Holy Grail or Wholly Frail?

The Cold Corrugator

There is a strong imperative to pursue it – how about ultrasonic welding?

Tony Pinnington

A cold corrugator could offer a shorter, lower capital cost corrugating process with lower running costs and less energy consumption. Significant benefits indeed, but the search has been on for over 40 years, and so far, without convincing success. Special adhesives, hot melt and radio frequency heating have come and gone. Could ultrasonic welding now prove to be the success with paper that it has become with plastic films and some non-woven natural and synthetic fibre textiles? BHS have always invested heavily in the development of wider and faster corrugators and are concentrating on potential economies, so they teamed up with a top University research group and paper technologists to explore the boundaries.

A direct approach was taken, straight to the heart of the matter in hand – the single facer bond between the newly formed flute tips and the liner. This is a brave start, given that the requirement is to establish a viable bond between the two papers within a minutely short period of time – at a machine speed of 300 metres per minute. The time span that the papers are within the influence of the ultrasound projector, or sonotrode, is less than 0.2 milli seconds (0.0002 s). This is no less than the time available on the pressure roll type conventional single facer, though the paper is preheated in that case, and one of the objectives for ultrasound welding is to eliminate the need for residual water (which currently carries the starch) which always carnes the danger of affecting the flatness of the board.

At the outset of the research programme into the potential of ultrasound welding, the following benefits were deemed reasonable expectations compared with the current conventional corrugating process:

- elimination of starch and its affendant water portion
- elimination of corrugating roll heating
- reduction of warp
- elimination of unbonded single-face on restarting after stoppage

The Ultrasound Equipment

For practical reasons, this research project was confined to the use of either longitudinal or roll-type sonotrodes (see Fig 1).

To put this in context, ultrasonic oscillation in a material is created by the welding unit – which consists of the ultrasonic generator, a converter, a booster and finally the sonotrode. The ultrasound generator initiates the wave and with the converter, the initial amplitude and wavelength are continuously monitored and controlled (uncontrolled amplitude growth could seriously damage the complete system). The booster magnifies this amplitude to achieve the requisite oscillation amplitude at the sonotrode, which is the output end of the system and has to be tuned (as does the booster) to the resonance wavelength in order to resonate. The titanium matenal Ti-6AI-4V is often used to reach the highest oscillating amplitude. The ultrasonic resonance is mechanical and must be directly transmitted through pressure contact, directly on the material, to be welded against a backing anvil. In this case, the anvil is the rotating upper corrugating roll.

The Papers

Paper as a material is based on cellulose fibres which do not have thermoplastic characteristics. The suitability of many plastics to ultrasonic welding is due to their inherent thermoplastic features and their reaction to the localised heating at the bonding point as a result of the dissipation of the oscillation energy. So, a search was on for another characteristic which could establish bondability between two papers.

As a preliminary to the project, tests were carried out on different paper grades with variations in certain process parameters to determine the suitability of ultrasonic welding to bonding paper layers and to understand and clarify the bonding mechanisms. Paper research institutes were approached to produce purpose-made samples and the results

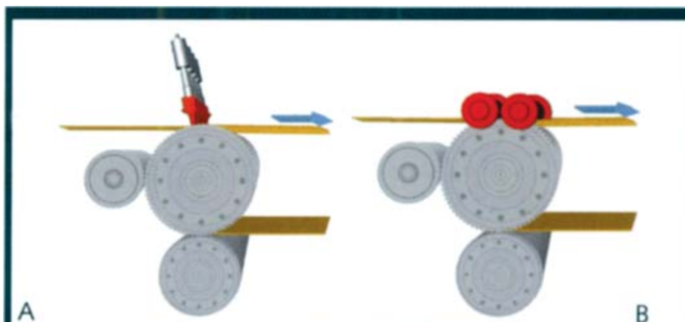


Fig. 1: Concepts for ultrasound welding to bond fluting medium and liner in the Single Facer
A) Longitudinal sonotrode concept B) Roll sonotrode concept

