilised power supply. The solar cell was connected to a pen recorder, via a sensitivity and polarity control. The recorded trace showed a graph of time against distance. The end load may be varied for any of the experiments.

From this work Sneath was of the opinion that cutting lands are better than no lands, that the spiral point shape is better than the four facet shape and that an included point angle of 130 - 140 degrees gave optimum results. Drills of this specification have now been accepted for inclusion in B.S. 3531 Part 3, the British Standards Institution implant materials section.

4.4 The Drilling and Screwing of Bone

The most commonly used orthopaedic implant is the surgical screw (43) and many orthopaedic procedures today depend upon screw fixation of implanted devices to the bone. For this reason the quality of the drilled hole is important and one explanation for the occasional failure of procedures demanding stable fixation, apart from the thermal damage caused by the drilling, may be the result of the mechanical drilling process itself.

When two fragments of bone are screwed together they can only be placed under compression if the hole drilled in the first

cortex is at least as large as the external diameter of the screw. The screw threads will then be in the far cortex and when the screw is tightened the two parts will be brought together.

Thus the holding power of the screws depends upon the quality of the threads cut in the bone. Any factor which decreases or increases the depth of bone threads or damages the bone decreases the holding power accordingly. Disproportion between drill size and screw diameter is one of the most serious errors since too large a drill hole leaves insufficient bone engaging the screw. Too small a drill hole necessitates excessive pressure for insertion of the screw with a danger of breaking the screw or damaging the bone. Peterson (44) 1952, says that it is important that drills be of constant diameter in relation to the screws and this means there is only one optimum drill size. Even with the standardising of drills and screws, the actual drill geometry would give various sizes of holes as shown in Figs. 52 to 61; it is therefore important to standardise both drill and drill shape. Peterson also suggests that each screw should be properly centred in the hole or slot in order to avoid damage to the screw thread as it is inserted, and in order to make the screw head fit the countersink in the plate. For this purpose a drill guide is essential.

Rigid internal fixation by necessity depends on the production of local pressure areas between implant and bone or between bone ends, Fig. 11. Wherever pressure necrosis and consequent

bone resorption occurs, there will be a loss of stability. Compression fixation in particular demands a high degree of precision with regard to the position and stability of the fixating screws. The recommended levels of compression are achieved with an axial movement of 10 - 20 μ m after contact between the fracture fragments. Consequently a loss of bone at the screw site could easily negate any beneficial effect of this type of device. This work was done by Perren et al. (45) who measured the effect of various forms of bone resorption and instability on the applied pressure, by using strain gauges attached to internal fixation plates screwed to intact and osteotomised sheep tibiae.

4.4.1 Factors Affecting Screw Insertion

There are a variety of screws in use. Some surgeons advocate screws with a self-tapping point, while others are satisfied with non-self-tapping or plain screws (43). Another group of surgeons drill and tap the bone before inserting the screw (2). This is the method recommended by the Swiss Association for the Study of the Problems of Internal Fixation as their research has shown that temperatures in excess of 90°C can develop with the use of a self-tapping screw, thus damaging the bone cells.

Ansell and Scales (43) 1968, carried out a study of some of the factors which affect the strength of screws and their insertion and holding power in bone. For this they investigated

the influence of drill size in relation to the diameter of the core of the screw and the relative merits of self-tapping and non-self-tapping screws. The effect of continuous and intermittent rotation on the stress developed in the screws during insertion was also studied.

The bending or breaking of a screw on insertion is usually caused by the application of a torque greater than that particular screw can withstand, because of:

- (a) the use of an incorrect drill in relation to core or minor diameter of screw,
- (b) the insertion of a non-self-tapping screw into a hole in which the thread has not been formed by the appropriate tap,
- (c) the incorrect alignment of a screw in a hole. This is particularly relevant when the opposite cortex is being engaged,
- (d) the seizing of a screw when the distal cortex is engaged when no clearance hole is drilled in the proximal cortex.

During tests with human femora using self-tapping and non-self-tapping screws it was shown that less torque was developed during the insertion of self-tapping screws. As already stated some authorities, however, prefer to drill and tap the hole with the correct thread (2) and use a non-self-tapping screw.

Using three different drill diameters to drill the hole for the same size of screw, the mean insertion torque developed was lower for the self-tapping screws compared with the

non-self-tapping screws. There was also a decrease in insertion torque with increase in the size of the drilled hole. The size of drill hole within a limited range and the presence or otherwise of self-tapping flutes had little effect on the mean extraction force required to pull out the screws.

It was also shown that when there was a pause in rotation during insertion of a screw the torque developed increased. This increase was most noticeable in the case of the non-self-tapping screws. Conditions such as this can arise in clinical practice since few screws are inserted by continuous rotation.

Bone is a viscoelastic material, and with a non-self-tapping screw there is less cutting of the thread form, hence the torque is mainly due to the friction of the screw on the bone. Once rotation is stopped the bone is able to relax on the thread and a higher static friction force has to be overcome than in the case of a cut thread.

Because of the variations in the properties of animal and human bone and the difficulties of obtaining suitable human material a phenol formaldehyde fabric laminate which complied with British Standard 2572 : 1955 was used for the specimens during a series of tests. The results of these tests indicate that this material could be used as a substitute for bone in studying screw design and performance.

It was concluded that if the correct diameter of hole is drilled and tapped in a bone and a screw having optimum mechanical

properties is inserted using a torque limiting screwdriver, it would be possible to prevent many failures of surgical screws. This method is shown in Fig. 12.

4.5 The Effect of Speed and Thrust on Temperature

Until recently almost all the work on the temperature measurement in cortical bone had been done using bone pins or dental burrs as the cutting tools (46) (47). In no case had data been presented relating the temperature in bone to conditions of drilling using standard orthopaedic drills.

Extensive work on the effects of drill performance on temperature has now been carried out by Matthews and Hirsch (4) 1972, their work being done to establish the optimum conditions for drilling human bone with standard A.S.I.F. 3.2 millimetre twist drills. Drilling was done on a machine shop drill having a number of speeds, force in drilling being applied manually with the drill feed handle.

For temperature measurements, four chromed-alumel shielded thermocouples with diameters .25 mm were used. These were positioned at .5, 1.0, 2.0 and 3.0 millimetres from the drill hole wall, a drill jig being used to accurately locate these holes.

Femoral specimens were used for these tests, these being circulated with Ringer's solution to bring the specimen up to 37°C. The specimen was perfused until the moment of drilling,

the surface never being allowed to dry. The force applied to the drill was measured by means of a cantilever dynamometer, the output being recorded on an ultra-violet recorder. All the tests were carried out on the first cortex of the bone as there was no change in temperature recordings when the second cortex was drilled.

The maximum cortical temperature recorded was 140°C measured .05 mm from the drill. Temperatures greater than 100°C were recorded in 37 out of 158 examinations when there was no provision for cooling.

