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ADHESION BETWEEN FIBRE WEBS AND METAL SURFACES DURING DRYING

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Synopsis The dry-creping process is dependent on a balanced adhesion of the paper web to the MG-cylinder at the moment of removal of the web by the doctor blade. The adhesion of the web usually is on a layer of organic origin attached to the metal surface. The physical appearance of the intermediate layer has been studied on production machines and on various model surfaces and its chemical composition analysed. Laboratory techniques have been developed for studies of the peeling of fibrous webs from metal surfaces. Variables associated with the building-up of the intermediate layer and their effect on the peeling resistance have been investigated. Different pulps show widely different adhesion and react to different degrees to drying variables.

Introduction

WHEN fibre bonds are under discussion, the only ones taken into consideration generally are those developing between the fibres themselves. However, during the manufacturing process, the fibres do in fact come into contact at various stages with a variety of materials, such as metal, rubber, synthetics and ceramics. As long as the fibres form a dilute water suspension and are in vigorous motion, the contacts between other surfaces and the fibres are of extremely short duration, and as a rule no bonding forces develop. The situation changes as the fibres proceed through the system, and adhesion problems are developed between the wet web and the wire.(1–3) In the wet presses again, the fibres may stick both to the felts and to the roll coverings.(4) However, when the web, which still contains a considerable percentage of water, proceeds into the drying section and there contacts the drying cylinders, the conditions are such that a certain degree of bonding may occur between the surfaces of the fibres and the metal. The extent and the tenacity of these bonds, as well as the location at which adhesion occurs, have different consequences in practice. The picking of fibres by the drying cylinders is a source of

Under the chairmanship of Dr J. D. Peel dusting, and is thus a completely unfavourable phenomenon. However, one essential point, if a high MG finish is to be imparted to paper and board on a Yankee-dryer, is that the web adheres very firmly to the polished cylinder surface up to a point of sufficiently high degree of dryness, and is then released without sticking. Sufficiently close contact is also essential for efficient heat transfer from the cylinder shell to the paper. Another example of a case in which some extent of controlled bonding is required between fibres and metal is the case of dry creping. Although the dry creping process is the most common method of making tissue paper, it has a drawback associated with the difficulties experienced in the control of the adhesion between the fibre web and the metal. These difficulties prompted a study of the adhesion between fibre webs and metal, or more specifically, iron.

The metal surface

In the dry-creping process, the wet paper web, with a solids content of 20–30 per cent, is pressed against the hot metal surface of the Yankee-cylinder at a temperature of approximately 100° C. The paper web is dried to a solids content above 90 per cent, and is then creped by the doctor blade. During one revolution, the Yankee-cylinder surface, at elevated temperatures, is at brief intervals exposed in turn to air and to oxygen-containing aqueous solutions of the wet paper web. As a rule, it is an extremely difficult matter to obtain pure metal surfaces and to keep them pure. Even if the metal is noble and if, for example, mechanical cleaning is performed, immediately subsequent to this, adsorption of oxygen and water vapour results on exposure to air. With cast iron, the susceptibility to atmospheric conditions is naturally more pronounced than that with noble metals, although for other iron alloys as well the physical and chemical properties determine the reactivity of the surface.

The so-called metal bond forms the inside bonding of the atomic lattice of metals, and may be regarded as an extended covalent bond in which the shared electrons form a uniform, negatively charged ‘glue’ which is spread throughout the material. This ‘glue’ holds the positively charged metal ions together by means of electrostatic attraction. Despite the non-localised nature of the metallic bond, it is of moderate strength. The relatively free electrons in the metal lattice also influence the accumulation and bonding of other compounds to the metal surface. With reactive metals such as cast iron, even in the initial stages of exposure there occurs some chemisorption, which soon leads to chemical raction, and in the presence of oxygen, as in air, the formation of oxides. Subsequently the oxides may grow in thickness as a result of diffusion processes. On the other hand, when a metal is in contact with an aqueous solution of different compounds, a difference in the electro-chemical potential may be generated between the metal surface and the solution, as is the case when a wet fibre web is pressed against the drying cylinder surface. The value of the potential difference depends on the composition of the metal lattice at the surface, and on the electrolytical properties of the aqueous solution in the paper web. Chromium steel is nobler than cast iron, and consequently different potential differences develop at such surfaces. It is probable that the potential difference will influence the adhesion of different compounds to the metal surface; similarly, the corrosion properties of the metal are determined by the potential difference. Certain less noble metals, such as aluminium, are oxidised very rapidly, although the oxide layer on the metal surface gives protection against further corrosion. Despite the thinness of the aluminium oxide layer, it is very strongly bonded to the metal surface, and the diffusion of oxygen through this layer is negligible. A cast iron surface also reacts rapidly, but the protective properties of the oxide layer that is formed are very poor. In the corrosion of cast iron, the main problem that arises is that the oxide layer grows very thick, and then breaks off easily. Alloyed steel with an adequate content of chromium is protected by the formation of a thin chromium oxide film on the metal surface, and further corrosion is inhibited. This will of course influence the bonding of other materials to the metal surface.

