FPCM-6 (2002)
The 6th International Conference on Flow Processes in Composite Materials
Auckland, New Zealand
15 ~ 16 Jul. 2002

PROCESS ANALYSIS OF ROLL FORMING OF THERMOPLASTIC COMPOSITES

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SUMMARY: Roll forming as a production route to produce a large variety of profiles from sheet metal has found widespread use in many industries due to its high productivity. By adopting this technology to be used with fibre reinforced thermoplastic composites, long components which possess all the performance advantages inherent to thermoplastic composites can be formed in an economically efficient manner. After adopting the process technology to be used with thermoplastic composites, textile reinforced composite sheet materials, GF/PP and GF/PA66, were successfully formed into top-hat sections. The ability of crystalline thermoplastics to be formed below melting temperature upon cooling from the melt is exploited. Special attention had been given to the tool design with respect to forming behaviour of continuous fibre reinforced composites. Shape conformance of the profiles is primarily affected by the inlet temperature of the sheet into the first roll station and the exit temperature from the last one. The temperature profile and the process layout have to be modulated to each other as a function of process speed and material properties in order to produce profiles of high geometric quality. Process speeds of up to 10 m/min could be realised with the available roll forming line.

KEYWORDS: Roll Forming, Sheet Forming, Thermoplastic Composite, Fibre Reinforced, Processing

INTRODUCTION

The availability of so called organic sheets, eg. by a continuous double belt press production procedure and their ability to be shaped by application of heat and rather low forces fuelled the commercial interest in economically more efficient and reliable thermoforming operations in order to take advantage of the potential for fast processing. In recent years significant progress has been made in the development of forming techniques for continuous fibre reinforced thermoplastic (CFRT) consolidated sheet feedstock, some of them being adoptions from one of the most sophisticated industries, sheet metal forming. In case of sheets metals, roll forming is one of the most productive processes and hence it has found widespread use in a variety of industries. Due to its versatility and high process speeds, roll forming has been quickly recognised as an interesting technique for production of light weight, corrosion resistant, (semi-) structural, long narrow profiles in an economically competitive manner. However, it has only been adapted little more than a decade ago [1-3]. In spite of the work done, compared to other forming operations it has so far been given rather little attention by research.

PROCESS TECHNOLOGY

In roll forming the cross-section of a plane sheet is progressively deformed into some desired shape by passing through a succession of rotating rolls arranged in tandem. Instead of using a strip of material, frequently coiled sheet feedstock is being used, Fig. 1. According to DIN 8586 it is classified as a continuous bending operation with rotary die motion.

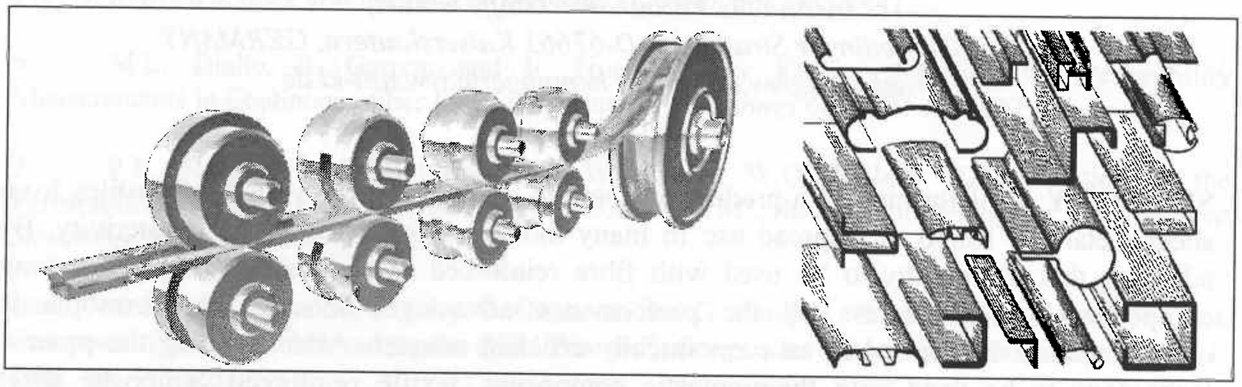


Figure 1 Schematic of roll forming operation and typical roll formed profiles

The most significant advantages of the process which contributed to its widespread use in sheet metal forming are its high productivity due to (semi-) continuous operation and high process speeds as well as the variety of shapes that can be manufactured. The processing speeds are mostly dependent on the complexity of the shape to be produced, which ranges from open section to more complex closed sections which go beyond the capacity of press forming. (Semi-) continuous forming allows to produce parts of any desired length, only limited by handling and shipping capabilities. Numerous "secondary" operations such as cutting, punching, curving and even joining can be incorporated online without stopping the process. However, the process requires the cross-section to be constant throughout its length and the feedstock must be of uniform thickness. The operating efficiency lies in the range of medium to large batch sizes due to tool cost and in particular time consuming set-up until a profile leaves the machine in desired quality [4,5].