In order to examine the effect of speed and drilling force, observations were made at rates of rotation of 345, 885 and 2900 rev/min. Drilling forces of 20 N, 59 N and 118 N in all possible combinations were used. The highest average maximum temperature measured was 93.1°C at a drill speed of 2900 rev/min and a force of 20 N. In every case increasing the drilling force caused a decrease in average maximum temperature measured at each thermocouple position, Fig. 13. Increases in drilling force from 20 N to 59 N and from 20 N to 118 N were associated with significant decreases in the average duration of temperature elevation above 50°C . A force change from 59 N to 118 N did not increase the period of temperature elevation significantly. There were no significant differences in maximum temperature which could be attributed to drill speed.

Manual irrigation with water at room temperature was tested as a method for decreasing the cortical temperatures and was found to be highly effective in limiting the maximum temperature elevations.

There is evidence that damage to bone occurs at 50°C. Bonfield and Li (37) have found that the mechanical properties of bone which had been heated to 50°C were irreversibly altered.

The authors claimed that there is little relationship between the drilling speed and either the maximum temperature or the duration of temperature elevation. Increases in the rate of advance of the drill with the associated increase in drilling force caused less heat production. The distribution of heat was also altered by increasing the force with a greater proportion of heat in the chips and less both in drill and specimen.

This is in agreement with Schmidt and Roubik (87), who used calorimetric techniques to measure the heat generated in the drill, the chips and the specimen when drilling metal. They found that the heat generated was virtually independent of the rate of rotation of the drill. The total amount of heat produced was reduced by using a heavier feed, and as the chip thickness increased a greater percentage of the total heat went into the thicker chips with less in both tool and workpiece.

Because of this relationship it was recommended that a drilling force of up to 118 N should be applied to assure a steady progression of a sharp drill through the cortex.

It was concluded that heat generated when drilling was due to friction and to fragmentation of particles of bone at the cutting edge of the drill. It was therefore said to be related to the total number of revolutions required to complete the hole. When drilling at an increased force level, the drill cuts deeper, progresses more rapidly and completes the hole in fewer revolutions. The fact that the cutting edge does not move as far, and that less total cutting has been done at the higher force level, together with the possible redistribution of heat to the chips, was assumed to explain the decrease in temperature and the decreased duration of temperature elevation when the drilling force was increased.

The condition of the drill proved to be important. Much greater temperature elevations were noted when a worn drill was used, Fig. 14.

Eichler and Berg (48) were also concerned with the increase in temperature when drilling compact bone. For their investigations a drilling rig was developed which allowed variations in direction and magnitude of thrust, temperatures being measured by means of thermocouples situated .5 mm from the drill, these being coupled to a recorder.

Standard A0 twist drills were used with helix angles of 20 degrees for the 3.2 mm diameter drill and 25 degrees for the 4.5 mm diameter drill. This angle corresponds to normal drill types. The point angle in both cases was 90 degrees. The importance of a correctly ground drill was also stressed, uneven grinding of the drill producing oversize holes. The authors recommended that surgical drills should always be ground on a drill grinding machine.

Both fresh corpse and calf bones were drilled at speeds of 500 or 700 rev/min. Using a speed of 700 rev/min and a thrust of 12 N temperatures up to 74°C were recorded when using the 3.2 mm diameter drill. The drill thrust was found to influence the heat generated, the greater the thrust the higher the temperature, the most favourable drill pressure with lowest working temperature being 22 N. There was a considerable difference in the temperature rise (17°C) when drilling under the same conditions but using different diameter A0 twist drills. The authors found that the larger diameter drill was better at conducting the heat away and had a better helix angle combined with good chip clearance.

CHAPTER 5 EXPERIMENTAL WORK

5.1 Introduction

Advances in drilling research can be made either by the development of a fundamentally new type of tool or by progressively bringing the existing geometric features such as helix angle, point angle, point shape and web condition to an optimum value for a particular drilling operation. The cumulative effect of bringing the many features of a drill to an optimum can result in a marked overall improvement in performance, although the individual contributing factors can be relatively small.

5.2 Types of drill point used

Three different drill point geometries were used. They were:

- (1) radial relief point,
- (2) four facet point,
- (3) spiral point.

Radial Relief Point

The conventional twist drill point has radial, circular or curved clearance flanks developed by most drill grinding machines, Fig. 16. This is difficult to define because its shape is dependent on the method of generation inherent in each machine (56) (57). Basically the drill point is ground by traversing the flanks past a straight line of contact on the face or periphery of a grinding wheel. The grinding wheel

face envelops part of a conical surface in its motion relative to the drill point, and the flank surface produced on the drill point is part of the surface of this cone as already mentioned. However, in many drill grinding machines the grinding motion is more complex. This geometry has the flat chisel edge or chisel point which is practically a "dead" point with very poor penetrating ability where the web forms the flat edge.

Because of the flat on the very point the drill tends to wander or walk from the intended position. For accurate work it is usually necessary to centre drill or use a drill jig for location. Owing to the relatively dead point considerable thrust is required to feed the drill into the work. The action of the chisel edge is one of displacement or extrusion of the workpiece material rather than a cutting action.

Four Facet Point

The four facet or prismatic point geometry has flat primary and secondary clearances rather than a radial or spiral clearance. Because of these clearance faces the flat chisel edge is replaced by four flat surfaces or facets, similar to a split point or crankshaft point geometry, Fig. 17. It is claimed that the elimination of the flat chisel edge provides a better self centring action, together with better hole finishes and more accurate hole size. The flat land left by the primary clearance can be equal to the width of the margin or wider; this type of clearance can be easily measured and varied without regrinding the secondary clearance angle which is usually twice as large as the primary.

The Spiral Point

This drill point configuration was developed by Ernst and Haggerty (88). The point shape is produced in a single grinding operation by a mechanism which provides a controlled relative movement of the grinding wheel and drill point axially, radially and circumferentially all in properly timed relationship to the flutes of the drill. As indicated by the name "spiral point" the entire flank surface extended rearwardly from each main cutting edge is formed as a "3 dimensional spiral" surface from the axis of the drill to its periphery. Because of the way in which these surfaces are ground the drill has a true point and a free cutting action close to the axis of the drill. The chisel edge is gone and in its place is the characteristic "S-shaped" cutting edge, Fig. 18.

The authors illustrated the difference in the rake angle across the chisel point of a conventionally ground drill as compared to a spiral point drill by taking a series of photomicrographs at various sections through a $\frac{1}{2}$ in. (12.7 mm) diameter chisel point drill. Along the entire chisel edge from .010 to .030 in. (.254 to .762 mm) radius the normal rake is about minus 56 degrees and therefore the opposition to chip flow is very great. Towards the periphery the cutting action is much better, because of the increase in normal rake and cutting speed.

A similar set of photomicrographs of sections through the spiral point drill shows that across the point the normal

rake angle is much less negative, the shear angle is higher and the chip space ahead of the tool is greater. The opposition to chip flow is therefore much less. In the sections along the main cutting edge there is no significant difference, as the normal rake angles here are virtually identical for both drills.

