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ADVANCES IN BEATING AND REFINING

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Synopsis Advances in understanding the factors involved in beating chemical pulps, which have occurred since the symposium on 'Fundamentals of Papermaking Fibres' held in 1957, are surveyed and selectively reviewed.

The status of current knowledge of refining and grinding is summarised.

THE first symposium in this series was devoted largely to an examination of various aspects of mechanical treatment of chemical pulps for papermaking. Otto Maass, in his summary remarks, stated that the symposium set a new standard for conferences in the field of papermaking. This, indeed, has proved to be the case. It is evident, in retrospect, that many of the discussions, particularly those of a speculative or controversial nature, have provided new insights and posed new questions which have stimulated further study. There is no field in which this is more evident than that dealing with the preparation of papermaking pulps. However, in attempting to assess the progress which has been made in this field one is struck by the enormous quantity of technical and patent literature it has spawned during the past twenty years. It seems advisable, therefore, to employ a method adopted by some reviewers[1–3] and identify areas of selective emphasis in the general field of inquiry. Before so doing, some brief comments on the proposed use of the terms *beating* and *refining* are in order.

Nomenclature

BEATING is an art as ancient as that of papermaking itself. Apparently, the term had its origin in the rather primitive practice of beating an aqueous slurry of papermaking fibres with a stick[4] in order to condition them for the subsequent sheet forming process. The term is generally reserved for mechanical treatment of isolated fibres, often liberated from a parent material by some form of chemical treatment, in an aqueous slurry at a consistency not exceeding about 10 per cent.

Under the chairmanship of J. Mardon

The term refining, as it pertains to the mechanical treatment of papermaking pulps, is of relatively recent origin and appears to have derived largely from the use of disc refiners. Before their introduction into the paper industry about a hundred years ago disc refiners were extensively employed for flour milling and extraction, or refining, of oils from vegetable seed. The refining process for the production of papermaking pulps often combines some measure of separation of fibre aggregates with the development of acceptable papermaking characteristics in the separated fibres. Refining of semichemical, chemimechanical and mechanical pulps may be conducted at consistencies as high as 50 per cent. When disc refiners are used for low consistency mechanical treatment of low yield chemical pulps the terms *beating* and *refining* are synonymous.(5) In fact, the term *refining* could be adopted to embrace the whole field of mechanical treatment. However, because the somewhat arbitrary division that the two terms provide is a convenient one for the present purpose both will be retained and employed in the context of the rather loose definitions given.

A current view of beating

The physico-chemical hypothesis

An interesting feature of the contributions on beating presented at the 1957 symposium and of the monograph on beating by Emerton(4) published in the same year is that attention was focussed primarily on fundamental changes produced in papermaking fibres during beating. No attempt, other than a purely hypothetical one,(6) was made to analyse the mechanics of beating. It may be an entirely fortuitous consequence but knowledge of fibre structure and structural changes which accompany beating has advanced considerably, whereas the mechanical efficiency of the process whatever it may be(6, 7) has changed little, during the intervening years. In this regard, the influence of Emerton's ideas(4) was noteworthy since he demonstrated the value of conventional and novel techniques of microscopy for evaluating ultrastructural changes which occur in *pulp* fibres during beating. He also reiterated and extended some ideas of Campbell whose theory of beating was based on the physico-chemical phenomenon of sorption.(8–10) Campbell suggested that during beating 'mechanical flexing . . . (caused) . . . loosening of the surface fibrils from each other which will precede their actual appearance as broken out from the fibre. Such loosening, which may be termed "internal fibrillation", would render the fibre more flexible and at the same time give an appreciably greater opportunity for contact and bonding between fibres.'(8) Emerton retained the term internal fibrillation and incorporated Campbell's ideas with later ones advanced by Steenberg,(11) Lewis,[12] Gallay[13] and Cottrall[14] into a concept which concentrated on the important consequences of water uptake in concentric lamellar spaces in the *middle* secondary wall which he postulated were created by the mechanical action of the beater. This concept contained some novel and speculative ideas which are worth recalling:

> 'During beating . . . constricting outer layers of the fibre . . . are disrupted and in part removed, thereby permitting the fibre to swell . . . partly as a result of this swelling and partly as a result of repeated flexing . . . bonds between successive coaxial lamellae of the middle secondary wall are to some extent severed. This results in still further penetration of water between the fibrils . . . (exerting) a plasticising effect upon the cellulose structure which consequently deforms more readily, the coaxial lamellae sliding over one another during water removal into relatively stress-free positions where lateral bonds are reformed. When the distance between neighbouring cellulose molecules is small enough hydrogen bonding can occur and, if the molecules form parts of different fibres, these fibres are bound together by forces essentially akin to those of crystallisation.[4]'

Thirteen years later, in a review of the mechanical treatment of chemical pulps, Fahey described the beating action in substantially identical terms.[3]

Delamination of the middle secondary wall—Internal fibrillation

One of the major premises of Emerton's thesis, the development of coaxial delamination of the middle secondary wall during beating, was based largely on intuition. Supporting experimental evidence was sparse and circumstantial.[4, 15, 16]

Ten years later the first reasonably unambiguous proof of such delamination was obtained by direct light and electron microscopical examination of beaten chemical pulp fibres. Page and De Grâce[17] observed delamination in low yield (44–55 per cent) sulphite and sulphate fibres, prepared from various softwoods and hardwoods, as they were progressively beaten. No delamination was found in samples of stone groundwood and 90 per cent yield neutral sulphite pulps. Two particularly striking and representative electron micrographs of ultra thin transverse sections of beaten sulphite and sulphate fibres, embedded in nonswelling Epon 812, are reproduced in Figs. 1 and 2. It is seen that more delamination occurs in the beaten sulphite fibre than in the beaten sulphate fibre. The micrographs also show that for both types of beaten fibre swelling occurs *inwards* towards the lumen. McIntosh[18] observed similar delamination and swelling in transverse sections of gelatin embedded holocellulose fibres of beaten loblolly pine by light microscopy.

Almost simultaneously, Stone and Scallan[19] proposed a delaminated structural model of the cell wall similar in many respects to that observed

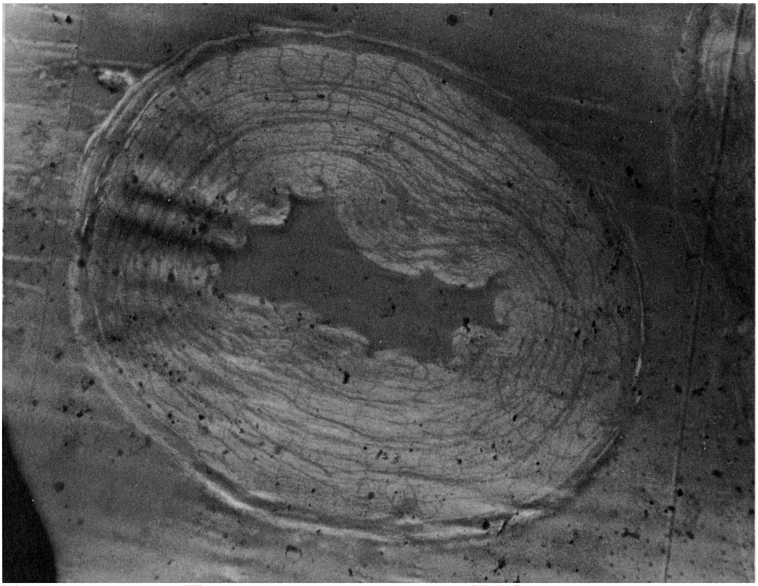

Fig. 1—Electron micrograph of thin section of beaten sulphite fibre (× 3 150)[17]

Fig. 2—Electron micrograph of thin section of beaten sulphate fibre (× 2 800)[17]

microscopically in beaten fibres, for water swollen wood pulp fibres. This model was based on results obtained employing a technique, originated by Samuelson to determine the fibre saturation point of rayon(20) and developed by Stone and Scallan for wood pulps, known as 'solute exclusion'. The technique is used to measure the accessibility to certain macromolecules, of known molecular diameter in solution, of the water swollen pore structure developed in a pulp fibre wall. In this manner the size distribution of the water filled pores of swollen pulp fibres was quantitatively and unambiguously determined. The results also showed that solvent exchange procedures used previously by many investigators did not maintain the full extent of the water swollen structure of a wood pulp fibre. In a subsequent study, Stone, Scallan and Abrahamson(21) employed the solute exclusion technique to determine the effects of beating never-dried and dry-lap fibres. Bleached low yield sulphite and sulphate pine fibres in the wet-never-dried state were found to