Process Adoptions for Thermoplastic Composites

A commercially available roll forming line has been purchased and modified for the use with thermoplastic composite materials. Top and bottom rolls are driven by chain and sprocket and the speed is infinitely variable.

While sheet metal is being cold roll formed, thermoplastic composite materials need to be heated above the melting point of the matrix resin prior to forming. Therefore the basic machine unit, which can also be used for forming light gauge metals, was extended by a heating line. Medium wave length infrared radiator fields were employed to allow fast and contactless heating of the organic sheets. The material supply towards the forming stations was realised by a stainless steel mesh with a net width of 5 mm in order to allow for double sided heating. Sideways guides were used for accurate positioning of the sheets. The surface temperature of the sheets was measured at different points throughout the process by infrared thermometers.

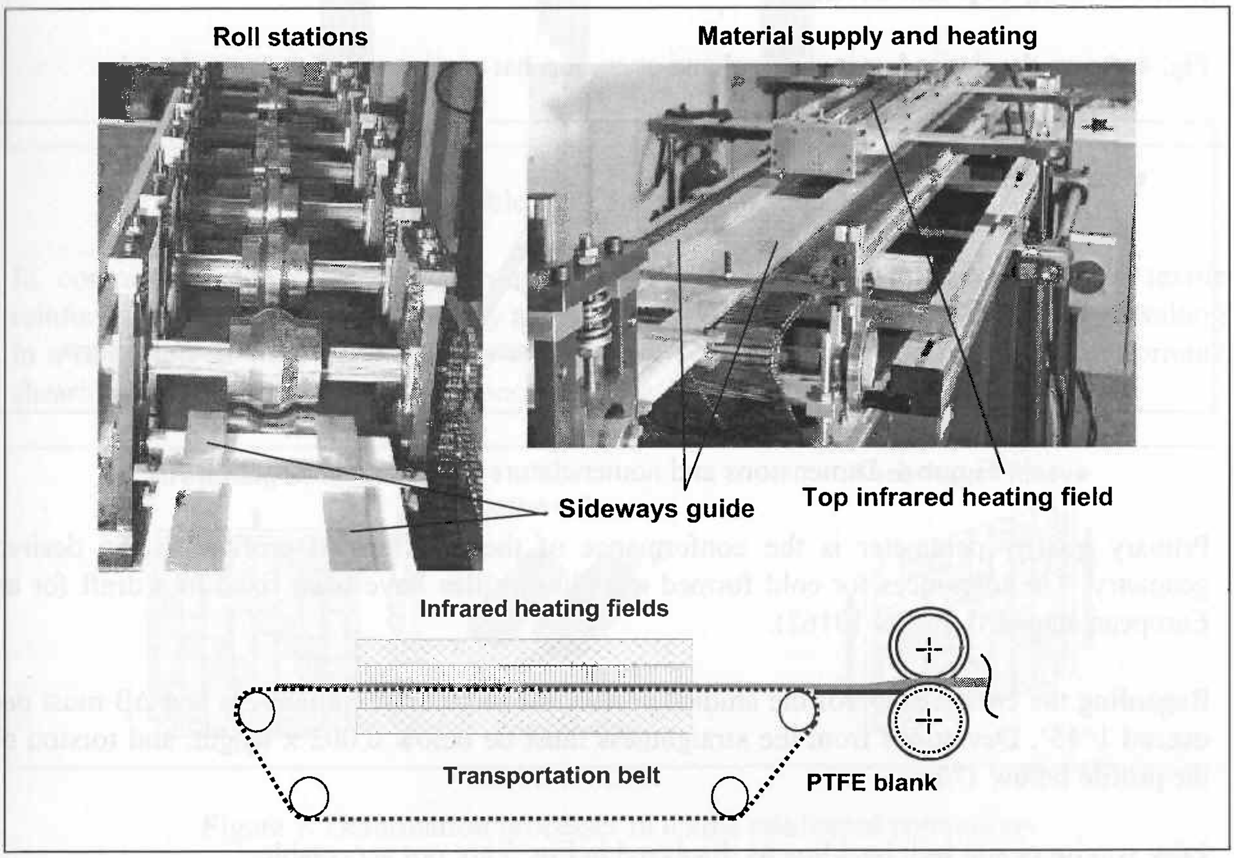


Figure 2 Roll forming line with infrared-heating and material supply

Forming Behaviour

During roll forming the sheet requires a complex three dimensional shape while gradually deforming over the deformation length until the geometry of the gap between a pair of forming rolls. Not only transverse bending is taking place, but also undesired stresses in longitudinal direction which limit the degree of forming per stage.