The spiral point is especially useful where self-centring action is required. Additional advantages claimed are: more accurate hole sizes, smoother hole finishes, reduced thrust requirements (although torque remains largely the same compared with conventional chisel point) and improved roundness of hole. The self-centring action is provided largely by the spiral clearance and the increased clearance compared with the normal chisel point at the web. The cutting zone therefore extends practically to the centre of the drill at the point. The decreased thrust simultaneously improves self-centring action.

The Spiropoint drill point grinder was originally developed by the Cincinatti Machine Tool Company to produce this drill point geometry. Although this particular machine is no longer being manufactured by Cincinatti a similar machine called the "Winslow" is made in the United States of America.

5.3 Drill Point Geometry

The effective rake angle, the normal rake angle, the angle of inclination and the chip flow angle, together with drill relief

angle may all be considered as fundamental angles controlling the cutting efficiency. They have been theoretically derived and can be calculated when certain basic features of the drill are known. These angles are shown in relation to the drill point in Fig. 20.

In order to determine the various rake angles for any tool with inclination angle i , it is necessary to know the direction the chip takes as it crosses the tool face. This is most effectively specified by the angle η between the chip flow direction and the normal to the cutting edge as measured in the plane of the tool face.

Stabler (89) 1950, has shown that when the angle η is known the effective rake angle γ_e may be determined from

$$\sin \gamma_e = \sin \eta \sin i + \cos \eta \cos i \sin \gamma_n \quad \dots\dots(3)$$

the effective rake angle being the angle between the drill velocity vector and the chip-flow velocity vector less 90 degrees. The normal rake angle γ_n is the angle measured from a normal to the finished surface in a plane perpendicular to the cutting edge.

The results of Stabler's investigation suggest that the angle of chip flow η is approximately equal to the inclination angle i and using this approximation the expression given previously for effective rake becomes:

$$\sin \gamma_e = \sin^2 i + \cos^2 i \sin \gamma_n \quad \dots\dots(4)$$

This, however, was later shown to be inaccurate, other factors having to be considered. (52) (90).

Shaw, Cook and Smith (90), using an oblique cutting tool, measured the chip width b_4 and knowing the width of the work b_3 were able to calculate η from the following equation:

$$\cos \eta = \frac{b_4 \cos i}{b_3} \quad \text{.....(5)}$$

Oxford (52) used experimental methods to determine the true chip flow when drilling. Using a toolmaker's microscope the projected chip flow angle η_j could be measured at any point along the cutting edge. This needed converting to a true chip flow angle η along the face of the flute before it could be used by:

$$\tan \eta = \tan \eta_j \cos \gamma_a \quad \text{.....(6)}$$

The angle of inclination i of the cutting edge during the drilling process must be considered and this was shown by Shaw and Cook (51) to be:

$$\sin i = \frac{t}{r} \sin k \quad \text{.....(7)}$$

where $2t$ = web thickness

$2k$ = drill point angle

r = radius at any point

Their analysis of drill point geometry gives details of the influence of changes in drill features upon the significant angles for positions near the point and also near to the chisel edge. In the table, shown overleaf, a plus sign signifies an increase, a minus a decrease, while zero indicates an insignificant change in the angle in question.

For increase of:	Points near periphery			Points near chisel edge		
	i	γ_n	γ_e	i	γ_n	γ_e
Web thickness	+	0	0	+	-	0
Point angle	0	0	0	+	+	+
Helix angle	0	+	+	0	+	+

Galloway (56) derived the following expression for the rake angle at any point P on the cutting edge of the drill:

$$\cot \gamma_a = \frac{1}{(\rho^2 - \tau^2)^{\frac{1}{2}}} (\rho \cot \delta_p \sin k - \tau \cos k) \dots\dots(8)$$

where γ_a = rake at any point P on lips

δ_p = helix angle at P

$k = \frac{1}{2}$ point angle

$$\tau = \frac{t}{R}$$

$$\rho = \frac{r}{R}$$

the value of δ_p at any point being obtained from:

$$\tan \delta_p = \rho \tan \delta_o$$

where δ_o is the angle of the helix passing through P when P coincides with the outer corner of the drill. This angle γ_a had previously been called the face rake angle by Oxford (52) who used this, together with the angle ϕ , the angle the drill velocity vector is elevated above the reference plane, in order to find the normal rake angle

$$\gamma_n = \gamma_a - \phi \dots\dots(9)$$

The elevation angle ϕ is given by

$$\tan \phi = \tan \beta \cos k \quad \dots\dots(10)$$

where β = web angle = $\sin^{-1} \frac{t}{r}$

$k = \frac{1}{2}$ drill point angle

Using these expressions a programme was written for the present experimental work, using a Monroe Model 1655 electronic programmable display calculator. This programme was used to compute the face rake angle and normal rake angle at any point on the drill cutting edge for drills with different helix angles, point angles and web thicknesses. Examples showing the variation in these angles with different point geometries are given in Figs. 74 to 78.

5.4 Test Drills

As there appears to be no standard proportion of web thickness to drill diameter for 6.35 mm ($\frac{1}{4}$ in.) diameter drills, manufacturers recommend a web thickness of approximately 20% of the drill diameter at the point although this was found to vary considerably. Shaw and Cook (51) recommend the following sizes:

Drill diameter (mm)	Web thickness % of diameter
3.175 (1/8 in.)	20
6.350 (1/4 in.)	17
12.70 (1/2 in.)	14
25.40 (1 in.)	12
> 25.40 (1 in.)	11

The test drills comprised two groups:

Group A

These drills were 6.35 mm ($\frac{1}{4}$ in.) diameter high speed steel, bright finish parallel shank jobbers drills. They were selected to give a web thickness of $1.118 \pm .05$ mm at the point, which is 17.5% of the drill diameter.

Three helix angles were used, their mean values being:

Quick helix $36\frac{1}{2}$ degrees

Normal helix 27 degrees

Slow helix $14\frac{1}{2}$ degrees

These drills were within British Standards tolerance on diameter, Plate 2.

Group B

The drills of this group were similar to the foregoing except that the web thickness at the point varied from .74 mm to 1.60 mm.

5.4.1 Drill grinding

The importance of a correctly ground drill point has been discussed in section 4.2. A symmetrically ground point must be aimed for with equal height of the lips and with chisel edge accurately in the centre of the drill. A correctly ground drill not only has a longer life than a badly ground one, but under the same cutting conditions gives a more accurate dimension of the drilled hole. All the drills were machine ground and were inspected on the grinding machine for irregular

flutes, bent drills and incorrect setting. They were also checked on an O.M.T. toolmaker's microscope for size and to see that there were no burrs on the cutting edges of the newly ground drill and that the flank had a good ground finish.

Drills of Group A were divided into three sets, one set comprising 8 quick helix, 8 normal helix and 8 slow helix drills, each type of drill being ground with point angles of 80 degrees to 150 degrees inclusive in steps of 10 degrees.