Model experiments

IN our investigations of the adhesion of fibre material to cast iron surfaces, the first step was the application of a micro-Yankee technique. We used small ground and polished cast iron plates of the size and shape used for scanning electron microscope preparations. These plates were heated, and small wet paper sheets were pressed against the surface. The sheets were removed after drying. After metal-shadowing, the plates were examined in a scanning electron microscope, Fig. 1a. It can immediately be seen that the contours of the fibres that have adhered to the metal surface are still visible. Our interpretation is that these contours are attributable to dispersed and solute material of the water in the sheet. This material, consisting of dissolved hemicelluloses, extractives and lignin, along with dispersed fibrils in the wet paper web, diffuse in the sheet, against the hot metal surface, and deposit themselves, partly as a result of the action of surface tension forces in the wedges formed between the metal and the fibre surface. The very close contact with the oxide layer of the metal surface results in this very fine material adhering to the plates on removal of the bulk of the sheet. Fig. 1b, however, gives an indication of another type of deposit on the surface. It is evident that

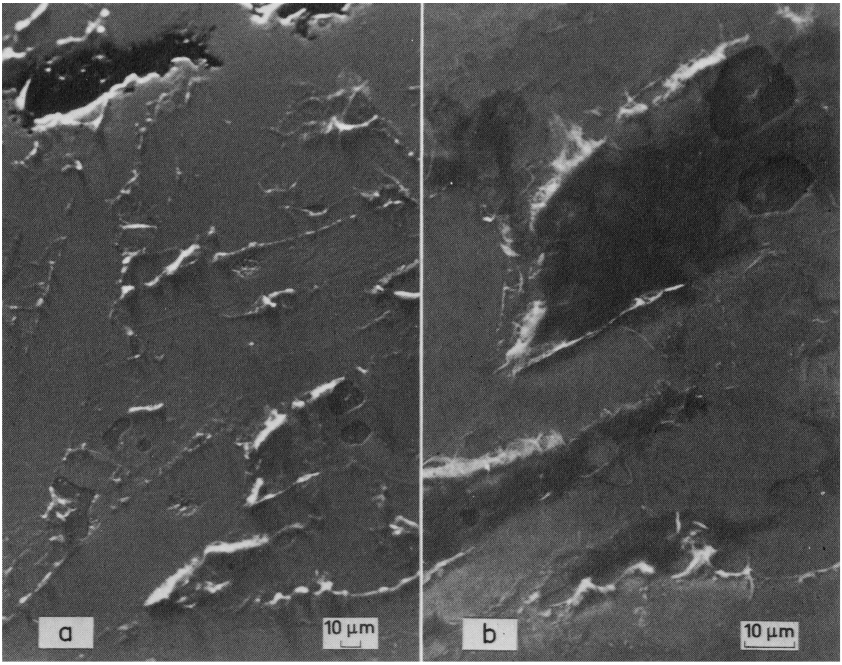

Fig. 1—Surface of the 'micro-Yankee' after removal of the sheet. (*a*) Contours of fibres on the metal surface. (*b*) Fragments of the wall on the metal surface

the material visible at this magnification has been removed from the sheet by picking of the fibre wall. In this case the adhesion between the metal and the fibre apparently exceeded the cohesion of the fibre wall itself. It seems that these two processes are those which are mainly responsible for building up the coating layer on the Yankee-cylinder surfaces.