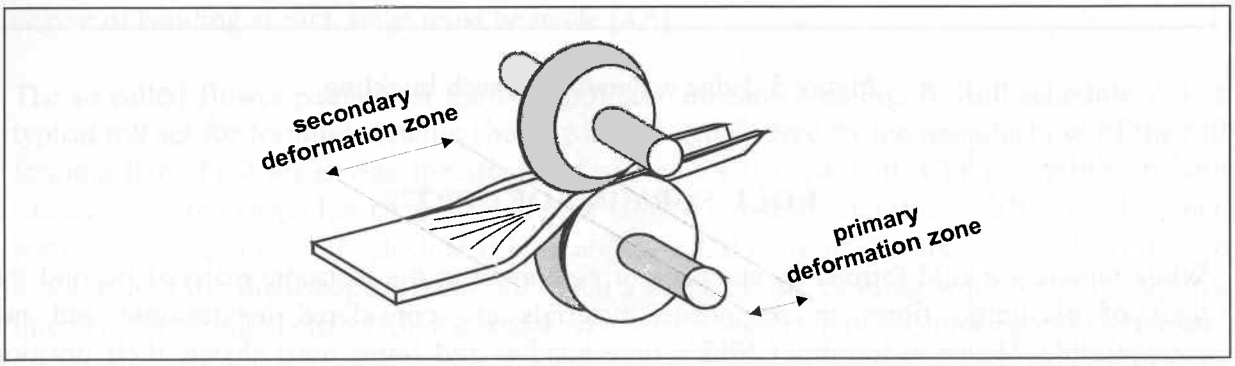


Figure 3 Schematic of the deformation process

Due to the exceptional complexity of the forming mechanism a comprehensive analytical description of the roll forming process has not been achieved in spite of intensive research activities in this field. Hence the practice of roll forming is heavily relying on empirically gathered knowledge.

Roll Forming Top-Hat Sections

Fig. 4 shows the desired, symmetrical and open, top-hat section which was produced.

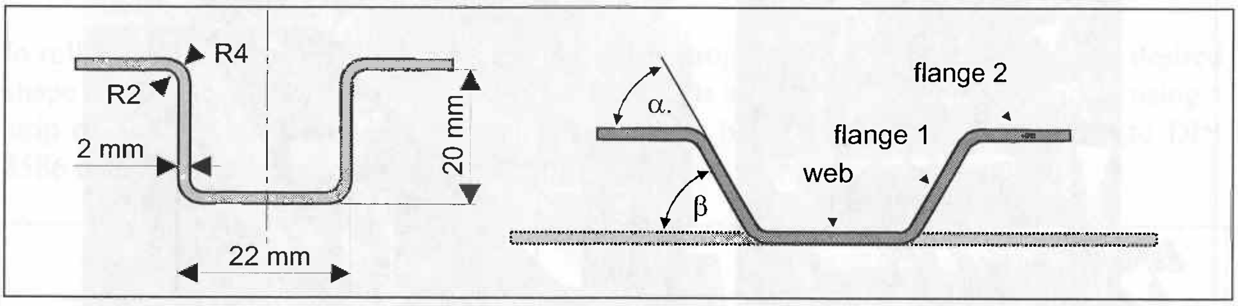


Figure 4 Dimensions and nomenclature of roll formed section

Primary quality parameter is the conformance of the roll formed profiles to the desired geometry. The tolerances for cold formed metallic profiles have been fixed in a draft for an European standard (pr EN 10162).

Regarding the cross section of the studied profile, the angular deviations $\Delta\alpha$ and $\Delta\beta$ must not exceed 1°45'. Deviations from the straightness must be below 0.002 x length, and torsion of the profile below 1°/m.

Edge waviness and web buckling as displayed in Fig. 5 are not acceptable.

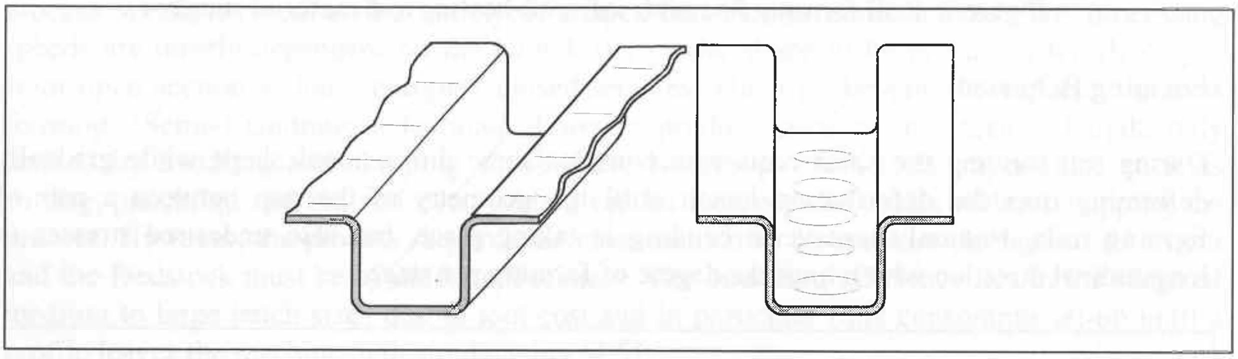


Figure 5 Edge waviness and web buckling

ROLL FORMING OF CFRT'S

While metals are cold formed by stressing or compressing the isotropic material beyond the limit of elasticity, fibres in composite materials are considered inextensible and not compressible. Hence in forming CFRT's fibre bundles and fibres must change their position relative to each other. Interply-slip is the most important process in a mostly two-dimensional bending operation in order to avoid fibre buckling and delamination or fibre breakage.