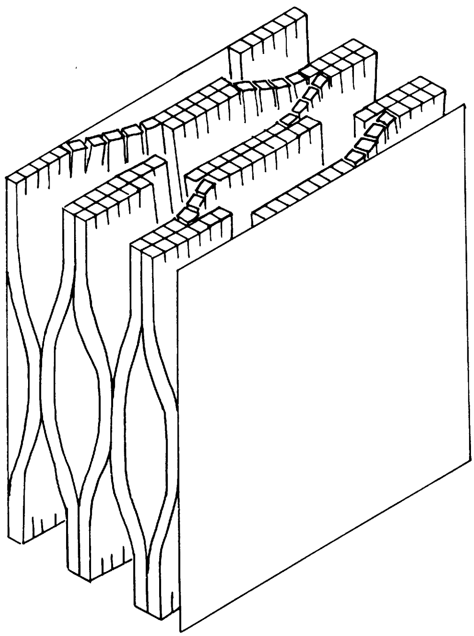

Fig. 3—Intermediate pattern of internal fibrillation of the cell wall with progressive swelling, as might be expected from the preferential cleavage of tangentially-oriented bonds. The sketch is of a small section of a wall with zero fibril angle(22)

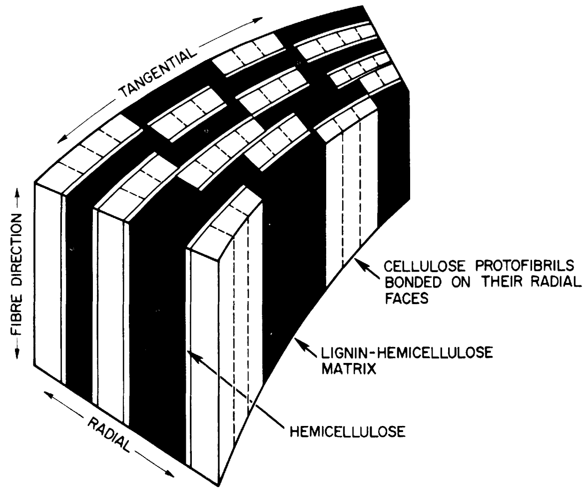

Fig. 4—Pictorial representation of the proposed interrupted lamella model for the ultrastructural arrangement of lignin, cellulose and hemicelluloses in the wood cell wall[23]

contain 1·42 ml/g and 1·29 ml/g respectively of water in the cell wall at the fibre saturation point. After beating to 45° SR (250 ml CSF) these values increased to 1·86 ml/g and 1·49 ml/g respectively, corresponding to a swelling of the fibre wall of 22 per cent for the sulphite pulp and 10 per cent for the sulphate pulp. Reslushed dry-lap fibres had lower fibre saturation points than never-dried pulps but attained the values quoted above, for beaten never-dried fibres, after beating. It was also found that sulphite fines (pass 100 mesh Bauer–McNett) contained approximately twice, and sulphate fines 3·7 times, as much water of swelling per unit weight of O.D. pulp than the corresponding fibres.

Based on results of these studies and electron micrographs of transverse sections of swollen delignified softwood fibres, Scallan proposed that during swelling the cell wall passed through an *intermediate* pattern of internal fibrillation shown schematically in Fig. 3.[22] The diagram represents a small section of middle secondary wall of zero fibril angle and shows preferential, though incomplete, cleavage between *elementary* cellulose fibrils along their tangential surfaces to form a disrupted honeycomb structure. Scallan's view is remarkably consistent with that of the 'interrupted-lamella' model, subsequently proposed by Kerr and Goring,[23] to depict the ultrastructural disposition of the major wood constituents in a similar section of middle secondary wall of an untreated black spruce fibre. The latter model, reproduced schematically in Fig. 4, was based on results of studies of electron micrographs of 100 Å thick transverse sections of permanganate stained fibres. It portrays rafts of cellulose, each containing between two and four *elementary* fibrils bonded along their radial surfaces, enveloped in an amorphous lignin-hemicellulose matrix. The model postulates that approximately one third of the hemicellulose, possible xylans, is associated exclusively with cellulose fibrils and the remaining two thirds with lignin. During pulping, interlamellar pores are formed as amorphous matrix is removed. When such delignified fibres are beaten more water is caused to re-enter the partially compacted structure and the tangential faces become almost completely separated whereas only small dislocations occur along the radial faces. The resulting appearance of coaxial delamination is similar to that postulated by Emerton.

Although these views represent a somewhat idealised and incomplete picture of the true situation they are based on a reasonably firm foundation of experimental evidence. Thus, they are consistent with several known features of delignification,[24] the net aspects of water sorption in a well defined porous network developed in the middle secondary wall during pulping and beating and microscopic observations.

The higher rate and extent of swelling of sulphite fibres relative to sulphate fibres during beating has been associated tentatively with increased amounts of separation of elementary fibrils along their radial faces in the middle secondary wall of the beaten sulphite fibres as indicated in the electron micrographs.

Unfortunately, this picture tells little of the nature of the forces which cause additional water to re-enter and be retained in the porous structure developed in the fibre wall during beating. There has been considerable speculation that osmotic effects and swelling pressures assist in mechanical separation of lamellae during beating and these have often been linked with the presence of extremely hydrophilic residual hemicelluloses.[25] However, specific information regarding the distribution and possible water sorption effects of residual noncellulosic components in the walls of chemical fibres is scant, as is an understanding of the effects of dye and electrolyte addition during beating.

Disruption of the outer layers of the fibre wall during beating

The outer layers of softwood fibres remain substantially intact following delignification by conventional pulping processes. Subsequent beating disrupts and progressively removes these layers. The nature of the physical disruption and of the chemical composition of the exposed surface are important on two accounts. First, the extent of disruption of the outer layers may control the amount of internal fibrillation[4] and external fibrillation.[26] Secondly, the strength of bonds developed between fibres in paper is determined ultimately by the chemical nature of those parts of the exposed surfaces which come into intimate contact during the later stages of water removal.

Thirty years ago, Clark noted that the values of certain paper properties such as density, tensile strength and opacity were linear functions of the logarithm of the beating time.[26] Indeed, this relationship is still used in papermills to monitor beating.[27] Clark also stated that these changes were accompanied by progressive removal of primary wall material. Giertz and Nisser[28] subsequently showed that the extent of primary wall removal during beating of sulphite and sulphate fibres was also a linear function of the logarithm of the relevant beating times. This finding supported Clark's suggestion that the high rate of primary wall removal during the initial stages of beating could explain the concurrently rapid initial development of tensile strength. Giertz suggested that the development of tensile strength may involve increased exposure of hemicellulose present in the outer secondary layer and fibrillation of the external surface.[25] The importance of the latter effect, originally proposed by Strachan,[30] has been stressed persistently by Clark.[29]

It is interesting to note that the development of internal fibrillation, as measured by imbibition of water in the cell wall during beating, is also a logarithmic function of beating time. This is seen in Fig. 5 which shows replotted data of Stone, Scallan and Abrahamson.[21]

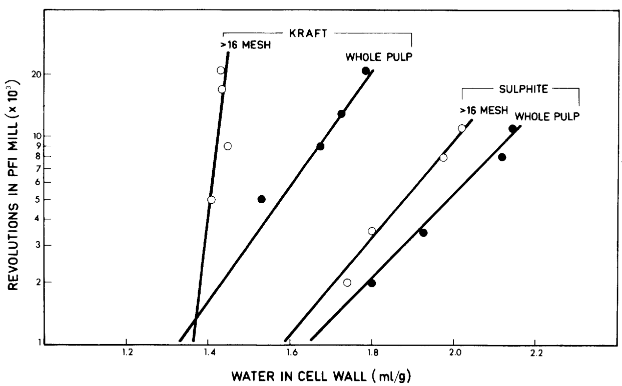

Fig. 5—A plot of the water sorbed in the cell wall, as measured by the solute exclusion technique, as a function of beating revolutions in a PFI mill[21]

It is now recognised that considerable portions of the outer secondary layer and even of the middle secondary layer are also removed during beating.[31, 32] The outer secondary layer of various softwood fibres has been shown to consist of at least five separate lamellae.[33–35] Kibblewhite has developed an interesting analytical technique, employing this fine structure of the outer secondary wall as an extremely sensitive criterion, to characterise quantitatively both the physical[35] and chemical[36] constitution of the external layers of *radiata* pine low-yield sulphate and high-yield bisulphite fibres exposed during beating. In the early stages of beating, lamellae consisting of primary and outer secondary wall are loosened and partly peeled from fibre surfaces; during later stages entire lamellae are removed or fibrillated. Extremely long fibrils are associated with external fibrillation of the middle secondary layer. There is also evidence of loosened structure within and between residual outer lamellae in addition to longitudinal and transverse wrinkling.

It was found that the distribution of carbohydrates in the outer walls of sulphate fibres differed from those in bisulphite fibres. 'In the sulphate fibres, glucomannan increased and other hemicelluloses decreased from the primary wall to the outer layer of the middle secondary wall. In the bisulphite fibres, hemicelluloses were uniformly distributed throughout . . . the primary wall, the outer secondary wall and the outer layers of the middle secondary wall. More galactan but less arabinan, xylan and glucomannan were found in the outer layers than in the inner layers of the bisulphite pulps through a yield range 53–80 per cent.'[36] Acid soluble and Klason lignin contents were also monitored through the outer layers. It is anticipated that these data will be correlated at some time with the bond strength characteristics of the surfaces.