A Christen 2-32 drill grinder, Plate 1, was used to grind and check one set of drills, each with a 15 degrees radial relief clearance angle. The characteristics of the radial relief are shown in Fig. 21. The same machine was used to grind a second set of drills to four facet point geometry with 15 degrees primary clearance and 35 degrees secondary clearance⁽⁹⁷⁾ The third set of drills was ground on a Cincinnati Spiropoint drill grinder to a spiral point shape with a 15 degrees clearance angle.

Drills of Group B were all ground to a point angle of 118 degrees with a radial relief angle of 15 degrees. Apart from the helix angle the only other variation was the web thickness which varied as shown in Tables 1, 2 and 3.

Point thinning

Another factor which must be considered when making drilling tests is the effect of point thinning. The drills of Group B were thinned as illustrated in Fig. 19, which means that the chisel edge is shortened.

5.5 Dynamometry

In order to carry out research into any cutting operation it is necessary to measure the forces acting on the cutting tool. It is from the knowledge of how these forces vary that deductions are made about the mechanism and efficiency of the cutting process. At the time of the initial investigation there were several types of dynamometer available but they were all designed for high loads compared with the small loads encountered in bone drilling. At this low level of loading the friction of movement and measurement would become proportionally too high to permit accurate readings. It was therefore necessary to design a dynamometer that would overcome these difficulties.

The general design considerations recommended by Rapier (91) for all types of dynamometers are as follows:

(a) Sensitivity

If the determination of the cutting force depends on the measurement of a small strain or displacement, for high sensitivity, this should be as large as possible at the point of measurement.

(b) Rigidity

If the rigidity of the dynamometer is low then onset of vibrations occurs at relatively low loads and high speeds. In general the smaller the rigidity the lower the natural frequency of oscillation of the tool holder and the smaller

the frequency range over which the dynamometer can be used for dynamic measurements. The requirements for rigidity clearly conflict with those for sensitivity.

(c) Ruggedness

Ruggedness of construction is essential for satisfactory performance under arduous conditions.

(d) Compactness

The space available on standard machine tools is limited.

(e) Accuracy and repeatability

In comparative tests small differences in cutting forces are often significant and high overall accuracy under all conditions is desirable.

(f) Interaction

Some interaction is experienced in most dynamometers designed for measuring more than one component of force. Whilst allowance can be made for such interactions when computing the forces from the readings of the measuring instruments, it is desirable to keep interaction effects within the overall limits of accuracy.

(g) Calibration

When more than one component of cutting force is measured it is desirable to load the dynamometer in the different directions simultaneously such that the lines of action of the applied forces pass through the cutting point and are accurately maintained in their nominal directions relative to the dynamometer.

(h) Damping

Vibration is controlled by the amount of damping present which may be inherent in the design or deliberately added to improve stability.

5.5.1 Dynamometer Design Features

The main structure of the dynamometer was manufactured from mild steel and made to generous proportions in order to ensure rigidity and reduce vibration, see Plate 3 and Fig. 22.

In order to eliminate as far as possible any friction between the spindle and bearing and therefore increase the accuracy and repeatability of the dynamometer an air bearing was used, this being based on a National Engineering Laboratory design (92) (93).

Spindle bearing	50.8 mm (2.0 in.) diameter
	2 rows of 6 orifices .508 mm (.02 in.) diameter
Radial clearance	.02 mm (.0008 in.)
Air pressure	413 KN/m ² (60 lb./in. ²)

The spindle was made of stainless steel mounted in a brass bush, rustless materials being used as a precaution against moist air, even though the air was passed through a filter-regulator to remove moisture and foreign matter.

The table is free to rotate and move downwards under the torque and thrust of the drill within certain limits imposed by two steel beams, whose deflection under load activates Sangamo electronic gauging heads. The amplified/demodulated signal

from each head is shown on an indicator and also as a trace displayed against a time base using an S.E. Laboratories Ltd. Type S.E. 3006 ultra-violet direct recording oscillograph, the instrumentation being mounted on a trolley for convenience.

The torque system was calibrated by placing dead weights on the hanger and the thrust system by placing dead weights on the dynamometer table.

Records from the ultra-violet recorder were obtained from the torque and thrust elements for a range of loadings and calibration graphs were drawn; these were checked frequently. It was found that interaction between the torque and thrust system was negligible.

5.6 Details of Work Material

Pig femora

As can be seen from Chapter 2 bone is a remarkable substance and many factors affect its physical properties. In order to standardise as far as possible the bone used for this research it was decided to use pig femora which are similar in many respects to human bone. This particular bone could be obtained fresh in large quantities, the animals being approximately all the same age and size. The animals were killed at regular intervals and as soon as the bone was available this was collected and stored in Ringer's physiological saline solution at room temperature. This is a solution of the chlorides of sodium, potassium and calcium and is named after the man who

first discovered that perfusion with this simple solution keeps an isolated heart beating (49). Drilling of the bone was done within 48 hours before putrefaction occurred. A number of bones were sectioned to ascertain the mean thickness of the cortex and this was found to be 5 mm approximately, Plate 4.

5.6.1 Preparation of Specimen and Drilling Sequence

The pig femora were approximately the size shown in Fig. 23, Plate 5. In order to accommodate them satisfactorily on the dynamometer table the ends had to be removed. This was done using a band saw, the cut being well clear of the proposed point of drilling. The specimens were then stored in Ringer's solution until the actual drilling operation. Four holes were drilled in the centre portion of each bone, a different drill being used for each hole. This ensured that no one bone would greatly influence a particular set of results.

5.7 Drilling tests

5.7.1 Drilling using a Constant Feed and Speed

A Kitchen & Wade Model V32 floor mounted drilling machine was used for this series of tests. The machine is equipped with a horizontal table on to which the drill dynamometer was clamped and positioned centrally under the spindle by means of a setting gauge, Plate 6.

The bone specimen was removed from the Ringer's solution and mounted in a small vice which in turn was fastened to the dynamometer table. A hole was drilled through the proximal and distal cortices using a constant feed of .102 mm/rev and a constant speed of 456 rev/min. The specimen was adjusted so that the drill was offered as square as possible to the bone face. When drilling was complete the bone was given an identification mark and returned to the Ringer's solution. After each drilling operation the drill was carefully cleaned of bone and marrow that had lodged in the drill flutes. This sequence was repeated for three complete sets of drills, the torque and thrust trace being plotted on an ultra-violet recorder.

5.7.2 Drilling using a Constant Load and Speed

During this series of tests a constant load was applied and the rate of penetration of the drill through the proximal cortex was measured, all the sets of drills being used. The drilling was done on a Meddings Driltru Mk. 2 drilling machine that had been fitted with a Variac autotransformer in the ac electrical supply that enabled an infinite number of speeds to be obtained, Plate 7. The stated drilling speed was set by the use of a tachometer; this agreed with the speed on the Kitchen & Wade Model V32 drilling machine.