Peeling tests from a plate

IN order to measure the forces developing between a wet sheet drying in contact with a metal cylinder and the cylinder surface, we built a laboratory instrument based on the adhesion tester described by Howe, Lepine and Gregory.(5) The equipment consisted of a sheet mould, a flat press, a thermostatically controlled cast iron plate, a device for pulling the laboratory sheet from the plate, and the instrumentation required to record the force continuously as a function of the distance of peeling, Fig. 2. The cast iron plate, $100 \times 145 \times 7$ mm in dimensions, was of the same composition as that used for the casting of Yankee-cylinders. It was fixed to a brass base containing a

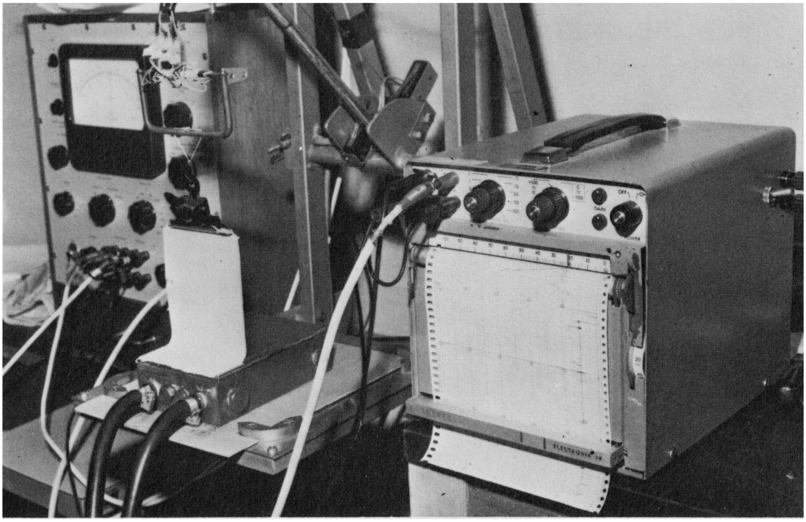

Fig. 2—Adhesion tester with thermostated plate

system of channels for pumping the thermostat liquid, polyethylene glycol, from a thermostat through the base. Without entering into details of the test method, the sheet is formed on a laboratory sheet mould, and cut to size; following this, a sandwich is formed from a press plate, a drying felt, the sheet, and the thermostated hot cast iron plate. The assembly is pressed in a plane press, so that the wet sheet sticks to the plate. After a given period, in which the sheet has attained the required dryness, a clamp is attached to one end of the sheet, and in the pulling device the sheet is removed from the plate by a peeling action. A continuous record is kept of the force required. It was found that constant conditions were not readily attainable, because of the considerable corrosion of the plate. This was the result of the long period of contact between the wet sheet and the plate in the press amounting to about one minute; under mill conditions, however, the corresponding period of contact is less than one second. The plate was soon covered with a layer, containing 48 per cent of iron oxide as Fe_2O_3. Corresponding results obtained from analyses of coating layers on commercial Yankee-dryers showed an iron content of less than 1 per cent. Since these obstacles seemed unsurmountable, it was decided to change the metal composition of the plate, with the aim to make it more resistant to the oxidising influence of the wet sheet. However, the organic adhesive layer on the stainless steel developed very slowly, because of the electrochemically relatively inactive metal surface.

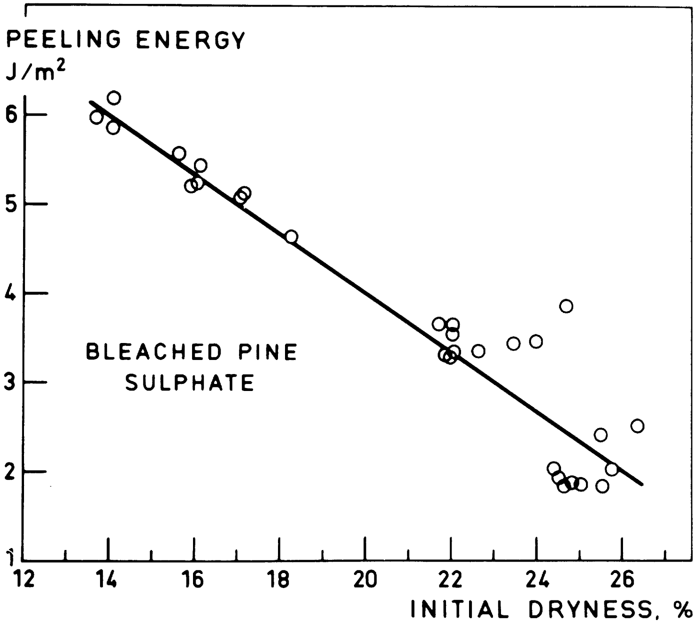

Fig. 3—Peeling energy as a function of initial dryness of the sheet when pressed against the metal surface. Bleached pine sulphate pulp

Only by the use of bleached pine sulphate pulp was the layer growing with relative rapidity, which eventually resulted in a steady and constant adhesion. This technique to establish fairly quickly constant test conditions with bleached pine sulphate pulp was used to prepare the test plate for testing other grades of pulp. It was found, in fact, that sheets made from any pulp reached constant conditions of adhesion on the test plate with relative rapidity if the metal had first been covered with a coating layer of the bleached pine sulphate pulp.