This technique has also been used to differentiate semiquantitatively between the actions of several different beaters on the outer layers of early and latewood samples of young, mature and compression wood of *radiata* pine low yield sulphate fibres.[37]

Despite the progressive damage to the outer layers and the fact that the external perimeter of delignified softwood fibres changes from a polygonal to a circular shape during beating, the length of the perimeter remains unchanged.[17, 18] Swelling of the fibre, which occurs due to uptake of water between the lamellae created in the middle secondary layer—and this is often substantial,[21] does so as previously stated by displacing the lamellae of the inner secondary wall through an equivalent volume into the lumen cavity. Thus, Emerton's postulate regarding the constricting effect of the outer layers on potential swelling is not substantiated.

Material removed from the outer layers of the walls of low yield chemical pulp fibres during beating, generally referred to as fines, often contributes little to paper strength,[38] except when fibres are heavily beaten.[39] However, fines have a considerable influence, in proportion to their amount, on the drainage properties of beaten pulps.[40]

Bonding of fibres

The general features of strength development in a paper web which accompany water removal on a papermachine are reasonably well understood. Drainage of initially dilute suspensions, such as issue from a typical headbox, occurs mainly by filtration rather than by thickening.[41, 42]

During the initial stages of drainage, before air is drawn into the water saturated web—corresponding to a solids content of up to about 12 per cent, fibres form loose layered networks with little felting. These networks consist of mutually entangled fibres. The tensile strength of water saturated webs increases with increasing solids content, and, at a given solids content, with the amount of beating.[43] This strength increase is accompanied by a moderate decrease of caliper as the water saturated web is consolidated by relatively low surface tension forces. Robertson's data on the relative effects of beating on pad compressibility and specific surface development strongly suggest that external fibrillation contributes more than the accompanying plasticisation to consolidation of the web in this phase.[44]

When air is drawn into the draining web, water is progressively removed from capillaries between fibres and fibrils until, at the so-called critical solids content, no 'free' water remains in the network. Residual water in the network at this point is said to be 'associated' with the fibres. Data of Stone, Scallan and Abrahamson[21] indicate that for unbeaten never dried spruce sulphite fibres slightly more than one half of this 'associated' water is trapped in interlamellar pores in the fibre wall. Presumably, the remainder is immobilised in larger enclosed cavities such as the lumen and in the interfibrillar structure. There is a drastic reduction in the critical solids content when delignified fibres are beaten. This is clearly evident in the data of Lyne and Gallay for spruce sulphite pulps where the critical solids content is reduced from 36 to 18 per cent after beating for one hour.[43] The fraction of 'associated' water held in the interlamellar pores decreases from 0·53 to 0·35, despite the reduction of lumen volume due to inward swelling of the beaten fibres. It has been suggested that the large amount of water taken up by fines produced during beating accounts for the relatively large increase in the amount of 'associated' water.[21] Although preliminary measurements of water swelling of fines tend to substantiate this view, further quantitative information is needed to provide a more sharply defined interpretation of the changes which occur in hydrodynamic specific volume on beating.

Consolidation of the web from the point of air intrusion to the critical solids content depends upon the relative effect of two opposing sets of forces; surface tension forces tending to draw fibres together and elastic recovery forces tending to separate fibres. Increased fibre plasticity resulting from internal fibrillation induced by beating, reduces the forces of elastic recovery and assists in consolidating the web. This is particularly marked in the region of the critical solids content, as indicated by the sharp caliper reduction and increase in tensile strength.[44, 45]

The next phase of water removal, which occurs in the press section of the papermachine, is of particular interest to papermakers. Web density and strength increase more rapidly than in the previous phase as the solids content increases to 50 per cent. Values of both these properties increase with the amount of beating at any given solids content through this range.

Associated water is removed mechanically in the press section from the fibrillar network and the lumen. Ever increasing forces of surface tension, assisted by mechanical pressing, cause extensive lumen collapse converting many fibres to ribbon-like structures. Nevertheless, it is found that less than 1 per cent lateral shrinkage occurs in the web through the 10–50 per cent range of solids content.[45] Hence, most of the associated water in the interlamellar pores of the fibre walls is retained. Following fibre collapse, at a solids content approaching 50 per cent, interfibre bonding is initiated.[46] At the onset of interfibre bonding the moisture content of the web is less than the fibre saturation points of most beaten wood pulp fibres.[47, 48]

Collapse of delignified fibres will occur when their transverse compression moduli are reduced below a certain threshold value. These moduli which are inherently low in thin-walled earlywood fibres and much higher in latewood fibres are reduced substantially by beating. Thus, beating helps to induce collapse and consequently increase fibre conformation at crossing points prior to bond formation. Studies of Page and Tydeman[49] have shown that considerable interfibre bonding precedes water removal from the interlamellar pores and the gross shrinkage of the drying web. The extent of true interfibre bonding at this stage of drying is somewhat controversial and there has been considerable discussion regarding the degree of correspondence between 'optical bonding' and hydrogen bonding in such contacts. However, it is remarkable how well fibre surfaces replicate the fine structure of surfaces of areas in optical contact against which they dry.[4, 50] Whether or not this replicating ability of wood pulp fibre surfaces is affected by beating, and there is reason to believe that any such effect is small, it does deserve further study.

Based on direct observation of the size, shape and frequency of 'optical bonds' in handsheets made from bleached spruce sulphate, Page, Tydeman and Hunt[51] showed that, owing to increased fibre plasticity, the size of such bonds increased and the distance between bonds decreased as a result of beating. In an electron microscopical study of fibre bonding, Jayme and Hunger[52] draw somewhat similar conclusions for the effects of beating but make the following observation '. . . during beating the contact between various layers within the cell wall will loosen, therefore, first the upper, then the deeper layers of lamellae and bundles take over the bonding function . . . the term fibre loses its significance and the sheets have become practically an entanglement of microfibrils in various stages of aggregation and disaggregation. In . . . (a) . . . highly beaten pulp . . . microfibrils . . . (are) . . . joined again to a new form, a microfibril sheet'.[52]

Dodson reviewed the subject of hydrogen bridging between natural cellulose fibres and in a paper sheet at the 1973 Symposium.[53] Hence, it will not be considered here in detail. However, some data obtained recently by Mohlin on the shear strength of optimally delineated bonds formed between unbeaten and beaten low yield sulphite and sulphate fibres against a cellulose substrate are worthy of mention; data are also presented on the effect of beating on the conformability of these fibres.[54] It is found that beating has little effect on shear strength but a relatively large effect on fibre conformability and these effects are reflected in the tensile strength of sheets made from the corresponding pulps. These findings are consistent with the generally accepted picture of paper strength development.

Mechanics of beating

Detailed aspects of the mechanism of energy transfer from a beating element to fibres undergoing treatment are still an enigma. There is little doubt that, when beaters are operated under conditions which promote both internal and external fibrillation with a minimum of fibre length reduction, the operative stresses are transmitted through a water film. Indeed, it is highly probable that this is the most desirable method of operation. Thus, the hydrodynamic phenomena in drum and conical type beaters bear some resemblance to those which occur in lubricated journal bearings.[55, 56] Similarly, disc refiners resemble lubricated thrust bearings and ball mills resemble lubricated ball bearings. Wear of beater elements may occur for a variety of reasons, as in their bearing counterparts, but will generally result from the lubricating pulp slurry being unable to provide the requisite load bearing capacity. Under conditions of incipient contact between relatively moving elements in a beater high fluid shear stresses set up in the pulp suspension will promote severe fibre length reduction. Similar breakdown of long chain polymer additives in lubricating oils and greases occurs in heavily loaded bearings. Often, when fibre length reduction is required, a beater is operated under these conditions. Although the physical mechanisms involved in fibre length reduction are not as obvious as has sometimes been suggested[8] they are now amenable to direct assessment using currently available sensing instrumentation. Such an assessment has not yet been made.

Promotion of both types of fibrillation by beating probably involves more complex mechanisms than those occurring in fibre length reduction although it may prove that the latter are a special case of the former. Fibrillation and fibre length reduction are statistical processes resulting from a stochastic treatment of particles of different shape, size, physical and chemical constitution. The consequent heterogeneous nature of most industrial beating operations, particularly those with limited recirculation, has long been recognised. Some of the major factors which contribute to the heterogeneity have been examined by Nordman and Laininen,[57] Arjas and Ryti,[58] reviewed by Fahey[3] and illustrated empirically, in terms of their effects of pulp and sheet characteristics, by Danforth.[59] Relationships of the type derived by Danforth may be employed beneficially to monitor the uniformity of treatment in mill beating operations.