The load was applied to the hanger attached to a cord which in turn was wrapped around the grooved pulley. The load could

be increased or decreased depending upon which way the cord was wound. The dynamometer was set up as in the previous tests. The value of the applied load was transmitted via the dynamometer and amplifier to an ultra-violet recorder, the signal was also monitored on an indicator coupled to the amplifier. Thus it was possible to see the magnitude of the applied force throughout the drilling operation. The dynamometer was checked from time to time by placing weights on the work table and the deflection of both trace and indicator noted.

The rate of penetration of the drill into the bone was given by the trace from a linear transducer attached to the drill. The movement of the armature was plotted against a time basis on the ultra-violet recorder, the transducer having previously been calibrated to ensure linearity. Using this method two simultaneous traces were obtained, one showing load the other penetration.

The femoral specimen was removed from the Ringer's solution and clamped to the dynamometer table. The point of the drill was brought into contact with the top surface of the bone, the correct load having been applied to the hanger. The armature of the linear transducer was then brought into contact with a stop attached to the moveable drill quill, a deflection being noted on the ultra-violet recorder trace. The body of the transducer was locked in this position. The ultra-violet recorder was switched on followed by the drill. As the drill advanced into the bone the armature of the transducer was

displaced, the trace of this displacement being drawn against a time base. Throughout the drilling operation the applied load of 19.6 N was observed to ensure that this remained constant throughout the complete cycle.

During both these series of tests the formation and disposal of chips was noted and a study of the hole quality and size was made later.

5.7.3 Drilling, with and without Point Thinning

The equipment was set up on the floor mounted drilling machine as described previously, the specimen being prepared and stored in a similar manner. A hole was drilled through the proximal cortex using a constant feed of .102 mm/rev and a constant speed of 456 rev/min. The drills used had different helix angles and web thicknesses. These are shown in Tables 1, 2 & 3.

A further series of tests was carried out using the same drills whose points had been thinned to .60 mm in the manner shown. In all cases the drill torque and thrust were recorded.

5.7.4 Measurement of Rate of Penetration when using a Constant Load

The portion of the cortex over which the rate of penetration was measured was the third millimeter from the outer surface. The linear displacement transducer was calibrated and a known distance on the ultra-violet recorder paper was equivalent to

a known displacement of the probe. Fig. 24 shows a typical trace and it can be seen that at the third millimeter position the rate of penetration has become uniform. Using the time basis of the ultra-violet recorder it was now possible to determine the rate of advance of the drill.

5.8 Hole Measurement

In order to measure the diameter of the drilled hole the periosteum was cleaned from the bone and any excess swarf or marrow that had lodged in the drilled hole was removed. During this time observations of the hole were made to see if burrs had formed or whether chipping had occurred. The bone was then cleared of excess moisture and immediately measured using a Matrix bore gauge which is calibrated in units of .025 mm, Plate 8. Care was taken with this measurement as too great a pressure or small pieces of swarf in the holes greatly affected the results. Both sides of the bone were checked, Fig. 58.

5.9 Drill Performance using a Hand Drill

A number of tests were carried out using a hand drill and the locating ability and the thrust and torque characteristics observed.

With the quick spiral drills a continuous chip was formed with a good cutting action but with the slow spiral vibration occurred with discontinuous chips being produced. The torque at break

through in all cases increased because the drill tended to snatch. If anything this was slightly less with the slow spiral drills than with the quick spiral type. With the spiral point drill the thrust was greatly reduced and the torque decreased as the point angle increased. The locating ability of the spiral point was good until a point angle of 140 degrees was reached.

5.10 Drill Performance using a Hand Held Electric Drill

In the conventional and four facet drills there was a rapid break through with increase in torque because the drill tended to snatch and great difficulty was experienced in controlling the drill feed. The locating ability decreased as the point angle increased and the torque appeared to decrease slightly with increase in point angle. The spiral point drill located reasonably well at all point angles and at 120 - 140 degrees break through was not as severe and there was less snatching, particularly with the slow spiral drill.

CHAPTER 6 COMMENTS AND DISCUSSION

Throughout this work the sizes given, and each graph point, represent the average of four results.

6.1 Effect of Drill Point Angle on Torque and Thrust when using a Constant Feed and Speed

Radial relief point Figs. 25 to 30

With all the drills used, as the point angle increased so did the thrust force, the quick and normal helices giving slightly lower values of thrust than the slow helix. The average increase in entrance thrust over the total range of drill points tested was 98% approximately; the thrust required to drill the proximal cortex was greater than that required to penetrate the distal cortex in all cases.

The value of torque developed when using an 80 degrees point angle was the same for all three helices used and they all reduced linearly as the point angle increased. The percentage reductions of torque at a point angle of 150 degrees were: quick helix 32%, normal helix 22% and slow helix 15%.

Four facet point Figs. 31 to 36

As the point angle increased the thrust force on the drill also increased. The thrust curves for the quick and normal helix drills followed a similar pattern over most of the range of point angles, the quick helix giving slightly lower values of thrust. The thrust for the slow helix drill increased

proportionally with point angle and at a point angle of 150 degrees gave a smaller value than the quick and normal helix drills. The average increase in entrance thrust over the whole range of drill points used was 134% approximately. The thrust required to drill the proximal cortex was greater than that required for the distal cortex.

The torque was uniform in all cases throughout the range of drill points tested and was 2.5% greater when using a slow helix angle when compared to the quick and normal helices.

Plucking occurred when using an 80 degrees point angle quick helix drill, and 80 degrees and 90 degrees point angle slow helix drills.

Spiral point Figs. 37 to 42

The thrust curves followed a similar pattern for all three helices, the quick helix giving the lowest values, the slow helix the highest. Minimum values of thrust were recorded as follows: quick and normal helix 150 degrees point angle, slow helix 95 degrees point angle although there was a trend at 150 degrees for a further reduction in thrust. The thrust required to drill the proximal cortex was greater than that required for the distal cortex in all cases.

The torque curves for the quick and normal helix drills were similar, falling to their minimum values over the centre of the range of point angles. The lowest value of torque was recorded by the normal helix drill followed by the quick helix

drill. The torque graph for the slow helix drill was still continuing to fall at a point angle of 150 degrees.

Considerable "chatter" occurred both in torque and thrust over a wide range of drill point angles when drilling with the slow helix drill.

6.2 Effect of Drill Point Angle on Rate of Penetration when using a Constant Load and Speed

Radial relief point Figs. 43 to 45

The three curves had similar characteristics, the rate of penetration being the greatest with a point angle of 90 degrees, the average value being 4 mm/min approximately, this then falling as the point angle increased. The curves for the quick and slow helix were similar, using a point angle of 150 degrees the rate of penetration for both was approximately .28 mm/min. The normal helix drill with the same point angle had a rate of penetration of .5 mm/min.

Four facet point Figs. 46 to 48

From the results of the tests shown graphically in the figures it can be seen that the maximum rate of penetration was obtained using a point angle of 80 degrees, this being 8.6 mm/min approximately, falling away as the point angle increased. The rate of penetration at a point angle of 150 degrees was: quick helix .5 mm/min, normal helix .57 mm/min, and slow helix .63 mm/min.