combinations of paper samples	1	2	3	4
liner	test liner	test liner	test liner	liner
weight in g/m2	120	210	135	120
caliper in mm	0.18	0.28	0.2	0.18
fluting medium	medium	medium	medium	medium
weight in g/m2	105	105	135	135
caliper in mm	0.16	0.16	0.2	0.2

of ultrasonic welding tests were analysed. Defined fibrous raw materials (bleached and unbieached pine pulp as well as mechanically ground wood pulp) were produced. These included 100 per cent bleached pulp, 100 per cent mechanical pulp and 50 per cent bleached and 50 per cent mechanical pulp.

Exploratory tests were carried out on samples under different conditions of loading pressure, exposure time and oscillation amplitude – with and without added moisture or starch – in an effort to determine which parameters could really make a difference. Initial results indicated that additional starch and moisture are both essential to achieving viable bonding. It simply was not possible to bond papers, made of pulp alone, by ultrasonic welding.

In a second series of tests, starch in four separate levels of dilution in water were applied to the paper surfaces and ultrasonic bonding was achieved under certain conditions. Peeling resistance tests were used to 'measure' the effectiveness of the bond in every case. The conclusions were broadly that:

- It was not possible, ultrasonicaily, to establish a finn bond in non- humidified papers or those which contain no glue, even if they were rich in lignin.
- It was possible, ultrasonically, to weld humidified papers which contained various levels of starch size. The bonding strength, however, displayed wide variations.

Tests with Common Medium and Liner Papers

A third series of tests involved commonly used medium and liners and measured results of standard corrugated board bonding were used as reference values. The sample combinations in Table 3 were tested for suitability for ultrasonic welding.

In preliminary tests, the ultrasound exposure period, static welding pressure and oscillation amplitude were varied to limit the variations required in process parameters. The test series which followed used dry papers (natural moisture content 5-8%) then the same papers with added moisture. The flute geometry was C flute.

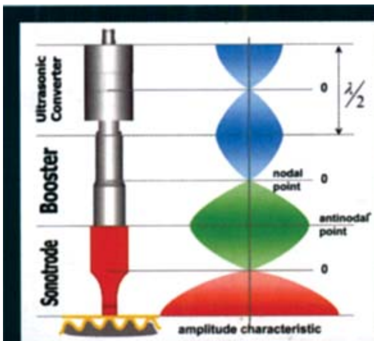
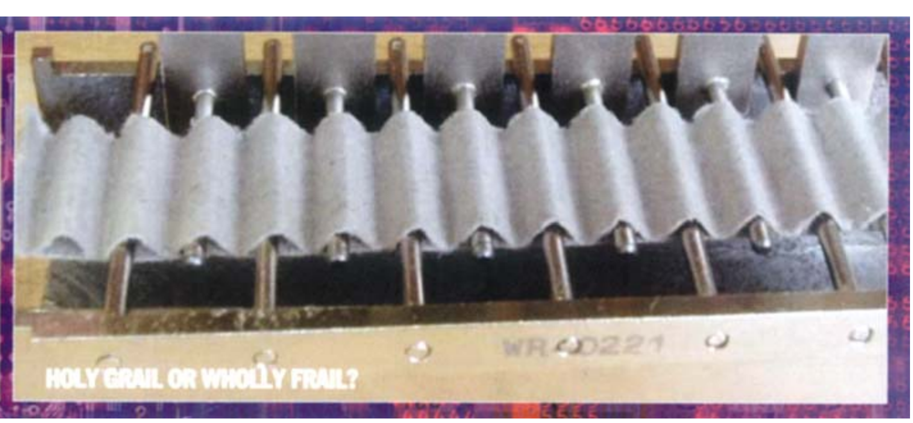


Fig 2: Structure for 'longitudinal' sonotrode and amplitude characteristic.