The historical evolution of the concept of 'specific edge loading', which gives an empirical measure of the 'relative severity' with which a beater element 'impacts' a fibre and the 'relative number' of such impacts, has been outlined by Halme.[60] Recent refinements of this concept by Brecht,[61] Danforth,[62] and Leider[7] show that optimum pulp strength development occurs when the heterogeneity of treatment is reduced to a minimum. This is promoted by impacting fibres at a 'relatively low level of severity' a 'relatively large number of times'. For beaters which contain bar elements this condition is approached by using elements with finer bar patterns and increasing rotational speed, albeit at increased gross levels of specific energy application. Fahey[3] notes that complete elimination of bars results in a loss of beating effect—though it should also be noted that the Lampén mill and the Clark Kollergang which contain no bars induce a definite beating action. Useful as the concept of specific edge loading is in the empirical design of refiners it provides little insight into the basic mechanism of the beating action.

The real problem is that the nature and magnitude of the forces transmitted to the fibres are not known. Nissan has been quoted as suggesting that the operative energy transfer mechanism is one that imparts a 3 per cent tensile strain to the fibre.[7] Such a mechanism would lead to a high mechanical efficiency for the beating process. Possibly the main features of this hypothesis will be divulged at this conference. It is known that unbeaten fibres are often twisted and kinked due to mechanical handling in pulping and transfer operations. These twists and kinks are normally removed during beating(63) and fibres are straightened. Thus, it would appear that fibres are subjected to some measure of tensile strain during beating.

Although there has been some question(64) regarding the draping of fibres over the edges of bar elements during beating, there is considerable supporting evidence for the 'fibrage' theory originally advanced by Sigurd Smith.(65–67) Goncharov has recently measured the normal and tangential forces exerted per cm length on a typical bar in a single rotating disc refiner during the

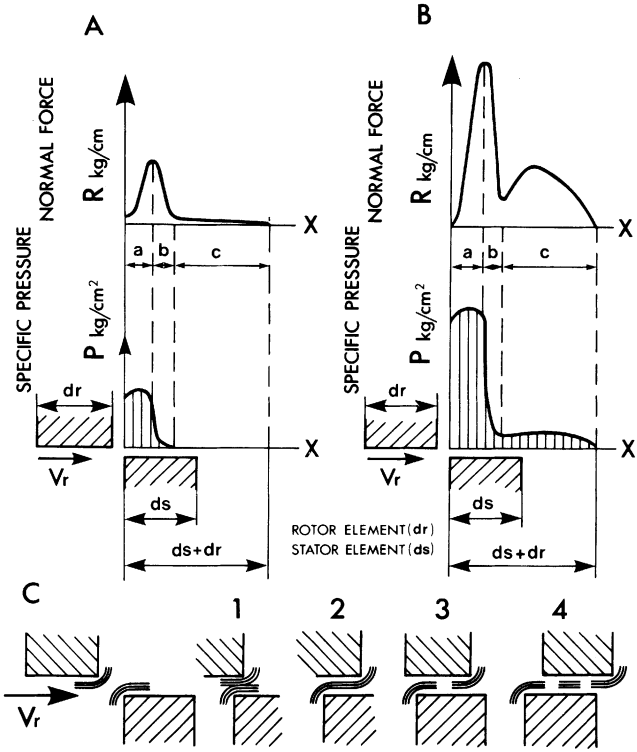

Fig. 6—Variations in normal force (*R*) and specific pressure (*P*) when the rotor element is passing over the stator element:

A—pressure in zone a, P_a < 20 kg/sq. cm.;
B—pressure in zone a, P_a > 20 kg/cm²;
C—various stages as a rotor element passes over a stator element

beating of a 'medium hardness' unbleached sulphite pulp at a nominal consistency of 2·5–3 per cent.[67]

Three different disc patterns were employed having bar widths of 2, 4 and 10 mm respectively and each pattern had the same total contact surface between the rotor and stator elements. Fig. 6 shows schematically the variation in normal force per cm, and the derived values of specific pressure, developed on a stator bar as a rotor bar moves over it during the beating operation. Two types of variation are obtained differing mainly in magnitude, depending upon whether the maximum pressure is less than or greater than 20 kg/cm^2, as seen in Figs. 6A and 6B respectively.

Fig. 6C 'represents the various stages during the passage of the rotor element over the stator element. When the edges of the elements, each with an overhanging fibre layer, approach each other a double fibre layer is brought into the gap and this results in a very high degree of fibre compression. This stage corresponds to the maximum pressure zone *a*. Evidently the most intensive action on the fibre takes place in this stage. . . . The second stage is characterised by the pulling apart of the fibre layers, accompanied by a gradual decrease of specific pressure in zone *b* owing to the decreased total thickness of the layer in the gap. In Stage 3 the fibre layers become separated and their thickness is partially reinstated due to elastic recovery of the fibres. This corresponds to the first section of the low pressure zone *c*. In the final stage, as the rotor element moves away from the stator element, the contact surface gradually decreases and the specific pressure remains fairly constant and finally drops to the ambient value'.[67]

Goncharov found that the width of the zone of rising specific pressure, through the distance, *a*, along the axis, was always 2·5–3 mm and was *independent of the width of the beating elements.*

'High speed ciné-film recorded at 4 500 p.p.s., taken through a transparent stator disc with 4 mm wide plexiglass elements, showed a fibre layer on the frontal edge of the elements extending 2–3 mm along the width . . . equal to the extent of the maximum pressure zone.'[67]

It was found that for beating this particular pulp optimum sheet properties were obtained when a maximum specific pressure of 35 kg/cm^2 was exerted. This pressure is thirteen times higher than the corresponding calculated nominal pressure over the total contacting surface area between the rotor and stator elements.

The tangential force was found to follow the same pattern, in phase with the normal force, corresponding to a localised friction coefficient to $0{\cdot}11 \pm 0{\cdot}02$. Such a value corresponds to frictional dissipation of energy, arising solely from hysteresis losses accompanying bulk deformation of the fibres, such as would be expected in a water lubricated sliding interaction.[68] Thus, it is consistent with transmission of stress from the beating element to the fibres and between the fibre layers through water films.

Based on these data it may be postulated that fibres in the beating zone are subjected *along* their length to reverse shear and compression such as occurs, for instance, when a loaded rolling element passes over any deformable substrate.[69] A similar type of straining of wood fibres occurs in a *transverse* direction during grinding as will be described later. In addition to this type of straining it is suggested that as the pressure pulse moves along the draped fibres water is pumped through the honeycomb structure of the middle secondary wall by a peristaltic action. High pressure water forced into the 'crack' tips of the honeycomb structure would release fibrils from each other at points of attachment inducing the final state of coaxial delamination. The former mechanism would promote both external and internal fibrillation and the latter internal fibrillation. It is apparent that the operative stress level of both processes are such as to lead to fatigue type failure mechanisms if they are to be consistent with the empirical finding for optimum strength development according to the specific edge loading approach and with the logarithmic dependence on beating time. Furthermore, such mechanisms would also account for the beating actions which occur in the Lampén mill and the Clark Kollergang, since lubricated sliding in beaters containing bar elements is equivalent to the lubricated rolling action occurring in beaters containing no bar elements.

Finally, as Goncharov points out, in agreement with the empirical finding of Danforth,[62] the operative width of the bar is approximately equivalent to the average fibre length of the pulp to be treated. Thus, by operating at this level of bar width the maximum number of fibres are treated per unit available area of the beating zone leading to the most uniform beating action possible for a single passage of the pulp through the beater.

A current view of refining

A SOMEWHAT arbitrary distinction between beating and refining was retained in this review on the basis that refining may be conducted at consistencies in excess of 10 per cent and often involves separation of fibre aggregates. The effects of these differences from conventional beating will now be examined.

High consistency refining of chemical pulps

Investigations by West[70] revealed that certain paper properties are enhanced when the chemical component of the furnish is refined at a nominal consistency through the range 15–40 per cent. Compared to conventional beating, refining at high consistency leads to increased tear, stretch, bulk and porosity, but reduced tensile strength, of the resulting paper. The introduction of this new technique created quite a flurry of activity since combinations of properties including higher tear and stretch are particularly desirable in certain grades of paper.[71–74]

It is generally thought that mechanical treatment at high consistency involves considerable fibre–fibre interaction and that the straining of individual fibres in these interactions must be at a lower level than occurs in beating. These lower strain levels are reflected in increased average fibre length and reduced fines production in the resulting pulps. Another characteristic and distinguishing feature of fibres refined at high consistency is that they are kinked, curled and twisted. Page has shown that chemical pulp fibres exhibit considerable transverse wrinkling, attributed to axial compression, as the refining consistency is increased.[75] Dahm suggested that some fibre wrinkling may arise from transverse flexing[76] similar, as Underhay remarked, to creasing in 'a well-worn pair of trousers'.[77] Whatever its origin, it confers a significant increase in both wet web and paper extensibility. This is used to advantage in the production of packaging papers.