Spiral point Figs. 49 to 51

A constant rate of penetration of 13.3 mm/min was obtained when using point angles from 100 degrees to 150 degrees inclusive with the quick and normal helix drills. The curve for the slow helix spiral point drill fluctuated over the whole range of drill points used, giving a maximum rate of penetration at a point angle of 95 degrees and 150 degrees, this being 10 mm/min. In all three cases the minimum rate of penetration was given with the 80 degrees point angle.

6.3 Effect of Drill Point Angle on Hole Dimensional Accuracy

Throughout this series of tests a constant speed and feed was used and the drills were ground as described previously.

Radial relief point

Quick helix Fig. 52

The smaller the point angle the smaller the diameter of hole at both entrance and exit. As the point angles increased so did the diameter of holes produced but they were all considerably less than the drill diameter, the exit diameter holes being smaller than the entrance diameter holes. There were large burrs on break through.

Average diameter of hole: entrance 6.29 mm exit 6.28 mm

Average diameter of drill: 6.35 mm

Normal helix Fig. 53

The smaller point angles produced slightly smaller diameter holes than the larger point angles at both entrance and exit

and in two cases the entrance holes exceeded the drill diameter. All the exit diameters were smaller than the entrance diameters. Average diameter of hole: entrance 6.34 mm exit 6.32 mm
Average diameter of drill: 6.34 mm

Slow helix Fig. 54

There was very little difference between the hole diameters over the whole range of point angles, the exit diameter being smaller than the entrance diameter in all cases. No holes were produced that were larger than the drill diameter.

Average diameter of hole: entrance 6.34 mm exit 6.32 mm
Average diameter of drill: 6.35 mm

Four facet point

Quick helix Fig. 55

The entrance diameters were smaller than the drill diameters and they did not vary with the point angle. The exit diameters were much smaller than the drill diameters and there was only a very slight tendency to increase with increase in point angle.

Average diameter of hole: entrance 6.31 mm exit 6.27 mm
Average diameter of drill: 6.34 mm

Normal helix Fig. 56

The entrance diameters were similar throughout the range of drill points. Two holes were larger than the drill diameters, the remainder were almost the same. The exit diameter holes were slightly less than the drill diameters and none was

oversize. They did not increase with increasing point angle.

Average diameter of hole: entrance 6.35 mm exit 6.33 mm

Average diameter of drill: 6.35 mm

Slow helix Fig. 57

Seven out of eight entrance holes were larger than the drills used; one exit hole was slightly larger than the drill used; the rest were almost drill size. Both entrance and exit diameters did not vary with point angle. There were slight burrs on entrance and exit to holes.

Average diameter of hole: entrance 6.35 mm exit 6.33 mm

Average diameter of drill: 6.34 mm

Spiral point

Quick helix Fig. 59

There was no trend to increase in diameter with increase in point angle, all the entrance diameters were considerably smaller than the corresponding drills. The exit diameters also had a random fluctuation and they were all far smaller than the drills used. Slight burrs were formed on the entrance and exit of the holes.

Average diameter of hole: entrance 6.31 mm exit 6.27 mm

Average diameter of drill: 6.34 mm

Normal helix Fig. 60

Two of the entrance diameter holes were considerably larger than their corresponding drills, the remainder were approaching

drill diameter. One exit diameter hole was slightly larger than the drill diameter, the remainder were drill size or slightly smaller. There was no tendency to increase in size with increase in point angle. Slight burrs were observed on the entrance diameters.

Average diameter of hole: entrance 6.35 mm exit 6.33 mm

Average diameter of drill: 6.34 mm

Slow helix Fig. 61

Exceedingly large entrance holes were produced by seven of the eight point angles used, the remaining hole being almost size. Seven of the exit diameters were smaller than the drills used, one being slightly larger. Again there was no tendency for holes to increase in diameter with increase in drill point angle. Almost all the holes had burrs on the entrance side and very large burrs on the exit side. Some of these covered the hole completely as though the bone had not been cut correctly.

Average diameter of hole: entrance 6.39 mm exit 6.33 mm

Average diameter of drill: 6.35 mm

6.4 Effect of Helix Angle on Hole Size

Quick helix

In all cases the entrance diameter of the hole was much smaller than the drill diameter, the exit diameter being smaller than the entrance diameter.

Medium helix

The entrance diameters and exit diameters were slightly smaller than the drill diameters in 75% of cases although they were considerably larger than the holes produced by the quick helix drill. Two of the exit holes were the same diameter as the entrance holes, one pair of these being oversize.

Slow helix

With the exception of the drills ground with radial relief, which were all below size, the entrance diameters of only 12% of the remainder were undersize. The exit holes were all smaller than the entrance holes and in only two cases did they slightly exceed the drill diameter.

6.5 Influence of Web Thickness on Torque and Thrust

The three curves, Figs. 63, 65 and 67, show that as the web thickness increased the thrust increased. The percentage increase in thrust over a range of web thicknesses from 1 mm to 1.3 mm was: quick helix 32%, normal helix 14% and slow helix 32%, the normal helix having a much smaller rate of increase over this particular range, although this increased at a greater web thickness.

The torque did not vary with increase in web thickness although this was influenced by the value of helix angle used, Figs. 62, 64 and 66. The torque was maximum when using a slow helix drill, the normal and quick helix being 92% and 79% of this value respectively.

6.6 Point Thinned Drills

The graphs showing thrust after point thinning all exhibit similar characteristics, Figs. 69, 71 and 73. The drills below the points shown had web thicknesses smaller than 1.13 mm and it can be seen that as the original web thickness increased there was a corresponding increase in thrust until this point was reached, after which no increase in thrust occurred. The thrust values below this point were similar in many cases to the original values.

The following approximate percentage reductions in thrust were achieved by point thinning at an original point thickness of 1.3 mm: quick helix 21%, normal helix 11% and slow helix 17%.

The graphs of torque for the quick and slow helix drills were constant for each set of drills used and increased by less than 3% of the values originally recorded for the unthinned points. The values of torque for the normal helix drills reduced proportionally over the range of drills used, the drill with the largest original web thickness having the smallest torque which was 9% less than the previous value, Figs. 68, 70 and 72.

6.7 Types of Chip Formation

Three types of chip defined by Ernst (94) have been commonly accepted by engineers, these are:

- (a) the discontinuous or segmental chip,
- (b) the continuous chip,
- (c) the continuous chip formed in the presence of built up edge.

The chips formed during the drilling tests did not fall into any particular one of the above categories. The drill geometry, however, does influence chip formation and for a normal helix drill with a 130 degrees point angle the following chip formations were observed, in each case the drill cutting the same bone so that the work material would be constant. It may be noted that the drill points with some cutting action near the centre produced chip interference which resulted in the segmentation of the chips produced.