More than 550 board samples were produced for this ultrasonic test series with the bonding strength determined using the Pin Adhesion Test (TAPPI T821) and statistically evaluated.



The 'dry' tests were carried out first and proved to be limited – between poor bonding at the one extreme and burning the paper at the other. Bonding strength increased with higher contact pressure and with longer time exposure. The best bonding achieved was 26 per cent of conventional glue bond strength at an exposure time of 0.1 seconds – over one hundred times more than that available under normal production conditions.

The 'moist' tests proved more complex. The equipment was limited by the lowest available exposure time setting being 0.06 seconds. These tests showed that the higher bonding strengths were achieved with lower exposure times and higher contact pressures. In one sample, a higher bonding strength than with conventional bonding was reached. Of course, the exposure time is still considerably in excess of that available in daily production conditions. Reducing the oscillation amplitude only has a marginal effect on bonding strength. The summary conclusions from these tests were:

- Moisture is essential to achieving sufficient bonding in commonly used papers, in contrast to the special papers, which under certain conditions (even if unsatisfactory), welding was possible without added moisture.
- Bonding strength varied greatly with the medium and liners used.
- Loading pressure and time exposure to ultrasound both influence bonding strength.

Optical and electronic microscope examination of the welding seams as well as infra-red spectrometry yielded the following:

- The bond strength of ultrasonic welding is significantly influenced by activation of starch in the papers. Moisture is needed in the medium flute tips prior to bonding, allowing the starch to swell and improving starch migration into the paper to key the bond. All tests indicated that with ultrasonic welding of corrugated, conventional starch size in production of medium and liner play a major role related to water addition at the bonding points.
- Interlacing of fibres contributes to adhesion to a minor extent. In the electron microscope picture, fibres can be seen to have moved to a vertical orientation at the seam. The application of ultrasound oscillations could be realigning and weaving the fibres anew. (Figs.6.1 and 6.2)

Fig. 6.1: Moist - bonding liner and medium (optical microscope photo)

Fig. 6.2: Moist - structural fibre bonding (electron microscope photo)

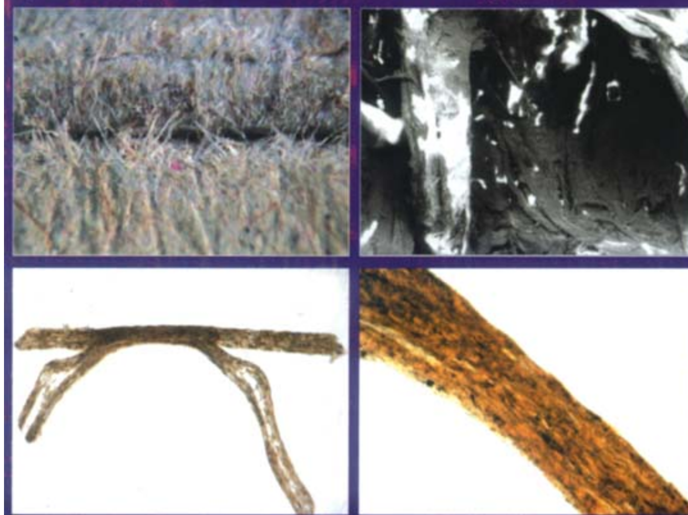


Fig. 6.3: Unbleached pine kraft pulp with surface starch - moistured, (microtome section)

Fig. 6.4: Unbleached pine kraft pulp with surface starch - moistured (microtome section, magnified),

- Any influence of lignin content seems minor.
- Based on past studies, the influence of chemical reactions between free hydroxyl groups in the cellulose fibres on the adhesion between medium and liner is also to be regarded as minor. During welding, the fibres are modified such that they are unable to swell later, suggesting that chemical reactions play at best a minor role in the bonding mechanism.
- Evaluation of microtome sections of humidified papers led to no findings regarding the appearance of cavitation or microjet formation. (Figs. 6.3 and 6.4)

