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# Adjustable forming of thermoplastic composites for orthopaedic applications

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The present study was focused on the development of a special thermoforming technique for manufacturing of continuous fibre reinforced thermoplastic composite parts with complex surface contours. In particular, a stamp forming process was modified to investigate the potential manufacturing advantages of thermoplastic composites in orthopaedic applications. An apparatus was designed which allowed the thermoforming procedure to be fully automatic, i.e. a cold pre-consolidated laminate panel, as the feed material, was heated up in an infrared heating zone and then transferred into a cold mould system, where it was stamp formed. Both halves of the mould were made of many tiny round metal sticks in a metal frame. This needle-bed mould allowed one to copy any contour by pushing it slightly on spring fixed sticks. The desired position of these sticks could then be adjusted by forcing the side plates of the metal frame together. To prevent any press mark of stick-tops on the composite, i.e. to achieve smooth surfaces of the themoformed composite parts, flexible rubber pads were needed to cover the mould surfaces. Experimental results showed that the surface profile of CF/PP and GF/PP composites formed by the needle-bed mould reproduced fairly well the contour of a saddle shaped, complex model sample. Unique properties of this needle-bed mould are that it can be repeatedly used, and that it can copy any complex surface contours, for example a bone surface, by simply adjusting the stick positions according to the special surface requirements. © *1998 Chapman & Hall*

## 1. Introduction

Until recently, internal fixation of fractured bones and joints has been managed by metal implants. Besides not being transparent to X-ray beams, e.g. during surgery, a prime disadvantage of metal implants is that the material properties are much stiffer than those of cortical bone, which can aggravate osteoporosis [1, 2]. When a rigid plate is used, the load is transmitted more through the implant than the bone. The load carried by the plated bone is not normal, and losses of bone mass and strength occur. Attempts to circumvent this problem include the use of composite materials as alternatives to metals for structural orthopaedic implant applications [3, 4]; this is because they offer a greater degree of design flexibility, i.e. they combine moderate strength, low cost, and easy raw material availability with the ability to regulate physical properties by design of composition, internal structural arrangement, and processing. Primary applications of composite materials in orthopaedics are artificial ligaments, internal (fracture) fixation plates and hip prostheses [5].

A composite material consists of two or more different phases that are deliberately combined to obtain a material whose properties are a mixture of those of the individual materials. Usually composites contain thermosetting matrices, such as epoxy or polyester, and reinforcing materials such as glass and carbon fibres. New developments have also focused on the use of thermoplastic matrices. High strain to failure, increased fracture toughness, better impact tolerance, short processing cycle time, infinite shelf life of prepreg, recyclability and repairability are some of the reasons cited for the growing popularity of these systems [6]. The most important advantage of thermoplastics, however, may lie in their potential for rapid, low-cost, mass production of reinforced composites [7]. The primary property of thermoplastics is a linear structure of their molecular chains. This means that below the melting/softening temperature they have their relevant mechanical properties; above the melting/softening point, however, they become soft and are easy to process. The existence of a melting/softening point opens up the possibility of producing intermediate forms of thermoplastic composite materials, such as preconsolidated flat laminate panels, that can be processed or post-formed at a later date.

Because patients' anatomies and life-styles are highly variable and, to a significant extent, unpredictable, it is very difficult to design and manufacture an

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implant with an "off the shelf" geometry for an individual patient. For example, Lindhal has shown [8] that a curved bone plate fitted the circular contour of the bone better than a flat one, and it was stronger in resisting bending moments in both the longitudinal and the lateral direction. This means for each "best" bone plate, e.g. to match the special geometry of the bone, a special mould will be needed for individual patients, which obviously increases the manufacturing cost and eventually may limit the use of composite materials in orthopaedy. How to make an implant part more economically is therefore critical to the application of these materials in this field. The present study focused on the development of a thermoforming technique for manufacturing continuous fibre reinforced thermoplastic composite parts with complex surface contours by using an adjustable needle-bed mould. According to similar ideas of other researchers [9, 10], an apparatus was designed which allowed the thermoforming procedure to be fully automatic, including the heating of a cold pre-consolidated laminate panel, as the feed material, in an infrared heating zone, its transfer into a cold mould system, and the final stamp forming process. One unique property of the needle-bed mould lies in the fact that it can copy any complex surface contours by simply adjusting the needle positions according to the special surface geometry of the model sample.

## 2. Stamp forming technique

Thermoplastic stamp forming is a variation of compression moulding, and it is similar to the traditional sheet metal forming process. The consolidated flat laminate is heated in an external heater above the melting/softening temperature of the thermoplastic matrix, and then the hot laminate is quickly transferred into the cold mould where it is stamped to conform to the mould geometry (Fig. 1). The transfer time is of the order of a few seconds to prevent significant cooling. During stamping, the laminate is cooled down under pressure by a cold mould to a temperature below the melting/softening point of the polymer matrix. A typical cycle time (including preheating of the preconsolidated laminate) is about 2–3 min [11, 12]. Because the heated laminate is exposed to a lower environmental temperature before deformation takes place, the use of high closing speeds (as realized by a mechanical or hydraulic press) plays an important role in successful stamp forming. The use of matched metal dies ensures close dimensional tolerances and good surface quality on both sides of the thermoplastic composite part. Metal dies can be internally heated to increase the quality of the final product, and high pressures (if desired) can be applied on the laminate due to the high stiffness of the metallic mould components.