Some interesting studies conducted by Stephens, Pearson and Lassman[78] have shown that kinking and curling of chemical pulp fibres are enhanced by the high temperatures which fibres attain during the high consistency refining operation. It was also found that, at least for *radiata* pine sulphate fibres, kinking and curling disappear almost completely when high consistency refined pulp is dispersed at a consistency in excess of 1·5 per cent. The principal objective of the studies was to increase the wet web rupture energy of a newsprint furnish by refining the *radiata* pine component at high consistency and thus increase its wet web extensibility. This objective was achieved in the papermaking operation provided that the refined chemical fibre component was reslushed, either solely or in the mixed stock, at an effective consistency below 1·5 per cent. Reversion, which occurs on reslushing at higher consistencies, is not due to removal of 'latency' known to exist in mechanical pulps,[79] but probably to 'a fibre–fibre rubbing action'—presumably involving tensile straining of the kinked fibres.

The property of kinking and curling of fibres can be of immense importance in many papermaking operations.[80] It is induced not only by high consistency refining but by any operation in which fibre is handled at a relatively high temperature and high consistency. Reversion may be inhibited almost completely by certain bleaching operations.[81] This area of stock preparation is one which deserves considerably more study and a better appreciation of the underlying factors could have significant technical and economic implications.

Refiner mechanical pulping

It is just over fifty years ago that *precision engineered* disc mills were successfully introduced into the paper and board industry. This led to serious consideration of their potential application in the whole field of stock preparation. The astounding rapidity with which disc refiners have been adopted and continue to displace other types of stock preparation equipment is, as Steenberg has noted,[82] mainly attributable to the efforts of equipment manufacturers.

Disc refiners were employed first as on-line stock preparation units ahead of paper machines then, in quick succession, for the treatment of semi-chemical pulps and screen rejects in the pulp mill.[83–88] It was probably inevitable that they would be modified eventually for use as primary units for mechanical pulp production. Pioneering work in this field was carried out by Eberhardt,[89–91] Textor[92] and de Montmorency.[93] When de Montmorency first produced newsgrade mechanical pulps by refining spruce chips he observed 'that . . . a pulp has been produced which looks like groundwood, acts like groundwood and tests like groundwood. *It is not groundwood*, but it might prove to be the mechanical pulp of the future'.[94]

Today, it is clearly recognised that refiner mechanical pulps, like chemical pulps, can be prepared with many different combinations of physical characteristics and consequently the term 'mechanical pulp' is used in a generic sense. Twenty years ago, however, wood grinding, which had been practised for over a hundred years, was such a firmly established, albeit little understood, industrial art that little serious thought had been given to a viable alternative. When such an alternative appeared, it was received with mixed reactions ranging from cautious optimism to marked skepticism. Even as refiner mechanical pulping gained wider acceptance such terms as 'refiner-grinding', 'groundwood from chips' and 'super-groundwood' were coined, reflecting a residual attachment to convention. Unfortunately, as Ashby has observed, convention is celibate—it breeds no new ideas[95] and such terminology now enjoys a well deserved retirement.

Advantages of refining wood chips at consistencies in excess of 15 per cent were first reported by Holzer, Henderson, West and Byington.[96] Their studies were not only a precursor to the development of the high consistency refining technique described in the previous section but also a major evolutionary step in the development of refiner mechanical pulping. Further commercial developments of refiner mechanical pulping processes, together with a consideration of their advantages and shortcomings, have been reviewed recently by Keays and Leask.[97]

There is a remarkable analogy between the manner in which the physical properties of chemical and mechanical pulps are enhanced by high consistency refining when compared to the corresponding low consistency treatments of beating and grinding. This statement anticipates a further analogy, that between the beating of chemical pulps and the beating of mechanical pulps in a grinder, which will be discussed in the next section.

Compared to paper made from conventional stone groundwood, paper made from refiner mechanical pulp has a higher tear, stretch, bulk and porosity; it also has a higher tensile strength, and in this characteristic it differs somewhat from the analogy drawn with the treatment of chemical pulps. Mechanical pulps produced by high consistency refining, as in the case for chemical pulps, require larger expenditures of energy and reflect an increase of average fibre length and a decrease of fines production. Refining of preheated wood-chip or wood residual feed at the lignin softening tempera-

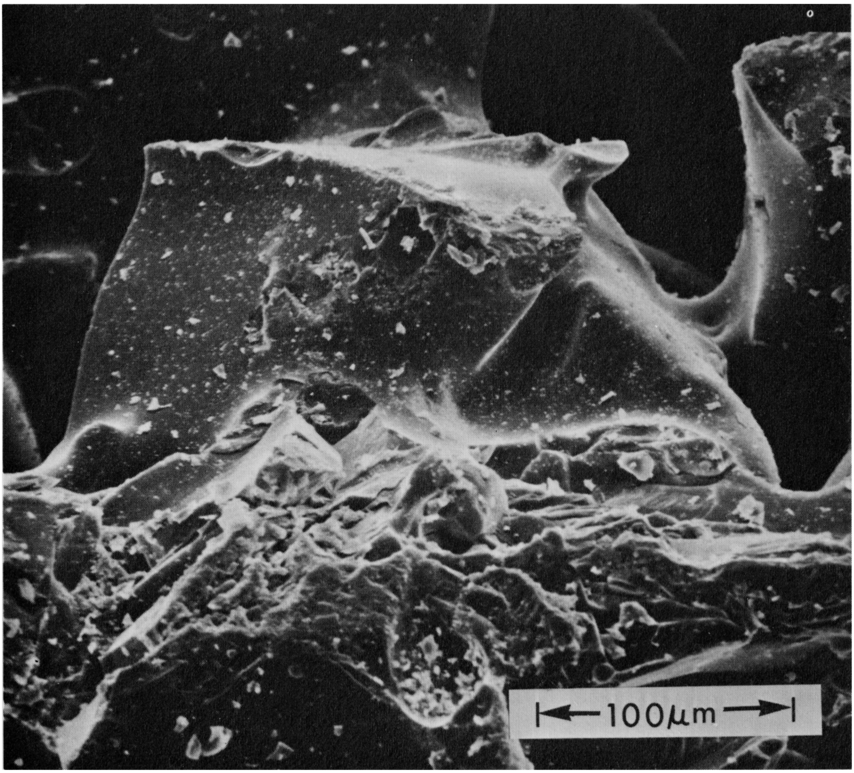

Fig. 7—Scanning electron micrograph of a typical sharp-edged abrasive grit in an unconditioned, single-60 grit silicon carbide pulpstone

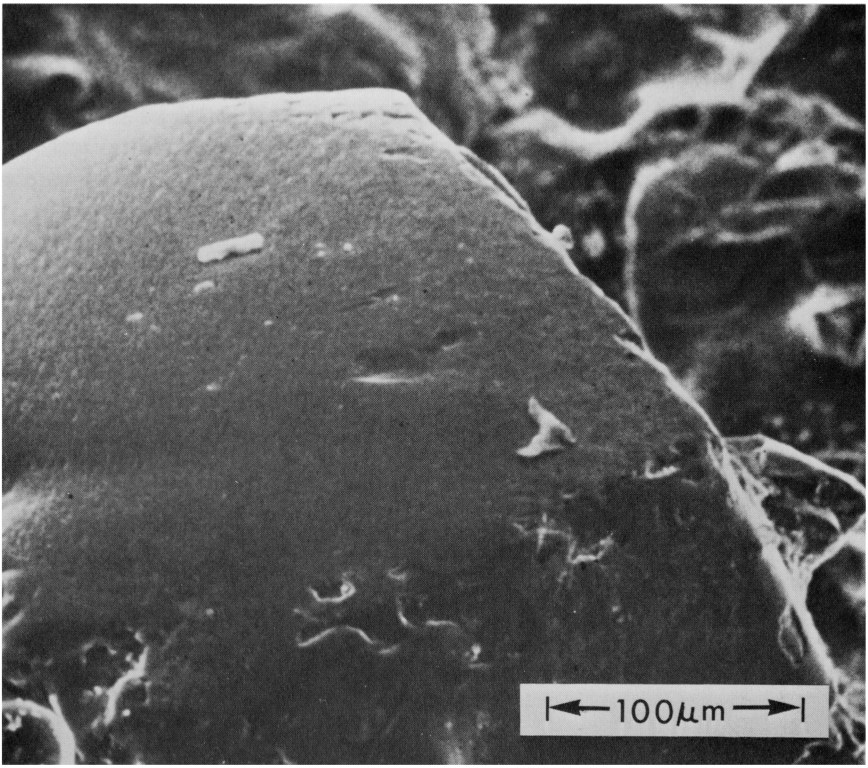

Fig. 8—Scanning electron micrograph of an abrasive grit, which has been smoothed and rounded, in a conditioned, average-62 grit, silicon carbide pulpstone

ture—as in thermomechanical pulping, or chemical pretreatment—as in chemimechanical or chemithermomechanical pulping, only serve to accentuate the extent to which these properties are enhanced.[98, 99] Fibres are also kinked, curled and twisted when they emerge from the refiner. These features, which are generally thought to result from built-in strains in the lignin component of the fibres, can be removed only by heating the fibres above the lignin softening temperature.[79, 98]

Development of paper strength in furnishes containing large amounts of mechanical pulp is extremely dependent on the extent to which fibre length is preserved and, contrary to the case for many beaten chemical pulps, also highly dependent upon both the amount and the *nature* of the intermediate and fines fractions.[100] This dependence was first quantified for stone groundwood pulps by Forgacs,[101] whose method has been extended and modified for the characterisation of refiner mechanical pulps.[102, 103] The whole field of mechanical pulp evaluation is currently in a rapidly changing state of flux. It appears that the first really effective on-line control methods for mechanical pulp production may emerge shortly based on the L and S parameters, introduced by Forgacs, *and their distributions.* It is, thus, premature to make any definitive judgements on mechanical pulp characterisation at this time.