In this way a number of different pulps of about the same degree of beating were tested for adhesion on the metal plate; the variable was the dryness of the sheet at the moment of its being pressed against the hot surface. Fig. 3 shows that the work of peeling, calculated per surface area, decreases with increasing dryness. The results given in this figure, obtained for bleached pine sulphate pulp, indicate a linear relationship. The regression lines calculated for other pulps tested are presented in Fig. 4. This figure thus gives an idea of the variation obtained between different grades of pulp. High adhesion seems

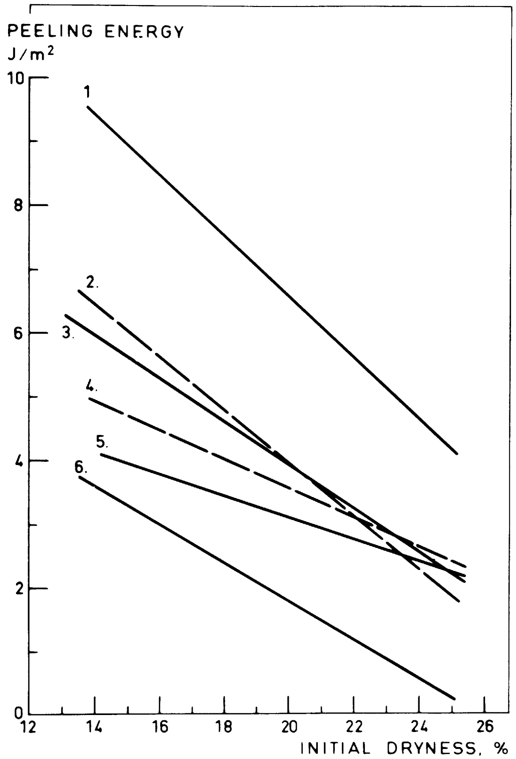

Fig. 4—Peeling energy as a function of initial dryness of the sheet when pressed against the metal surface. Sheets made from: 1. 50% gwd. + 50% unbleached sulphite. 2. Bleached sulphite. 3. Unbleached pine sulphate. 4. Cotton. 5. Unbleached sulphite. 6. Bleached birch sulphate

obtainable for sheets with a content of mechanical pulp, whereas bleached birch sulphate appears to have lower adhesion.

The pressure applied when the wet sheet is being pressed against the hot metal surface exerts the expected influence upon the resistance to peeling; with higher pressure, the adhesion increases.

The influence of the surface temperature of the metal plate was tested with a mixture of spruce sulphite pulp and mechanical pulp. The results shown in Fig. 5 indicate that with increasing temperature the adhesion decreases. SEM-graphs of the surfaces of the sheets removed at different temperatures exhibit a trend which is consistent with the reduced adhesion at higher

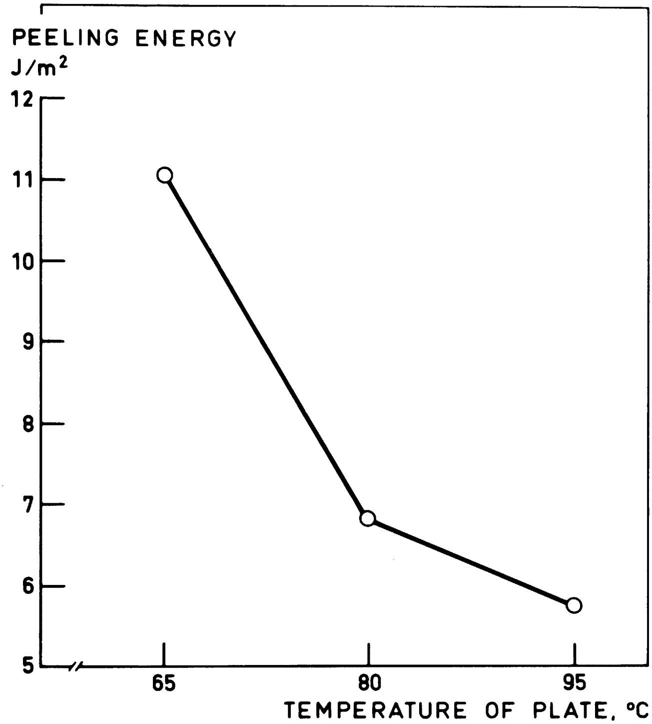

Fig. 5—Influence of the temperature of the metal plate on the peeling energy

temperatures. The contact surface, which appears flat, clearly decreases with increasing plate temperature, Fig. 6.