Plate 9 Radial relief point:- the majority of chips were large and tightly curled as shown.

Plate 10 Four facet point:- chips broken down into small segments.

Plate 11 Spiral point:- a combination of segmental and small curled chips.

6.8 Orthopaedic Drill Sizes

In order to check the geometry of existing orthopaedic drills a number of new drills produced by different manufacturers were measured and compared; the sizes are shown below.

Drill No. 1

Drill diameter	3.18 mm (1/8 in.)
Point angle	90 degrees
Helix angle	20.5 degrees
Web thickness	.533 mm
Web thickness as % of diameter	17
Lip clearance angle	16 degrees

The drill had body clearance and lands.

The cutting face of the drill was ground to give zero rake.

Drill No. 2

Drill diameter	3.2 mm
Point angle	90 degrees
Helix angle	17 degrees
Web thickness	.838 mm
Point thinned to	.43 mm
Web thickness as % of diameter	26 (unthinned)
Web thickness as % of diameter	13.5 (thinned)
Lip clearance angle	20 degrees

The drill had body clearance and lands.

Drill No. 3

Drill diameter	6.35 mm ($\frac{1}{4}$ in.)
Point angle	118 degrees
Helix angle	20 degrees
Web thickness	1.422 mm
Web thickness as % of diameter	22
Lip clearance angle	16 degrees

The drill had neither body clearance nor lands.

The graphs of face rake angle and normal rake angle for these drills are shown in Fig. 74.

6.9 Sources of Error

1. It is appreciated that there may be some small differences in the mechanical properties of the bones used, although these were obtained from the same source, from pigs of approximately the same age, and all were stored under the same conditions.
2. As bone is of a fibrous nature the cutting forces varied along and across the grain so that there was a slight cyclic variation in the torque during each revolution of the drill. It was therefore necessary to take the mean value of torque during the drilling process.

6.10 Conclusions

- (1) From the thrust graphs for the radial relief point and the four facet point it can be seen that as the point angle increases so does the force required to feed the drill through the bone cortex. This is verified by time graphs for these two point geometries, the larger the point angle the slower the rate of penetration. From these graphs it would appear that a point angle of 80 - 90 degrees was the most efficient. This is in agreement with Bechtol et al. (40) who recommended this point angle for surgical drills. Unfortunately when using a small point angle there is a tendency for the drill to jam as it passes through the bone cortex, particularly with the four facet point geometry. There is a slight difference in thrust depending upon which helix angle is used but this will have little effect on the overall efficiency.
- (2) The torque required to drill a hole using the four facet point geometry varies very little with helix angle and not at all with point angle. The torque required by the radial relief ground drill reduces proportionally as the point angle increases. With both point geometries there is a slight difference in torque depending upon the helix angle used.
- (3) The thrust graphs for the spiral point drills show that the helix angle of the drill affects the results, in this case the lowest values being recorded by the quick helix drill. From the time graphs, however, the rate of penetration of both

the quick and normal helix drills is the same over a wide range of point angles. The slow helix drill requires the greatest force and has the slowest rate of penetration of the three helices considered.

(4) The torque required by the quick and normal helix spiral point drills is approximately the same, the slow helix being slightly greater. Considering the thrust, the rate of penetration and torque, a point angle between 120 and 140 degrees would be the most satisfactory; this is in close agreement with Sneath (39) (42), who recommends a point angle of 130 - 140 degrees.

(5) The diameters of the finished holes are affected more by the helix angles of the drills used than by the point angles. The quick helix drill cuts the most efficiently, the holes closing in after drilling because of the viscoelastic property of the bone. The medium helix drill cuts to give a hole similar to the drill diameter while the slow helix drill tends to cut oversize when using four facet and spiral point geometry.

From the foregoing it would appear that the quick helix drill would be the most satisfactory, but from drilling experience it was found that this helix tended to catch on break through more than the normal or slow helix drill, the latter having the worst cutting action of the three used.

(6) Web thinning only becomes effective over a certain web thickness as can be seen from Figs. 68 to 73. There does not

appear to be any reason to go to extremely thin webs as below a web thickness of 1.13 mm a further thinning of the web had only a slight effect on the cutting forces. Above this value there was a considerable reduction in thrust brought about by the decrease in web thickness and in most cases a slight increase in torque which may result from a slight increase in the length of the cutting edge. In many cases point thinning may have a detrimental effect on drill performance because if the grinding were inaccurate the drill would cut off centre.

(7) Correlation of the results from the various tests indicates that a normal helix drill with a spiral point angle of 120 - 130 degrees and a clearance angle of 15 degrees is the most efficient. The web should be equal to, or less than, 18% of the drill's diameter. Drills of this shape are now undergoing clinical trials and a comprehensive report is expected soon.

6.11 Suggestions for Further Work

Further investigations are necessary in order to obtain more data on the drilling of bone and also on the machining of bone by other processes. It is suggested that the present work may form a useful basis for studies in some of the following fields:

(1) Investigation into the effect of speed on torque, thrust and temperature so that optimum speeds could be recommended to the surgeon.

- (2) The effect of the lip clearance angle on torque, thrust and cutting conditions.
- (3) The effect of using types of drill points, other than those used in this work.
- (4) The effect of using drills with special flutes.
- (5) The use of trepanning tools.
- (6) The effect of drill symmetry on hole accuracy.
- (7) The determination of the best rake angle for cutting bone. This could be applied to chisels, saws and other cutting tools.

LIST OF TABLES

- 1 Web thickness of quick helix drills.
- 2 Web thickness of normal helix drills.
- 3 Web thickness of slow helix drills.

TABLE 1 Quick helix drill

Drill No.	Web thickness (mm)
1	.737
2	.813
3	.889
4	.921
5	.991
6	1.067
7	1.118
8	1.194
9	1.245
10	1.295

TABLE 2 Normal helix drill

Drill No.	Web thickness (mm)
1	1.041
2	1.092
3	1.130
4	1.207
5	1.232
6	1.295
7	1.397
8	1.473
9	1.600

TABLE 3 Slow helix drill

Drill No.	Web thickness (mm)
1	.838
2	.914
3	.965
4	.990
5	1.143
6	1.181
7	1.219
8	1.346

APPENDIX

Twist Drill Nomenclature and Definitions (95)

The following elements, linear dimensions and angles are shown on the twist drill in Fig. 16.

Elements

1. Axis The longitudinal centre-line.
2. Body That portion of the drill extending from the extreme cutting end to the commencement of the shank.
3. Shank That portion of the drill by which it is held and driven.
4. Flutes The grooves in the body of the drill which provide lips and permit the removal of chips and allow cutting fluid to reach the lips.
5. Web (Core) The central portion of the drill situated between the roots of the flutes and extending from the point end towards the shank; the point end of the web or core forms the chisel edge.
6. Lands The cylindrically-ground surfaces on the leading edges of the drill flutes. The width of the land is measured at right angles to the flute helix.