One major difference between the high consistency treatment of chemical and mechanical pulps is that the latter consumes significantly larger amounts of energy which are dissipated as high pressure steam in the refining zone. This has created some technical problems the solution to which are currently being sought by somewhat different approaches.

Mechanics of grinding

Campbell suggested that the principles advanced in his physicochemical theory of beating '. . . in the main . . . apply to groundwood . . . (but) . . . the presence of large amounts of lignin and other materials must modify conditions to some extent. . . . the grinding process is one of breaking lignin-to-cellulose or lignin-to-lignin bonds, whereas the beating process is one of breaking cellulose-to-cellulose bonds. From analogy with the beating process, one would expect that any treatment which swells or softens or has a partial solvent action on lignin would lead to the fibrillation of wood fibres rather than to their cutting during the grinding process'.[8]

When wood is ground using a pulpstone with a newly trued and burred surface, a poor papermaking pulp is produced. The tips of abrasive grits which protrude from such a freshly prepared surface are sharp and angular as seen in Fig. 7. After some hours of grinding wood they become quite rounded and smooth as seen in Fig. 8. In the latter 'conditioned' state the pulpstone produces good papermaking pulp.

Protruding abrasive grits in the freshly prepared surface of a pulpstone compose an array of small, sharp cutting tools whose combined action is ideal for grinding metal to produce a smooth surface finish. However, in grinding wood to produce good papermaking pulp the aim is to remove fibres from wood as intact and flexible as possible. Cutting of fibres by sharp-edged grits is highly undesirable. During the conditioning period, sharp grit tips are broken down, smoothed and rounded by the lapping action of loose grit in the stone-wood interface.[104] As this action proceeds the amount of fibre cutting decreases and fibre removal is promoted by an entirely different mechanism to produce a pulp which is progressively more suitable for papermaking.

An 'average' representation of the geometry, dimensions, and spacing of

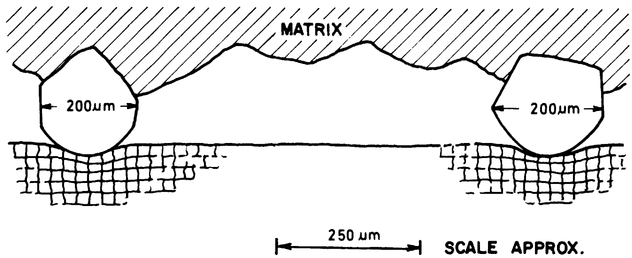

Fig. 9—Representation of idealised grinding zone conditions. The wood surface during grinding is deformed between 25–50 µm by a grit of 100 µm radius of curvature under normal grinding pressures. The most probable distance between 'conditioned' grits is about 625 µm

grits in the surface of a conditioned pulpstone, relative to fibre dimensions in a transverse plane of the wood, is shown roughly to scale in Fig. 9. Dimensions of this model of the pulpstone surface are the same along the longitudinal direction of the wood and hence, any fibre in the wood surface would normally be contacted almost simultaneously by either four or five conditioned grits along its length. Three important features of this representation of a conditioned pulpstone surface are:

(*1*) conditioned grits are rounded to a radius of curvature of approximately 100 µm,
(*2*) average separation between grits is approximately 625 µm,
(*3*) tips of conditioned grits protrude about 150 µm above the mean level of the pulpstone matrix.

This representation is a considerable simplification of the true state of affairs. There is, in fact, a fairly broad distribution about the mean values quoted. Justification for the use of this model was provided when it was found that a metal wheel, with a surface profile equivalent to that shown in Fig. 9, behaved in a manner almost identical to that of a conditioned pulpstone, when used for grinding wood under equivalent operating conditions.(105) Thus, the topographical features of a conditioned pulpstone essential for the production of good papermaking pulp in wood grinding are adequately reflected by use of the simplified model. Moreover, metal wheels with a profiled pattern closely approximating that shown in Fig. 9 have been successfully employed in commercial grinding operations.

When such an array of conditioned grits passes transversely over moist wood under load, at a speed of about 25 m/s, in the presence of water provided by the pulpstone showers, as in commercial operation, the following conditions are established.

Conditioned grits never come into actual contact with the wood but are separated from it by a very thin water film.[105, 106] Stresses imparted to the wood by the grits are transmitted through this film. The presence of such a water film is of practical importance for two reasons:

(*1*) it acts as a lubricating film between the grits and the wood, thereby substantially reducing the power required to drive the pulpstone at constant speed by eliminating the surface interaction component of the sliding friction between the two surfaces,

(*2*) it prevents burning of the wood surface by eliminating direct surface interaction between the grits and the wood.

In view of the fact that the temperature of the wood may rise as high as 140° C, *almost immediately before* it enters the grinding interface the lubricating film is in a pressurised state.[107, 108] The water film must provide a lubricating effect for when the shower water is switched off the wood surface is burned and the motor load rises rapidly.

The actual deformation of the wood structure by any grit is determined primarily by the force field exerted on the wood through the water film by that grit. Only those grits which protrude sufficiently above the pulpstone matrix, the so-called 'active grits', deform the wood. Assuming that there are N active grits/unit area distributed uniformly over the land area of a pulpstone surface, and that each exerts an equal normal force, the value of this force would be simply P/N, where P is the grinding pressure. This would correspond to a normal force per grit in the range 10–40 g for the range of operating conditions employed in conventional grinding. In actual fact, the force per grit will be distributed in some proportion to the distribution of grit heights above the matrix and hence will extend over a somewhat wider range of values. Under the influence of these normal forces, the tips of active grits deform the wood structure to a depth of between 25–50 μm, as indicated schematically in Fig. 9. The highly localised strain pattern may extend to a depth of 4–5 fibre layers in the subsurface of the wood but is mainly concentrated in the surface layer.

In a series of grinding experiments conducted with a metal wheel where the normal force per active grit, P/N, and the active grit density, N, were varied independently, it was found that the rate of fibre removal and the type of pulp produced were dependent on both of these parameters. The rate of fibre removal increased almost linearly with the normal force per active grit at constant grit density; weight-average fibre length and freeness, inversely proportional to the fines content, also increased. Increase of grit density, N, over a range of 3:1, at any given value of normal force per active grit, resulted in a linear increase in the rate of fibre removal with no significant change in pulp properties. Thus, it appears that each active grit provides an independent contribution to the rate of fibre removal. Under normal grinding conditions an active grit dissipates energy, on the average, at a rate of about 0·75 W.

The height of the grit tips above the matrix of the metal wheel was varied through the range 50–300 μm and all other dimensions and operating parameters were maintained constant. When the grit tips protruded 150 μm as shown in Fig. 9 the metal wheel produced a pulp similar in every respect to that produced by a conditioned pulpstone operated under the same conditions at approximately the same specific energy, as previously stated. As the height of the grits was progressively reduced to 50 μm the pulp became finer and the production rate decreased by as much as 70 per cent. Increasing the height of the grits also caused a rapid decrease in production rate but with little accompanying change in pulp character. At a height of 250 μm no pulp was produced at all and the wood surface became badly charred.

Substantially the same amount of power was required to drive the wheel in all of these tests.

This finding strongly suggests that there are at least two distinct actions occurring in the fibre removal process:

(*1*) preliminary breakdown, or loosening, of the wood structure into an embryonic pulp—this phase consumes most of the applied energy,

(*2*) removal of the loosened wood structure by some mechanism which is controlled by the height of the grit—this phase consumes relatively little energy.

A plausible interpretation of these findings is as follows. Fibres which are removed from the loosened wood structure are either forced into, or straddle, the cavities between the grits and the matrix in the land area. If the cavities are not too deep, the fibres in them can react on the loosened surface layer of the wood, either removing it by entanglement, or by some other means that helps to peel or strip it away. If the depth of the cavities exceeds a certain value, any fibres in them cannot provide sufficiently high reactive forces on the loosened wood structure to remove additional fibre and maintain the peeling cycle. Thus, although the walls of fibres in the wood surface have been fractured and the fibres are ready to be peeled away, the necessary peeling forces normally provided by fibres in the cavities are not available. Under these conditions mechanical strain energy is continually being pumped into the wood where it is dissipated as heat and retained in the wood structure. The rate of heat production in the subsurface of the wood exceeds that of heat removal by water passing through the grinding zone and the temperature of the wood rises. Eventually, the wood fibres lose moisture rapidly and burn, at which point the power level also increases.