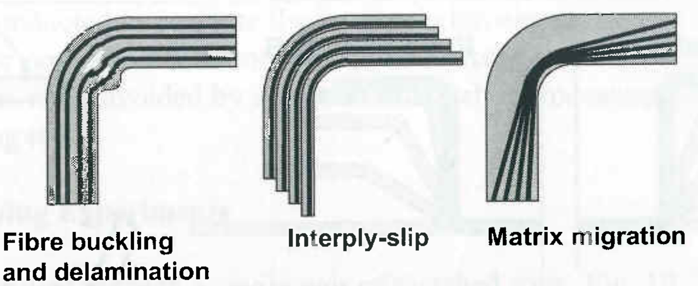


Figure 6 Possible fibre distributions after forming

In contrary to laminates build from several unidirectionally reinforced layers, textile reinforced composites have the ability to react to stresses by stretching of the weave, resulting in a reduction of fibre bundle crimp and compression of the fibre bundles. In roll forming shearing of the weave only plays a minor role, Fig. 7.

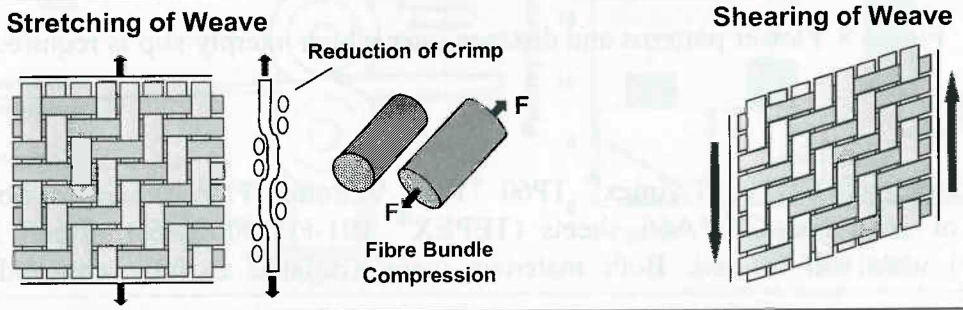
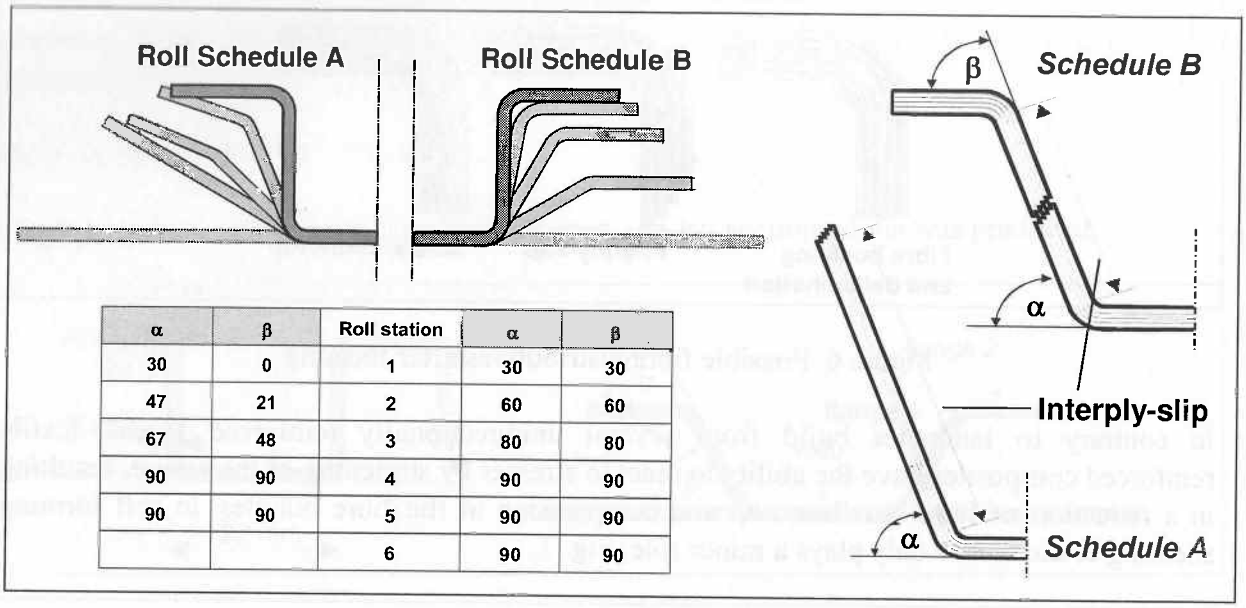