7. Body clearance That portion of the body surface reduced in diameter to provide diametral clearance.
8. Heel The edge formed by the intersection of the flute surface and the body clearance.
9. Point The sharpened end of the drill, consisting of all that part of the drill which is shaped to produce lips, faces, flanks and chisel edge.
10. Face That portion of the flute surface adjacent to the lip on which the chip impinges as it is cut from the work.
11. Flank That surface on a drill point which extends behind the lip to the following flute.
12. Lip
 (cutting edge) The edge formed by the intersection of the flank and face.
13. Relative
 lip height The relative position of the lips measured at the outer corners in a direction parallel to the drill axis.
14. Outer corner The corner formed by the intersection of the lip and the leading edge of the land.
15. Chisel edge The edge formed by the intersection of the flanks.
16. Chisel edge
 corner The corner formed by the intersection of a lip and the chisel edge.

17. Rotation of cutting Right-hand cutting drill. A drill which rotates in a counter-clockwise direction when viewed on the point end of the drill.
- Left-hand cutting drill. A drill which rotates in a clockwise direction when viewed on the point end of the drill.

Linear Dimensions

18. Diameter The measurement across the cylindrical lands at the outer corners of the drill.
19. Overall length The length over the extreme ends of the point and the shank.
20. Flute length The axial length from the extreme end of the point to the termination of the flutes at the shank end of the body.
21. Lead of helix The distance measured parallel to the drill axis between corresponding points on the leading edge of a flute in one complete turn of the flute.
22. Back taper (longitudinal clearance) The reduction in diameter per inch length of drill from the point towards the shank.
23. Depth of body clearance The amount of diametral reduction per side to provide body clearance.
24. Body clearance diameter The diameter over that surface of the drill body situated behind the lands.

25. Web (core) thickness The minimum dimension of the web or core measured at the point end of the drill.
26. Web (core) taper The increase in the web or core thickness from the point of the drill to the shank end of the flutes.
27. Lip length The minimum distance between the outer corner and the chisel edge corner of the lip.

Angles

- 28a. Helix angle The angle between the leading edge of the land and the drill axis.
- 28b. Slow helix angle A helix angle which is smaller in angular value (i.e. number of degrees) than the normal helix angle, thereby lengthening the lead of helix.
- 28c. Quick helix angle A helix angle which is larger in angular value (i.e. number of degrees) than the normal helix angle, thereby shortening the lead of helix.
29. Rake angle The angle between the face and a line parallel to the drill axis. At the periphery of the drill it is equivalent to the helix angle.
30. Point angle The included angle of the cone formed by the lips.

31. Lip clearance angle The angle formed by the flank and a plane at right angles to the drill axis; the angle is normally measured at the periphery of the drill.
32. Chisel edge angle The obtuse angle included by the chisel edge and a line from either outer corner to the corresponding end of the chisel edge; the angle is measured in a plane perpendicular to the drill axis.

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FIG. 2 LONGITUDINAL SECTION THROUGH A LONG BONE (14)

Detail of A

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Bone	Age group (years)					
	20 29	30 39	40 49	50 59	60 69	70 79
Compact bone tissue (femur)	0	3	6	12	15	18
Long bone (femur)	0	0	6	8	14	17
Vertebra	0	0	17	17	30	30
Average	0	1	10	14	20	22

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(a) The drill guide is placed so that its tip is at least 5 mm. from the fracture line and is then tightened up. The proximal cortex is drilled with a 4.5 mm. drill fitted with an arresting device.

(b) The long drill sleeve is used for a transverse hole and the shorter one for oblique drilling.

(c) The far cortex is drilled with a 3.2 mm. bit fitted with an arresting device.

(d) The hole in the far cortex is now tapped and the length of the screw estimated.

(e) A hole for the screw head is countersunk in the near cortex using the countersink tool.

(f) The AOI cortex screw is inserted with a screw-driver. The screw is first tightened slightly. Only after all the screws have been inserted, are they tightened up in series.

FIG. 12 THE ASSOCIATION FOR THE STUDY OF THE PROBLEMS OF INTERNAL FIXATION - METHOD OF SCREW FIXATION

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DRILL GRINDING

FIG. 18 SPIRAL POINT
DRILL GRINDING

$2t$ = Web thickness

W = Web thickness after thinning

$W = .5 \div .7 \times 2t$

FIG. 19 METHOD OF POINT THINNING (97)

Plane B-B is parallel to drill axis

Angles γ_j and k are measured in Plane B-B

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Block 'B' & gauge not shown

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Drill diameter
 Entrance diameter
 Exit diameter

FIGS. 52, 53 & 54 EFFECT OF POINT ANGLE AND HELIX ANGLE ON HOLE DIAMETER, RADIAL RELIEF POINT

Drill diameter
 Entrance diameter
 Exit diameter

Drill diameter
 Entrance diameter
 Exit diameter

FIGS. 55, 56 & 57 EFFECT OF POINT ANGLE AND HELIX ANGLE ON HOLE DIAMETER, FOUR FACET POINT

FIG. 58 MEASUREMENT OF HOLE DIAMETER IN CORTICAL BONE

Drill diameter
 Entrance diameter
 Exit diameter

Drill diameter
 Entrance diameter
 Exit diameter

FIGS. 59, 60 & 61 EFFECT OF POINT ANGLE AND HELIX ANGLE ON HOLE DIAMETER, SPIRAL POINT

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Drill:- 6.35 mm Diameter
1.12 mm Web thickness
27° Helix angle

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- PLATE 11 Chips produced by spiral point drill.

PLATE 1 Christen drill grinding machine

PLATE 2 Drills of 6.35 mm diameter with different helix angles

PLATE 3 Drill dynamometer

PLATE 4 Section through pig femur

PLATE 5 Pig femora before and after preparation and drilling

PLATE 6 Equipment used to measure torque and thrust
when drilling with a constant feed

FIGURE 7 Equipment used for drilling with a constant load

PLATE 8 Method of measuring hole diameter

PLATE 9 Chips produced by radial relief point drill

PLATE 10 Chips produced by four facet point drill

PLATE 11 Chips produced by spiral point drill

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ACKNOWLEDGEMENTS

The author wishes to record his thanks and appreciation for the encouragement and guidance given to him by his internal supervisor Mr. G. H. Farnworth, Senior Lecturer at the University of Technology, Loughborough, and to his external supervisor Dr. D. M. Clapp, Principal Lecturer, Harris College, Preston.

He would like to thank the Principal and Council of the Harris College, Preston, for permission to undertake this work and for the use of the necessary laboratories and equipment; also the members of the medical profession for their advice and information. Thanks are also due to Thornley & Son Ltd., Chorley, for supplying the requisite bone, and to the British Aircraft Corporation, Preston, for the preparation of the spiral point drills.

Finally, the author expresses his gratitude to the staff of the Harris College Library; to Mr. E. Shires for his help in the preparation of drills and specimens; to Mr. A. Boardman and Mr. T. Dean for the photographic work; and to his wife for the typing and secretarial work.