Fig. 7 shows a SEM-graph of the surface of a sheet made from bleached pine sulphate after removal from the metal plate, together with the matching area of the metal plate with its coating layer. The presence of fibre fragments on the metal is clearly visible. As a comparison, Fig. 8 illustrates bleached birch sulphate, which was found to have a very low adhesion value. The corresponding area of the metal plate shows far fewer fibre fragments, and generally provides a cleaner impression. At this point, it should be borne in mind that the base layer nearest to the metal surface again originates from bleached pine sulphate pulp, on top of which is deposited the layer built up by the birch pulp.

The reduced adhesion at higher temperatures is currently assumed to be attributable to the increased rate of water evaporation during drying, the

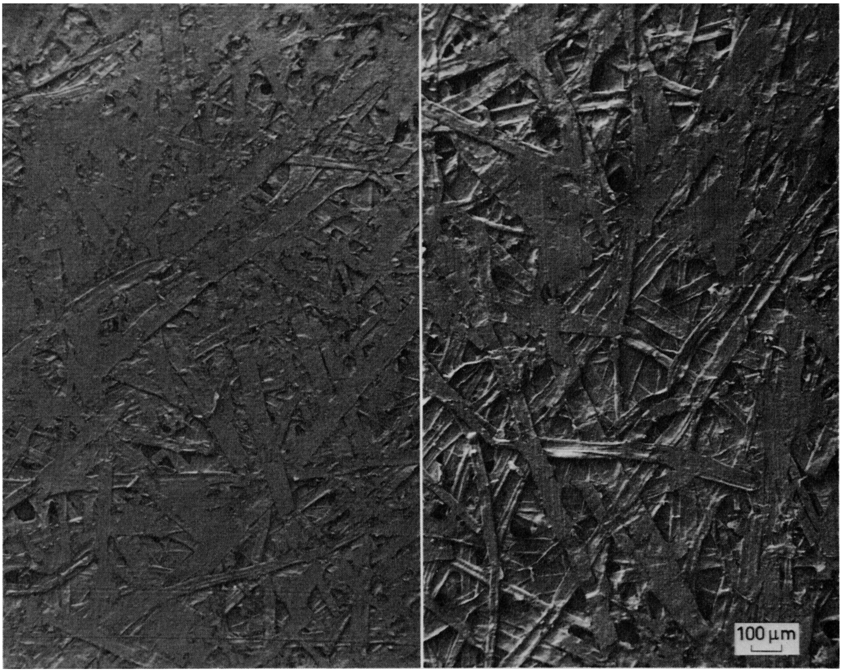

Fig. 6—Sheets of unbleached spruce sulphite pulp removed from the metal plate at temperatures of 65° C and 80° C

shorter period of contact, and the reduction of the surface tension of the water.

The degree of contact between the fibres and the metal was found to have a clear influence on the adhesion; a correlation was established between the adhesion value, and the FOGRA smoothness measured on the surface of the sheet after removal.

Peeling tests with a laboratory Yankee-cylinder

ALTHOUGH some insight was gained into the phenomena associated with adhesion between fibre webs and metal by the technique described above, some of the experimental factors proved to be unsatisfactory. The most undesirable features were associated with the time element in drying and testing, and the fact that for practical reasons a cast iron plate could not be used, which necessitated the use of stainless steel and an auxiliary coating layer. We therefore built a laboratory Yankee-cylinder working intermittently