Figure 7 Deformation processes in textile reinforced composites

Tool Design

Fundamental of every successful roll forming process is the design of the forming rolls. General design criteria known from sheet metal forming is applicable. For example, the roll diameters were selected as large as possible as the height of the roll stands permit for a smooth material flow. Available CAE-systems offer significant support in by performing calculation routines in the construction of the rolls, but can not generate independent solutions. Hence, the experience of the designer inevitable since a final section can be produced by numerous deformation routes. Decisions about sequencing of bends and the degree of bending at each stage must be made [4,5].

The so called flower patterns of the two tool sets are shown in Fig. 8. Roll schedule A is a typical roll set for forming metallic sheets which was delivered by the manufacturer of the roll forming line. Tool set B was specifically designed for the use with CFRT's. While in both cases the desired shape has been formed after stage 4, the most significant difference between both sets is that in case of schedule B both angles α and β are uniformly increased from stage to stage until the final shape is achieved. Such a design of the bending sequence only requires interply-slip along flange 1 of the sheet. By such a flower pattern, process reliability and conformity of the produced profiles was enhanced. This was attributed to a reduction of the likelihood of obstructions in inter-ply slip due to the shorter leg length over which this deformation mechanism has to occur.



α	β	Roll station	α	β
30	0	1	30	30
47	21	2	60	60
67	48	3	80	80
90	90	4	90	90
90	90	5	90	90
		6	90	90

Figure 8 Flower patterns and distance over which interply-slip is required

Materials

Textile reinforced GF/PP (Twintex® TP60 710C, Vetrotex, France) with a fibre volume fraction of 35% and GF/PA66 sheets (TEPEX® 101-FG290(8)/46%, Bond Laminates, Germany) were roll formed. Both materials were available as fully consolidated sheet feedstock.

Upon cooling from the melt, semi-crystalline polymers can be formed well below melting point T_m, as can be seen in Fig. 9. The thermoplastic resin is in the state of a supercooled liquid melt. The higher the cooling rate of the melt, the lower the recrystallisation temperature. However the width of the processing window shows no difference between GF/PP and GF/PA66 and remains mostly unaffected by the cooling rate.

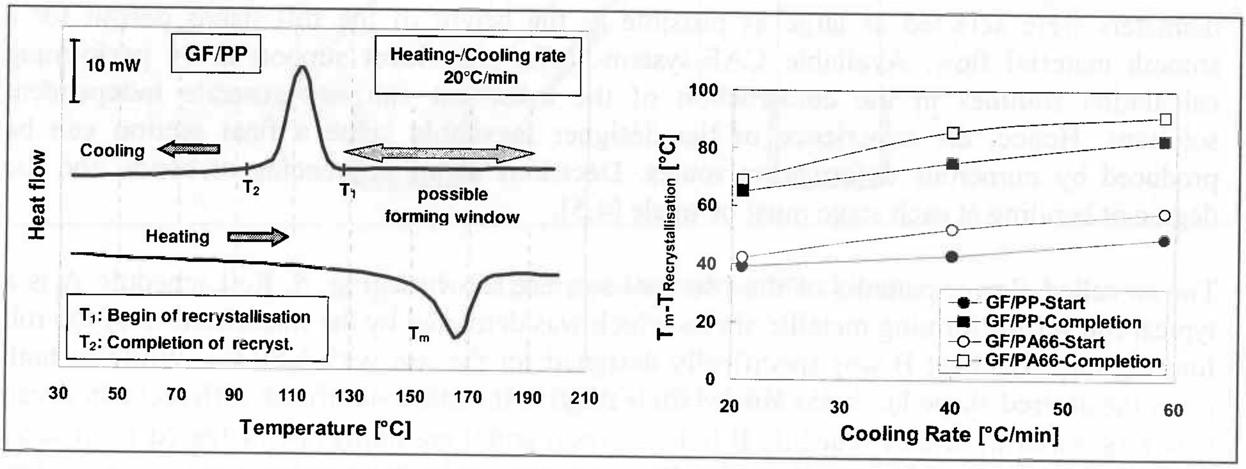


Figure9 DSC curve of GF/PP and cooling of GF/PP and GF/PA66

While fibre reinforced thermoplastic composites are usually formed above T_m, the large processing window is exploited in roll forming where forming occurs in several steps

Experiments were conducted to evaluate the heating behaviour in the infrared radiator field as a function of radiator power and radiator to composite distance. Excessive overheating of the laminates surface has to be avoided by selection of suitable processing parameters and hence is limiting the heating rate.