On the other hand, as the depth of the cavities is reduced, the reactive stresses provided by the fibres in them on the loosened wood structure cause the normal stresses exerted by the stone on the wood to be distributed, at a diminished level, over the whole of the land area rather than just at those parts where the grit tips touch the wood. This resultant reduction of the normal forces exerted by the contiguous grits on the wood reduces the amount of deformation by the grits and the preliminary breakdown of the wood structure. Thus, when the cavities are full, loosened fibre will be removed rapidly and packed very densely into the cavities where it is subjected to additional refining, or regrinding, to produce a very fine pulp. When all the loosened fibre has been removed from the wood surface, the cavities become depleted and the cycle of preliminary breakdown and *subsequent removal of all the loosened fibre* starts again. This means that the action of fibre peeling occurs at discrete intervals rather than continuously, leading to a reduction in the production rate. Furthermore, it is evident that under these conditions a considerable amount of energy is used in 'regrinding' the fibre during the peeling phase.

Localised stress concentrations set up in the wood structure as a grit passes over it are a function of the force field exerted by the grit and hence involve the shape of its tip. If the radius of curvature of the tip is very small, i.e. if it has a sharp irregular cutting edge, the grit tip will penetrate the water film and cut away a swath of fibre fragments. The length of the cutting edge is much less than the fibre length and since the sharp grits may penetrate quite a depth into the wood structure, the pulp fragments removed will be quite chunky and unsatisfactory for papermaking. As the radius of curvature of the grits is increased stresses imparted to the wood become more spatially distributed. Under these conditions the grits ride over the pressurised water film and deform the wood structure, promoting localised fatigue failure, which leads to widespread loosening of the structure. When the grits have a radius of curvature of about 100 μm, fatigue failure is found to be concentrated mainly in the surface layer of fibres. A small length of a surface fibre undergoes a cycle of deformation in its transverse plane as a grit passes over it, such as shown in Fig. 10. This complex cycle of deformation, which comprises reverse shear and compression, leads to fatiguing of the cell wall and subsequent formation of cracks. This is accelerated by the intrusion of pressurised lubricant into incipient cracks.

When the radius of curvature of the grits is increased still further, a larger volume of the wood structure becomes highly strained. The plane of maximum strain moves further away from the surface so that more than one fibre layer is broken in advance and ready for peeling.

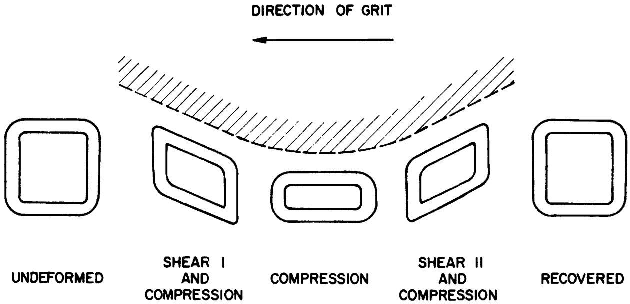

Fig. 10—Stages in the cyclic complex straining of a fibre in its transverse plane, and occurring along part of its length, when a conditioned grit passes over. This straining, which comprises reverse shear and compression, leads to fatigue failure in the cell wall

It is important to note that a single grit acts along only a small fraction of the length of a fibre. In fact, if the pulpstone grits were in a strictly ordered array, with a spacing of 625 μm as shown in Fig. 9, then each fibre, which is approximately 2·5 mm long, would be acted upon almost simultaneously by 4–5 grits along its length. In a pulpstone surface, however, the grits are not in

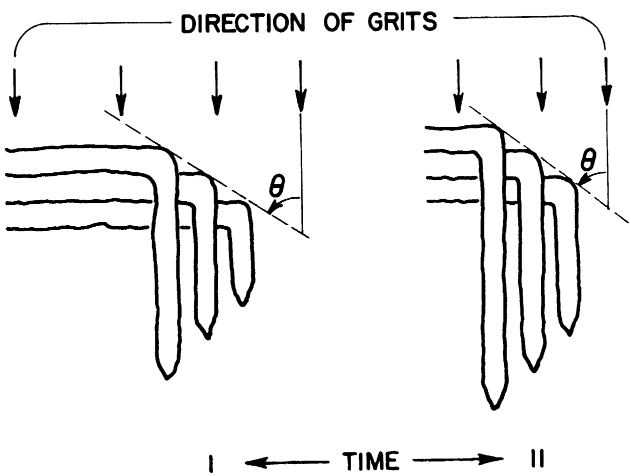

Fig. 11—In the grinding of wood to produce papermaking pulp, the wood structure is first loosened by the conditioned grits and the loosened fibres are subsequently peeled away. This schematic diagram shows two stages in the peeling of loosened fibre and as indicated, fibres are always removed in a strict sequence

an ordered array and every section along the length of each fibre is subjected to deformation at random intervals by many grits before the fibre is finally removed.

When the fibres in a certain area of the surface have been loosened they are removed from the wood by a peeling action that generally starts from one or other end of the fibre, but occasionally from both. Fibres always peel in strict sequence and in the same direction. This is illustrated schematically in

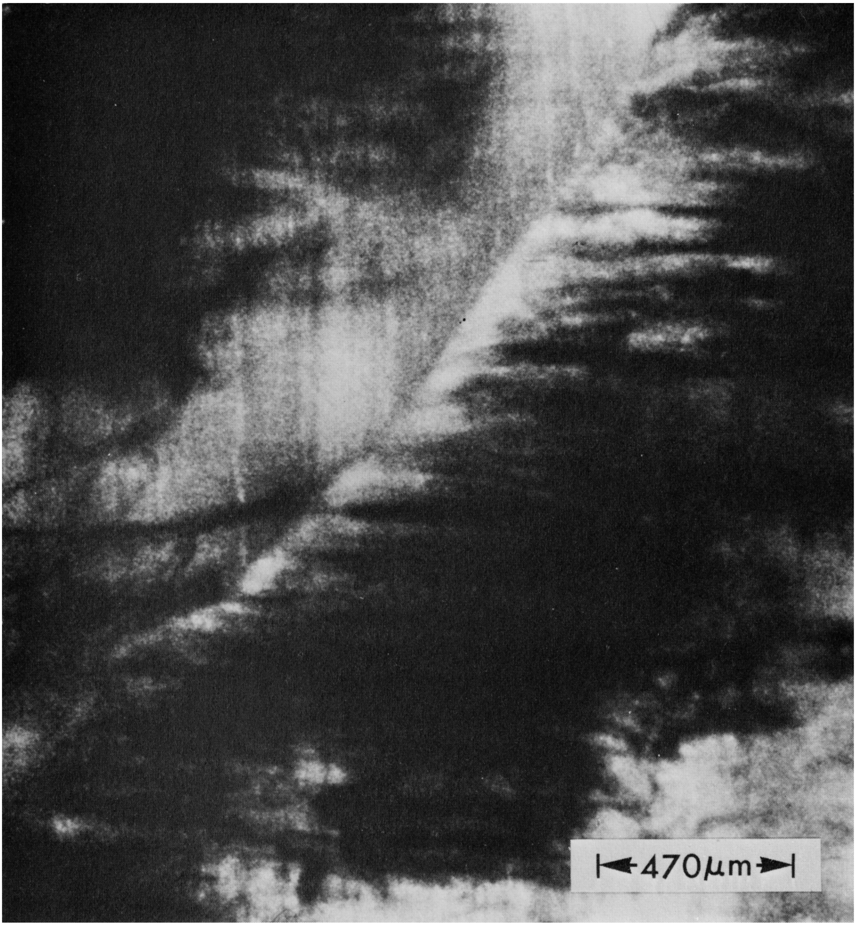

Fig. 12—Photographic print of a single frame in a ciné film recording of the peeling of fibres from sprucewood as it is being ground in a simulated grinder. A single layer of fibres is shown being peeled away and the peeling front is seen to be at an angle of about 45° to the longitudinal axis of the fibres in the parent wood

Fig. 11. The momentary state of peeling is shown for three contiguous fibres at two different times. It is seen that the fibre contacted first by the advancing grits always peels a little in advance of the next one, and so on. Those parts of the fibres that have been completely separated from the parent wood, and from each other, are combed into the direction of motion of the grits. Incipient peeling occurs over a front that is at an angle θ to the grit direction.