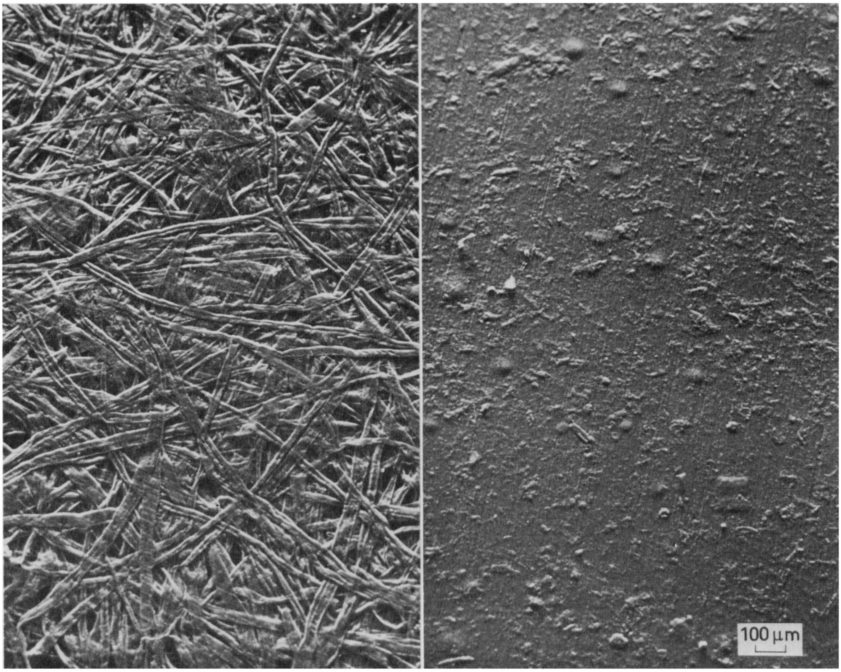

Fig. 7—Sheet surface and metal plate after removal of a bleached pine sulphate pulp sheet

with laboratory sheets, Fig. 9. The cast iron cylinder with a diameter of 20 cm is electrically heated. The cylinder rotates at a surface speed of 0·18 m/s. The press felt can be held against the rotating Yankee-cylinder by a cylinder roll. The laboratory sheet is carried by the felt to the cylinder, pressed against it, and then dried on the surface of the cylinder. When the desired dryness has been reached, the sheet is removed by peeling with the aid of a doctor blade equipped with a force transducer. The force registering system is critical, and is built in such a way that it measures the force in the direction tangential to the Yankee-cylinder. The positioning of the doctor blade is also critical; it is brought as closely as possible to the cylinder surface without actually touching it. The force measured contains not only the component necessary to split the bonds between the web and the cylinder surface, but also other components, of which the most important ones are probably the force for bending the sheet, and frictional forces between the doctor blade and the peeled-off web. Their actual influence upon the measured value has not been assessed, but it is believed that the contribution of these components remains

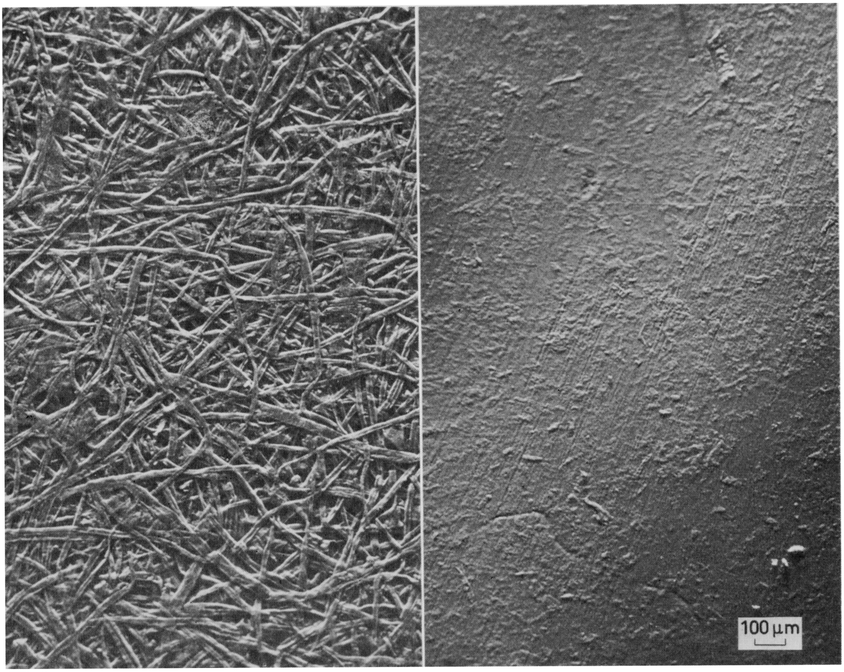

Fig. 8—Sheet surface and metal plate after removal of a bleached birch sulphate pulp sheet

fairly constant in all tests. A continuous record was kept of the force acting on the doctor blade. From this recording, the peeling energy was computed in J/m^2. Since the laboratory sheet covers only part of the circumference of the Yankee-cylinder, the sheets have to be placed on the felt in such a position that they always touch the cylinder surface at the same location. This enables the building up of a coating layer with a minimum of sheets, which further enables the cylinder to be run with several coating layers simultaneously.