Production Trials. Continuous Welding of Fluting Medium and Liner Using Ultrasonics

There are two different approaches to continuous welding of medium and liner. One has multiple adjacent sonotrodes arranged vertically, in line across the working width, so that when a flute tip passes below this line, ultrasonic oscillations are applied under pressure onto the liner and medium and a narrow welded seam is made. (Fig.1a - longitudinal concept). The second approach is the roll concept (Fig.1 b) in which two

Table 5: Pin Adhesion Test results

	US 'moist'		US 'dry'		Reference sample
combinations of paper samples sample no.	separating force (N)	versus the reference sample	separating force (N)	versus the reference sample	separating force (N)
1	36	141 %	4.5	18 %	25.5 - 100%
2	21	44 %	12.3	26 %	47.5- 100%
3	42	92 %	8.8	19 %	45.6- 100%
4	27	70 %	6.8	18 %	38.7- 100%

(Contd. on page 15)

(Contd. from page 11)

or preferably three roll sonotrodes can be arranged around the circumference of the corrugating roll. While oscillating axially, the rolls are designed to induce a radial oscillation and thus a 'pressure' oscillation in the paper. The radial effect is however limited to certain sections of the sonotrodes' length, which is why more than one sonotrodes offset axially to each other are required. The fluting medium is humidified in both cases.

On the basis of the preliminary static tests, a seemingly suitable medium-liner combination was chosen and the welding parameters – pressure, gap between sonotrode and corrugating roll and oscillation amplitude – were set. Since the static tests had shown up considerable temperature increases, both in the paper and the sonotrode, an infrared camera was set up to record temperatures during the continuous trials (Fig.8). It transpired that as running speed increased, so the measured paper temperature decreased and that additional heating of the paper was necessary to improve bonding strength. It was also deduced, on the strength of past experience, that flute formation without heating of the medium only produces adequate and consistent flute formation at relatively low speeds and with special papers. So, for all practical purposes, the corrugating rolls have to be heated for ultrasonic welding, just as they are with conventional production of single faced board.

Two basic findings resulted from tests using unheated corrugating rolls. One was that continuous ultrasonic welding did not form a successful bond without additional humidification of the medium. Probably, the natural moisture content of the paper (5-8%) is insufficient to reactivate surface starch in the papers during the extremely short contact time between sonotrode and flute tip (fig. 9). The second was that viable bonds could be made only with added moisture in the fluting medium, but the strength of the bond progressively fell as the speed increased. This was clear from both peeling and Pin Adhesion Tests (Fig 9 and 10).

Even at low running speeds, bonding strength values show wide variations, Indicating major quality variations during the procedure (Fig. 10). This can be explained by the low frequency vibration induced in the sonotrode by the repetitive passage of flute tips and valleys under the sonotrode (a hard anvil followed by unsupported paper). This superimposed low frequency vibration interferes with the ultrasonic oscillations, which not only imposes a mechanical stress on the sonotrode itself, but also stresses the piezo ceramics in the converter to an extreme level. This can result in periodic variations in the gap between sonotrode and corrugating roll with consequent effects on bonding quality.

The reduction in bonding strength at speeds over 10 m/min can be due to shorter welding exposure periods. Although the performance increases, the oscillation energy applied to the seam decreases with the reduced contact time (fig. 12). The times per flute tip are still at about 0.005 sec at a running speed of 10 m/min. Extrapolating to 200 m/min, the time falls to 0.0003 secs. This can be compared to the satisfactory bonding in static tests needing more than 0.06 sec.