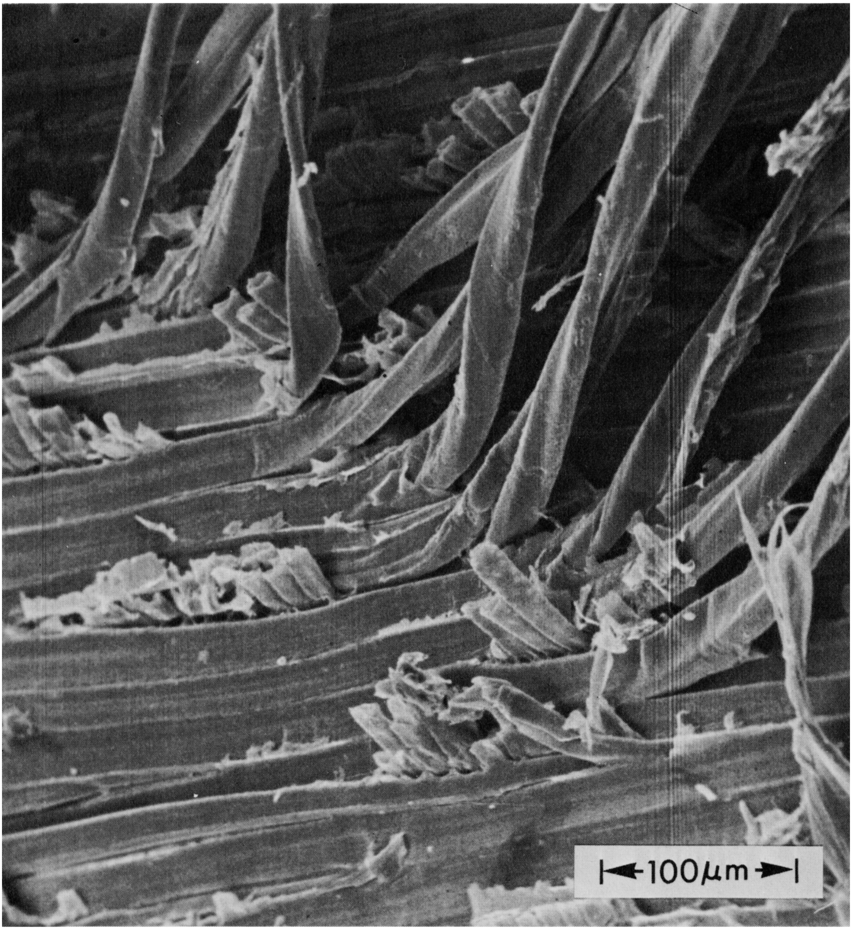

Fig. 13—Scanning electron micrograph of a peeling front in a sprucewood log which has been removed from the pocket of an operating commercial grinder. The partially removed fibres have risen away from the surface and twisted, since it was necessary to completely dry the wood specimen before insertion in the electron microscope

This angle, which is generally 45°, always bisects the angle between the longitudinal axis of the fibres in the parent wood and the direction of motion of the grits. Such a peeling front is shown in Fig. 12, which is a positive print taken from a selected single frame of a ciné film on which was recorded the dynamics of the peeling process in a simulated grinder. From an analysis of ciné film records, it was found that peeling of single layers of fibres occurs simultaneously over different small areas of the wood surface which have already been loosened by the action of the grits. While one area is being peeled away another is being loosened and so the action proceeds in continuous fashion.

Fig. 13 is a scanning electron micrograph of a typical peeling front in the surface of a spruce log which had been quickly removed from a pocket of an operating commercial grinder. The loose ends of the partially peeled fibres have sprung away from the surface and twisted, because the wood sample had to be completely dried before the electron micrograph could be taken. However, the main features of the peeling, similar to those shown in Fig. 12, can be clearly seen. Spruce and balsam fibres generally peel away relatively intact along their whole length and are broken down only in their further passage through the grinding zone.

As may be expected, the internal fibrillar structure of the wood fibres is loosened up quite considerably prior to their being peeled away. Such fibres exhibit increased water sorption compared to native fibres mechanically teased from wood by micromanipulation, though they do not exhibit coaxial delamination.(17) However, it is quite evident that there is considerable additional mechanical action exerted on the peeled fibres as they pass through the grinding zone. This action is essentially one of beating individual fibres produced by the peeling action. The pulpstone may be regarded as a rotating beating element, similar in many respects to that devised by Chiaverina,(109) and the surfaces of the wooden logs act as the bedplate. An attempt to analyse this beating action by high-speed photography has showed it to be both variable and uncontrollable. Furthermore, the nature of the action could not be determined unambiguously because of the complexity of fibre entanglement. Various empirical attempts to control the action and, in particular, to retain fibre length by changing the nature of the pattern in the stone surface have met with little success. It has been claimed that the use of deep multiple spiral grooves, which run circumferentially around the stone face are effective in maintaining fibre length. Only when the length of the grinding zone is reduced to about 25 mm is the breakdown of loose fibre in its passage through the grinding zone significantly reduced. In the Bersano-type grinder,(110) where the length of the grinding zone is approximately 6 mm, the beating action is virtually eliminated and fibre length almost completely preserved. However, in order to satisfy drainage requirements on a paper machine, such fibre generally requires further mechanical treatment. It is suggested that any basic improvements in the grinding operation must follow some such route as indicated by Bersano in which the fibre separation and the final strength development processes are separated.

Concluding remarks

IT is evident that considerable progress has been achieved during the past twenty years towards a better understanding of the essential changes which are wrought in chemical pulp fibres by beating. Furthermore, the manner in which these changes affect the subsequent consolidation of wood pulp fibres in a paper web are reasonably well understood. Basic technological guidelines, which will no doubt require some modification and refinement for specific cases, have been established on a sound scientific foundation. It must be gratifying, indeed, to the organisers of these symposia that some of the seeds which they so carefully planted twenty years ago have borne such wholesome fruit.

Dwindling forest resources, ever increasing costs of utilities, supplies and money will demand that, amongst other things, the continuing trend towards the more extensive use of higher yield pulps will accelerate. It is important, therefore, that the maximum potential of such pulps be developed with all due speed. As has proved to be the case for chemical pulps, a better fundamental understanding of the properties of their higher yield counterparts should assist in this development.

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Transcription of Discussion

Discussion

Prof. J. T. G. Overbeek May I make a comment on your last slide where you showed the action of cations in a range of valency groups? It looks as if it shows a hydrogen Schulze–Hardy rule flocculation. When you look closer you will see that the multivalent ions all work at the same concentration and that the bivalent and monovalent ions work at higher concentrations. In my opinion this looks very much like a reverse of charge by these multivalent ions either by the ions directly or by the hydrogen that they produce in hydrolysis. It would be worthwhile trying to correlate this effect either with mobilities or zeta potentials, but also with the concentration of the fibres. If it is really a reverse of charge by trivalent ions the concentration of ions necessary should be nearly proportional to the concentration of fibres whereas for the bivalent and monovalent ions the concentration of fibres should be less important. You would then have a clue as to where to look for the explanation of the effect.

Atack Thank you for your comment.

Dr A. de Ruvo I would like to ask you, Dr Atack, about the relationship between energy and properties that we have in refining. As you know we have improved the properties of mechanical pulps due to thermomechanical, CTMP, etc., but the disadvantages seem to be that we always increase the energy input. Do you think there is any chance that we can break this vicious circle, so as to reduce the amount of energy and still get better properties in refining?

Atack Yes I do think this can be done. But we need to do further work to be certain.

Prof. R. Marton We heard yesterday about the addition of alum to high yield pulps for refining. You have shown a diagram which refers to chemical pulps. Why don't you speculate a bit and put the two things together? Could

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you anticipate what these additives will do to the properties of mechanical pulps?

Atack To answer that would take far too long. I will submit a written answer to the recorders.

(*Written after the event*) Experience on the addition of alum to refiners during the refining of mechanical pulps is quite limited. Recent work by Charters, presented at the Appita Meeting in Queenston, New Zealand in 1976, suggests that alum addition increases the frictional resistance transmitted to the refiner plates. This is reflected in increased motor loads when alum is added. Subsequent repetitions of this procedure have not always produced similar results. In fact, in some instances no effect has been found at all. If the effect is indeed real, and could be reproduced at will, it would be technically important since refiners could then be operated at a given motor load with a wider plate gap to produce pulps with substantially the same properties as those of pulps produced without alum addition.

Alum is also frequently added to furnishes containing large percentages of mechanical pulp, particularly pine pulps, to control pitch during the papermaking operation.

Higgins Could I return to Dr Ionides's paper and make some comments based on discussions I have had with Dr Geoff Irvine who has been working in the field of wet web strength? He points out that one of the main thrusts of the argument is the basis for comparison of the wet web strength of pulps. As Ionides *et al.* say, there should be a given set of conditions of dewatering rather than a given wet web moisture content. This should be as close as possible to that occurring on the papermachine. We have been doing some work on the properties of high yield pulps, TMP and CTMP, where we find that in some experiments we have difficulty in removing sheets from the wire at a standard moisture content required for comparison. In practice sometimes we have to form on terylene mesh, or on the wire but at a considerably greater moisture content than we would like to. In Mardon's terms, we have to take pains to reduce the stripping tension so that it does not exceed the tensile strength of the sheet. I feel I should also mention the problem of what parameters we should use in wet web testing to assess the results. Some people use wet rupture energy, and as Mr Leask showed us yesterday extensibility is important. Mardon and his colleagues use the work to $3\frac{1}{3}$ per cent strain. We tend to use maximum tension and maximum extension as the main parameters, but without any very clear basis.