A series of different baled pulps were run on the machine; the results obtained are listed in Table 1. In general, unbleached pulps give higher adhesion than bleached pulps of the same type. A separate test with a bleached spruce sulphite slush pulp was found to give less adhesion than the corresponding dried pulp. This was accompanied by a change of the coating layer into a brown, inorganic layer containing iron oxide. This was probably the consequence of the higher content of pulping chemicals in the slush pulp, which gradually induces corrosion of the iron surface of the Yankee-cylinder.

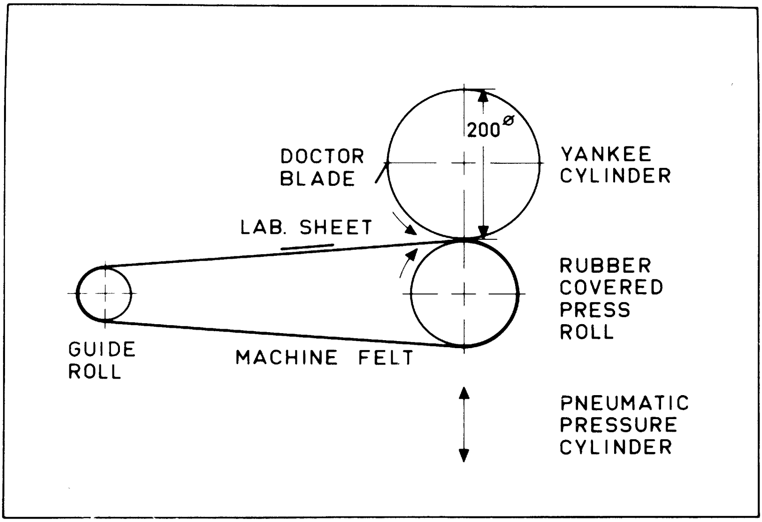

Fig. 9—Schematic drawing of the laboratory Yankee-dryer

Tests performed with mixtures of bleached pine sulphate pulp and mechanical pulps showed decreasing adhesion with increasing amounts of mechanical pulp. The adhesion of sheets made from high alpha pulps is extremely low, of the order of 2·5–6 J/m^2. Increasing the degree of beating also increases the adhesion between the sheets and the surface. With bleached pine sulphate pulp, the work of peeling of the unbeaten pulp was doubled when beaten to 40 SR°.

TABLE 1—PEELING ENERGY FOR LABORATORY SHEETS MADE FROM DIFFERENT TYPES OF PULP

Pulp	*Peeling energy* (J/m^2)
Unbleached pine sulphate	14–21
Bleached pine sulphate	13–20
Unbleached spruce sulphite	10–15
Bleached spruce sulphite	8–14
Bleached birch sulphate	3–6

Discussion

It is probable that the coating layers built up on the metal surface during the run of an experiment are not uniform in the Z-direction. When a suitable coating has been built up on the Yankee-cylinder surface and stabilised conditions of adhesion have been established, removal of the outer parts of the coating layer by a doctor blade frequently results in an increased adhesion of the fibre webs to the remaining coating layer. Typical results obtained with the bleached pine sulphate pulp are shown in Table 2. With increased pressure

TABLE 2—INFLUENCE OF LOADING OF THE CLEANING DOCTOR ON THE PEELING ENERGY FOR LABORATORY SHEETS MADE FROM BLEACHED PINE SULPHATE PULP

Conditions	*Peeling energy* (J/m^2)
No cleaning doctor	5·5–11
Cleaning doctor lightly loaded	13·5–17·5
Medium load	18·0–25
Heavy load	Sheet does not peel off

on the cleaning doctor, the point is soon reached at which the sheet does not peel off at all. In fact, most pulps even with a very slight pressure on the cleaning doctor, stick excessively to the remaining coating layer. One obvious explanation for this has already been mentioned: dissolved or suspended hemicellulose, lignin and fibrillar material moves with the liquid phase towards the hot cylinder surface, where it forms a continuous and sticky layer close to the metal, and is bonded to it by virtue of the metal oxide layer. On top of this extremely thin layer, fibrous fragments attach themselves to a certain thickness, which reaches a kind of dynamic equilibrium value when deposits and removal of material by the web are equal. At the same time, the contact between the sheet and the layer is not perfect, as both the coating layer and the web are of a fibrous nature. However, the removal of the topmost fibrous layer by the cleaning doctor exposes the extremely thin, sticky layer, and increases the adhesion.