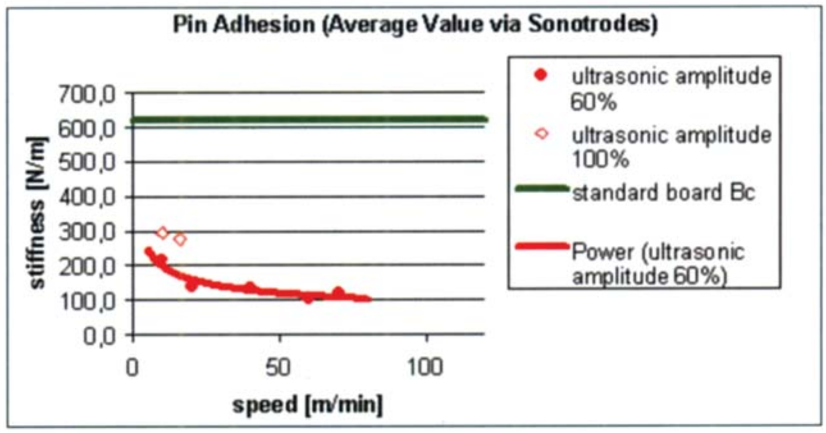


Fig. 11: Effects of web speed on bonding strength PAT

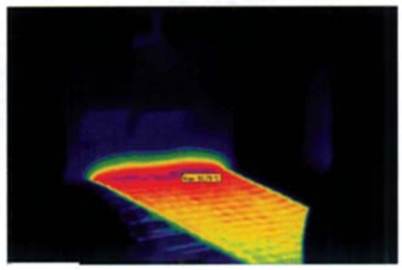


Fig. 8: Infrared thermal scanner image during ultrasonic welding

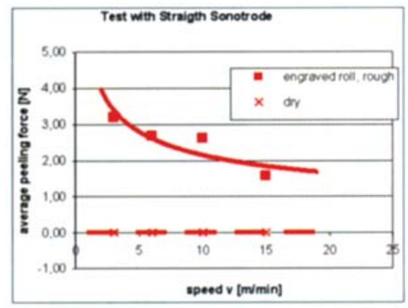


Fig. 9: Effects of web speed on bonding strength

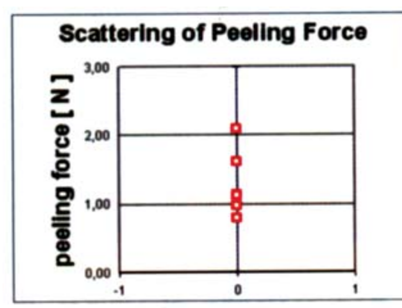


Fig 10: Reproductibility of ultrasonic bonding considering peeling force scatter.

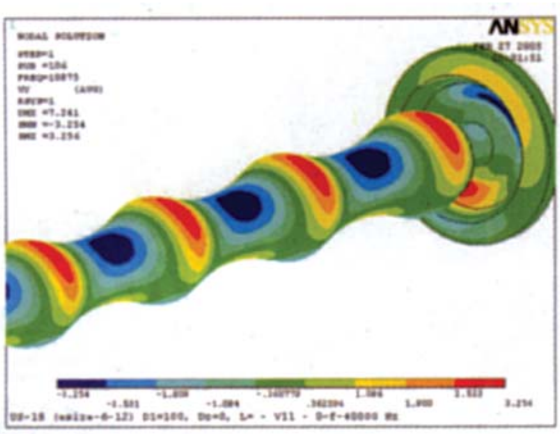


Fig. 7: Finite Element Method (FEM) simulation for roll sonotrode

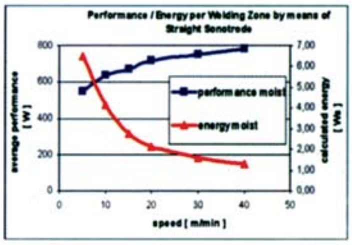


Fig. 12: Increase of performance by the Converter and decrease of the oscillation energy realised at the welding seam with increasing paper speed.