Fundamental Forming Experiments

Heated sheets were pulled through a single pair of matched rolls, Fig. 10. The results gathered found consideration in the layout of the process. With the aid of a load cell the required force was measured and also the deformation length was registered as a function of temperature, processing speed and geometry of the rolls.

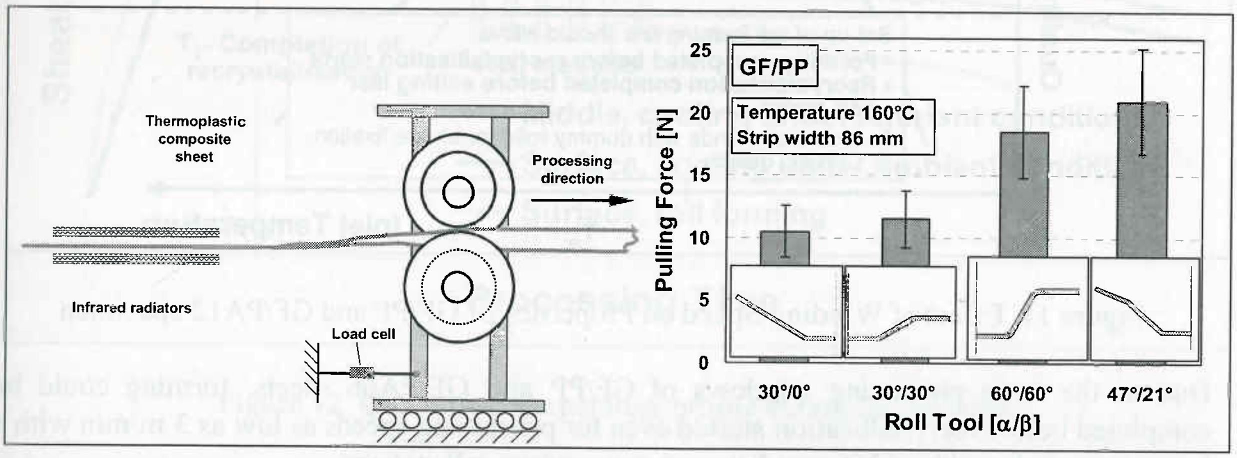


Figure 10 Schematic of the experimental set-up and influence of shaping rolls

The idea behind the measurement of the force to pull a sheet through a pair of profiled rolls is the concept of minimum energy, implying that for best forming results the total energy for bending and stretching should be minimised.

Quality assessment

Roll forming being a multi stage forming operation the temperature profile of the sheets must be closely controlled throughout the process. Entry and exit temperature of the continuous fibre reinforced thermoplastic sheet were found to be the decisive processing parameters with respect to shape conformance, as was already pointed out to for laminates from unidirectionally reinforced layers in [1-3].

As already mentioned the use of roll schedule A where the angles α and β are uniformely formed delivered improved results compared to schedule B. For the studied top-hat section best results were obtained if the inlet temperature of the sheets was approximately 20°C below T_m, also depending on the roll forming speed. Besides improved shaped conformance, in particular the failure rate could be reduced. For higher inlet temperatures frequent sideways tracking in combination with severe torsion of the sheet was observed in the first two forming stages in spite of the feeding system into the first roll station with the sideways guides for positioning. In these cases forming could not be completed. In addition a high degree of edge waviness had to be accepted if the inlet temperatures were higher than appropriate. For inlet temperatures above Tm edge waviness became so severe that frequently the sheet was folded back onto itself resulting in the sheet getting stuck between the rolls.

On the other hand, if the inlet temperature is too low, interply-slip was aggravated in the latter forming stations resulting in fibre buckling and delamination, Fig. 11.