Nevertheless the mechanism could also be explained, at least in part, by the mechanical treatment of the coating layer. The coating layer is evidently thermoplastic at the prevailing temperatures; the cleaning doctor can even out any irregularities in thickness, and thus increase the effective contact area between sheet and coating, and consequently improve the strength of adhesion. For instance, it was found that if the coating layer had been built up on only one sector of the Yankee-cylinder, and the cleaning doctor was allowed to run against the rotating cylinder, the adhesive coating layer was gradually transported to those parts of the cylinder surface which until then had been clean, thus producing an extremely sticky layer over the entire circumference. The layer is not visible; a magnetic thickness gauge indicated a thickness of no more than 0 to 3 μm.

When the coating layer is thick as a result of deposits of fibrous fragments, the bonding of the web to the layer is probably governed by the same laws as those that control the formation of internal bonds in the fibre web. In fact, it was observed that the adhesion values obtained for different grades of pulp were generally correlated to the mechanical strength of the sheets themselves. This may be a rare case in practice, however, since the mechanical action exerted by the cleaning doctor in addition to removing fibre fragments also pushes them into the thermoplastic and moldable coating layer close to the metal surface.

Conclusions

THE tests, although performed under idealised conditions, with a laboratory instrument that in many important respects differs from the conditions of full scale Yankee-dryers, have nevertheless given valuable background information on the basic factors which control the adhesion between fibrous webs and metal surfaces. The adhesion is always to an intermediate layer consisting of organic compounds of fibrous origin and fragments of small dimensions which are adhering to the oxide layer of the metal surface. The layer can grow in thickness by the deposit of more fibrous material, but this growth comes to a point of equilibrium which is dependent upon how the web is removed from the cylinder. In particular the doctor blade affects the equilibrium thickness of the coating, since in practical creping the doctor blade separates the paper web from the coating in different ways, inside the coating layer, inside the web, or at the newly formed interface between coating and web. This is dependent on the adhesion-cohesion properties of the coating-paper web sandwich and on the geometry of the doctor blade in relation to the surface of the Yankee-cylinder.

Finally it can be stated that the experiences gained in laboratory tests with the stainless steel plate, which showed slow and poor build-up of the adhesive coating layer, have in fact proved to be true in practice. Experiences gained with metallised Yankee-cylinders have sometimes indicated difficulties in controlling the adhesion of the web.

Acknowledgement

This work has been carried out over several years during which time a number of persons have been engaged in its different phases. The authors wish to acknowledge the contributions made by Mr P. Viilo, Mr T. Makkonen, Mrs L. Pelkonen and Mr A. Ansaharju. For the SEM-micrographs the authors are indebted to the personnel of the Microscopy Department of the Institute.

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Transcription of Discussion

Discussion

Dr J. Mardon The adhesion depends on the moisture content at which you pull it off. At what moisture content did you actually remove the paper?

Nordman The dryness was around 95 per cent.

Mardon A small change in the dryness can have a very big effect. I and my colleagues did a very similar experiment with a flat plate technique and we traced the variation from 60 per cent dry down to 95 per cent dry and the changes are very considerable towards the end of this range.

Mr R. J. Powley On your chart showing the doctor loads, could you clarify what the pressures were in force per unit of length?

Nordman No. We just put on weights qualitatively.

Dr J. Grant With so much intensive evaporation of water going on all the time, I am surprised not to see any indication of saline matter in your S.E. micrographs. What water did you use and did you find that it affects your results?

Nordman We used tap water only and there does not seem to be any salt deposited.

Dr D. Atack I know that you were dealing with metals in your paper but have you looked at any other surfaces such as plastics.

Nordman No, we haven't.

Mr J. W. Swanson Did you do any wettability measurements before you attached the wet paper to them?

Under the chairmanship of Dr J. D. Peel

Nordman No.

Swanson The reason for asking was that several years ago one of our students did some experiments of this type where the wettability of the metal surface was varied by several different techniques. He found that a water contact angle of 45° seemed to divide poor and good adhesion. At low values the contact was strong and at high angles it was very weak.

Nordman Thank you for that suggestion, I think that the coating layer which has built up may be a similar phenomenon to yours.