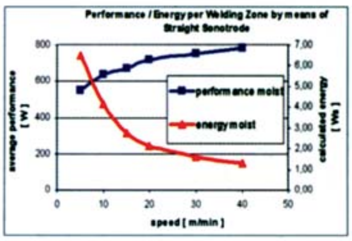


Fig. 13: FCT vs. speed

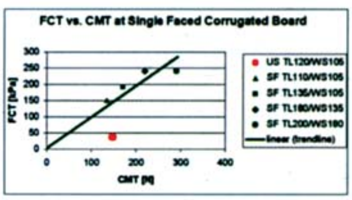


Fig. 14: FCT vs. CMT (Concora) compared to conventionally produced single-faced corrugated board.

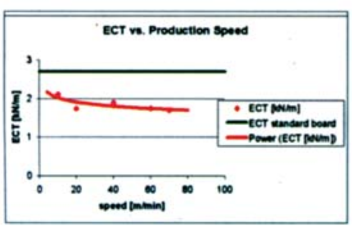


Fig. 15: ECT vs. production speed

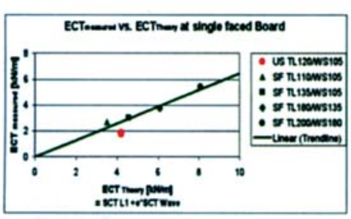


Fig. 16: ECT compared to conventionally produced single-faced board

The mechanical board strength values ECT (edge crush) and FCT (flat crush), which are frequently used to evaluate board quality, are not much influenced by the bond qualities achieved by ultrasonic welding. FCT shows a decrease from 140N to 40N with increasing running speed, but this is probably due to the poor flute formation in unheated corrugating rolls (figs. 13 and 14).

The ECT does not decrease significantly with increasing production speed (figs. 15 and 16). The crush value of board tends to be more dependent on the SCT values of the papers and the take-up factor than the bond strength.

Summary and Conclusions

The tests revealed the following:

- The use of papers containing starch glue is a must. Bonding strength depends significantly on the paper grade used.
- Additional moisture must be added to the flute tips, as the natural moisture content of the paper is insufficient to achieve a viable weld.
- Production trials showed that bond strength reduced as running speed increased.
- The mechanical properties of the board in terms of ECT and FCT are below those of conventionally produced board.
- Thermal problems can be expected during continuous running with heated rolls, in that the temperature sensitive piezo unit would need cooling.
- Vibration induced in the ultrasonic unit by the passage of flute tips can damage the sonotrode, booster and converter. It will be highly failure-prone.
- The sonotrode is expensive to produce and wears as a result of the pressure contact with abrasive paper. This will adversely affect running costs.
- It proved impossible to make the double facer bond ultrasonically. It will still have to be made in the conventional manner with starch adhesive and hotplates.

The possibilities of applying ultrasonic welding principles to corrugated board were quite comprehensively explored. The system achieved bonding but the restrictions on paper selection and running speed, the high cost of maintaining or replacing titanium sonotrodes, the requirement to continue applying moisture and heat to the medium – all coupled with the inability to apply the same principles to the double facer bond – clearly render ultrasonics unsuited to this application. Even under static tests, results varied considerably. Heat is still needed for satisfactory flute formation and as a tool for warp control. If ultrasonic welding cannot work without supplementary heating and can only be applied to the single facer bond, there seems little chance of it offering sufficient advantage to be worth considering for the conventional corrugating process. It could be of interest in some specialist niche product applications, especially in small width. Fire risk would have to be guarded against.

The cold corrugator would appear to be no nearer practical reality – in spite of new technology. This is largely down to the nature of paper and the importance of recyclability.

This article is adapted by Tony Pinnington from the paper "Use of Ultrasonic Welding for production of single-faced corrugated board" by dipling. Norbert Staedele (Technical Director, BHS Corrugated GMBH, Germany) and Professor Dr. -Ing.Claus Schliekmann (Regensburg University of Applied Science).

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