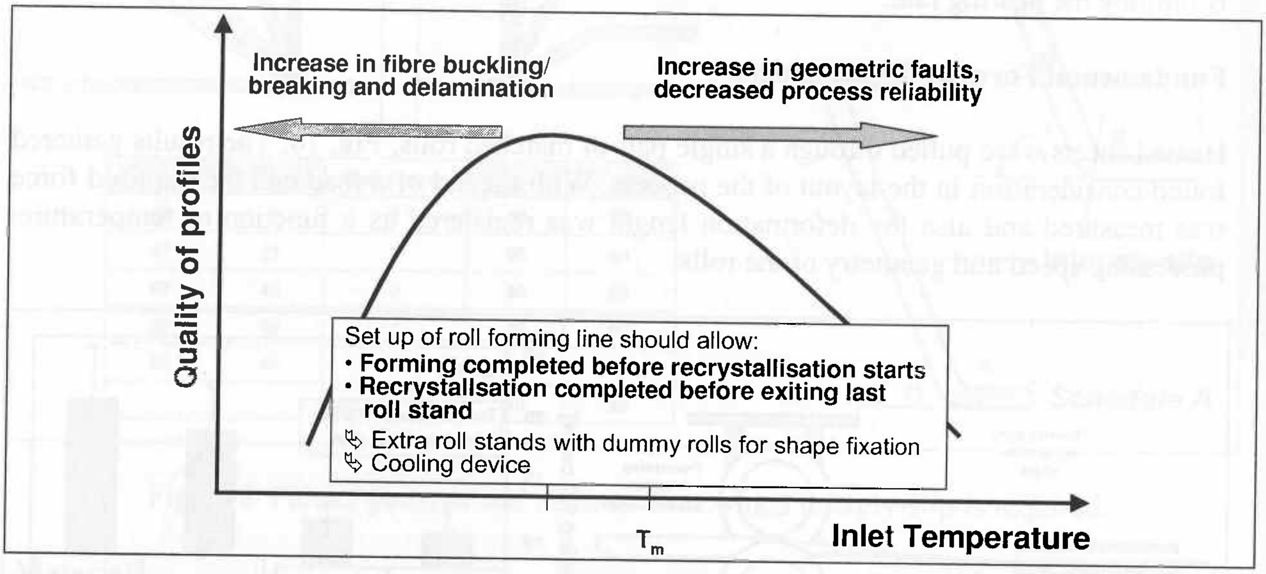


Figure 11 Effect of Winding Speed on Properties of GF/PP and GF/PA12 specimen

Due to the large processing windows of GF/PP and GF/PA66 sheets, forming could be completed before recrystallisation started even for processing speeds as low as 3 m/min with a horizontal pitch width of 265 mm between consecutive roll stations.

With an inlet temperature ca. 20°C below T_m, roll station 4, as the final forming station, must be passed before cooling another 20°C of the sheet has occurred; given recrystallisation begins approximately 40°C below T_m for GF/PP and GF/PA66, Fig. 9.

With processing speeds of up to 10 m/min realised, a limiting factor was found to be the necessity to cool the profile before exiting the last pair of extra rolls for shape fixation below the temperature for which recrystallisation upon cooling is completed. If the profile has not yet crystallised to a large degree there is a strong tendency for relaxation of the sheets accompanied by angular deviation. Recrystallisation of the matrix is completed about 40°C below the temperature when it was initiated (Fig. 9). This temperature reduction must be achieved before the second of two extra roll pairs available for shape fixation has been passed in the course of the process. Therefore the pitch width between the last three roll stations was doubled and a water spray cooling installed.

Other important effects of the forming speed than onto the temperature profile during forming could not be detected within the examined range. Hence by addition of further roll pairs for shape fixation the forming speed could be further increased.

Fig. 12 shows a qualitative temperature profile during roll forming. The temperature profile and the process layout have to be modulated to each other as a function of process speed and material properties in order to produce profiles of high geometric quality.

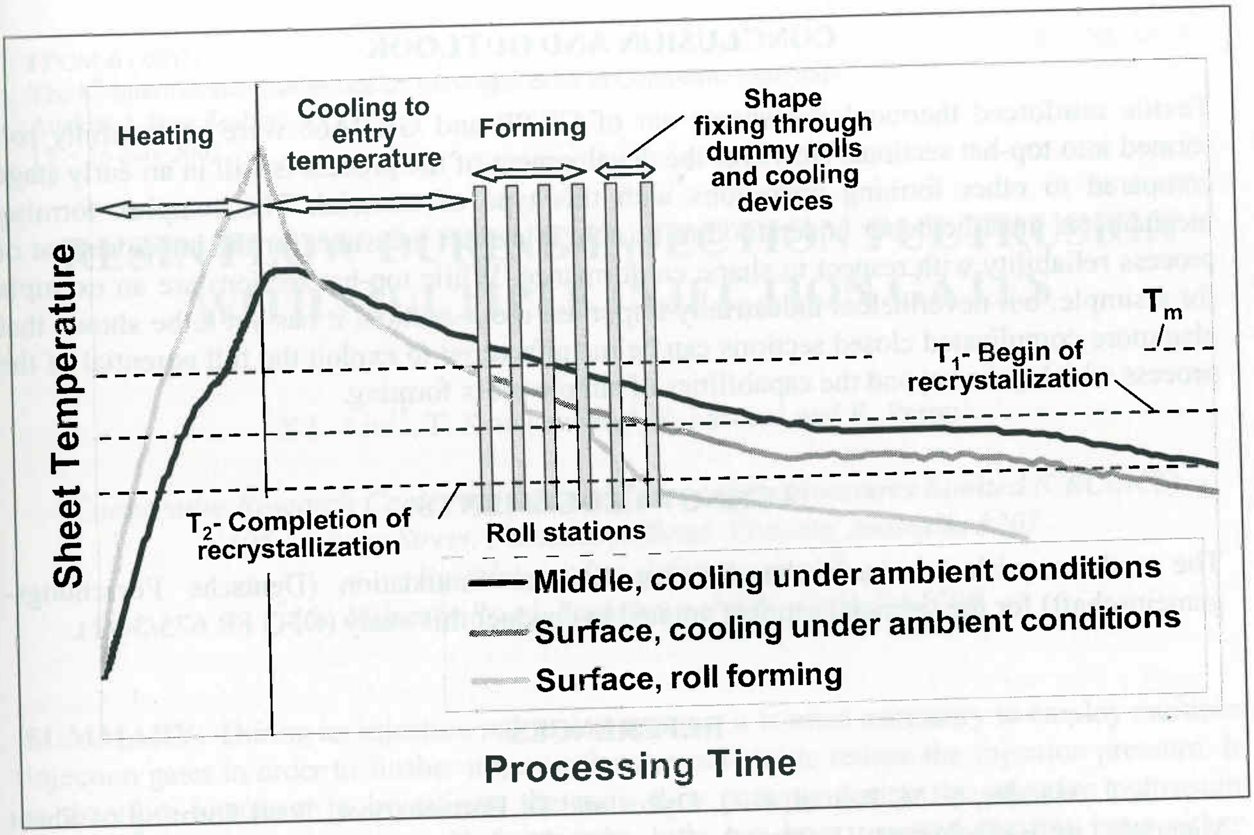


Figure 12 Qualitative temperature profile during roll forming

Fig. 13 shows roll formed top-hat sections which have been produced at a processing speed of 6 m/min. The lower GF/PP profile on the left hand side has been induction welded onto a sheet of the same material to demonstrate the enormous stiffening potential of such an application.

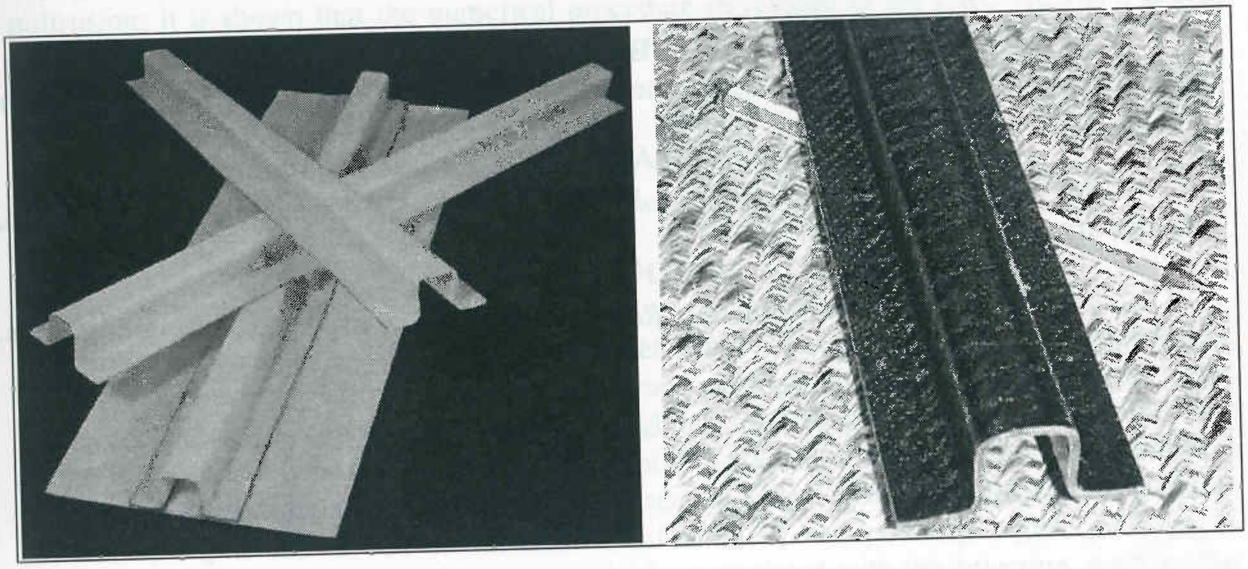


Figure 13 Roll formed GF/PP (left) and GF/PA66 profiles (right)

CONCLUSION AND OUTLOOK

Textile reinforced thermoplastic sheets out of GF/PP and GF/PA66 were successfully roll formed into top-hat sections. However the development of the process is still in an early stage compared to other forming operations with this type of material. The complex forming mechanisms must be better understood to be able to deduct measures for the improvement of process reliability with respect to shape conformance. While top-hat sections are an example for a simple, but nevertheless industrially important cross-section, it has yet to be shown that also more complicated closed sections can be manufactured to exploit the full potential of the process which goes beyond the capabilities of simple press forming.

ACKNOWLEDGEMENTS

The authors wish to thank the German Science Foundation (Deutsche Forschungsgemeinschaft) for the financial support granted to conduct this study (DFG FR 675/30-1).

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