The principal constraint imposed on forming continuous fibre composites is that the fibres can neither be lengthened nor shortened. That means other mechanisms have to be activated in order to finally fit the composite laminate to the complex geometry of the mould; the thermoplastic matrix will act as a lubricant between the prepreg plies and the fibre reinforcements. Fig. 2 shows five fundamental modes of deformation mechanisms in a composite laminate during a typical forming process [13, 14]. Resin percolation occurs when the resin flows through the fibres to the surface or edge of a ply, creating a resin-rich layer. Such resin flow heals any flaws in the structure, and in particular allows bonding between different layers of pre-impregnated tapes. Transverse squeeze flow of matrix and fibres in a direction perpendicular to the fibres is a very important deformation mechanism. It can result in ply thickness variations being dependent upon the pressure distribution. When a laminate is formed onto a curved surface the laminate must be deformed in such a manner that interply slippage can account for the gradual change in shape. If the laminates plies are not allowed to slip relative to each other to account for the shape change, wrinkling and buckling of the fibres can occur, since the fibre cannot be compressed. Clearly, this mechanism is essential in practical forming applications. Intraply shear is needed when a shearing strain occurs in the plane of the lamina, thus allowing part conformity to geometries with complex curvature. Interlaminar rotation is required for the forming of multi-ply laminates. This shear action occurs in a thin "resin-rich layer" that forms at each lamina surface during consolidation due to resin migration. Most parts with complex curvatures require a change of the initial fibre orientation between adjacent plies.

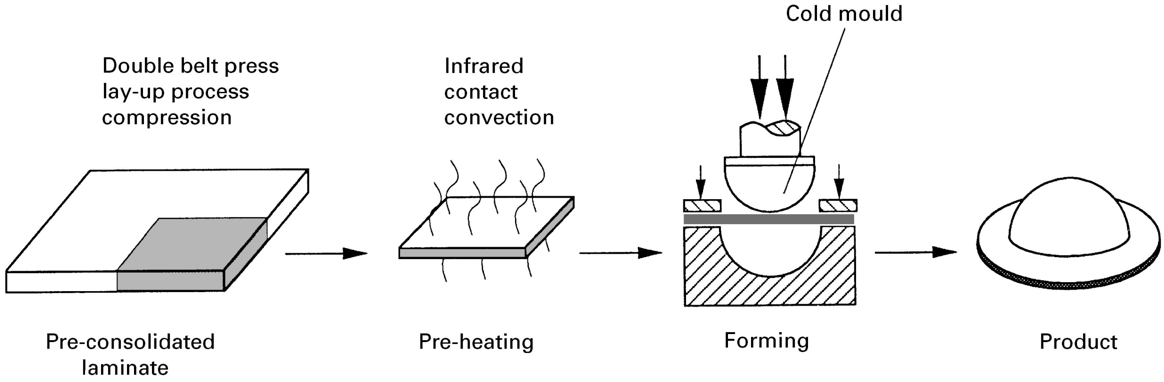

*Figure 1* Schematic illustration of the stamp forming procedure.

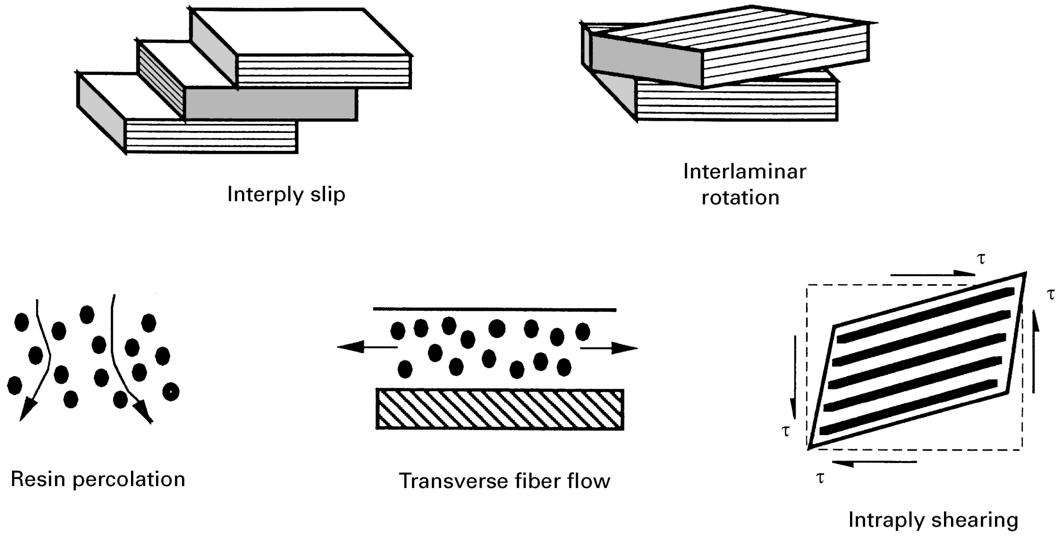

*Figure 2* Flow mechanisms in pre-impregnated composites during thermoforming.

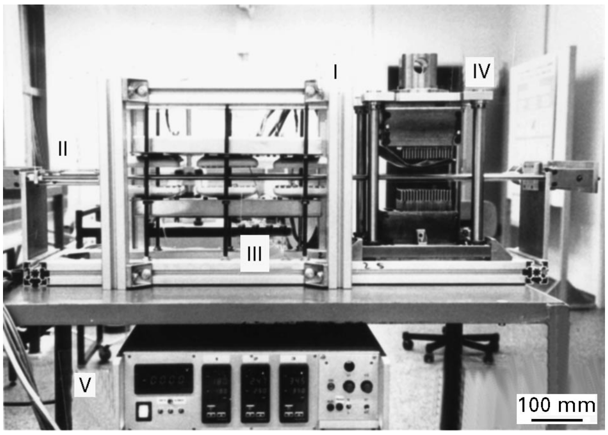

*Figure 3* Processing line of the thermoforming apparatus: I: Machine frame; II: Loading of transport sledge; III: IR-heating zone; IV: Needle-bed mould; V: Control system.

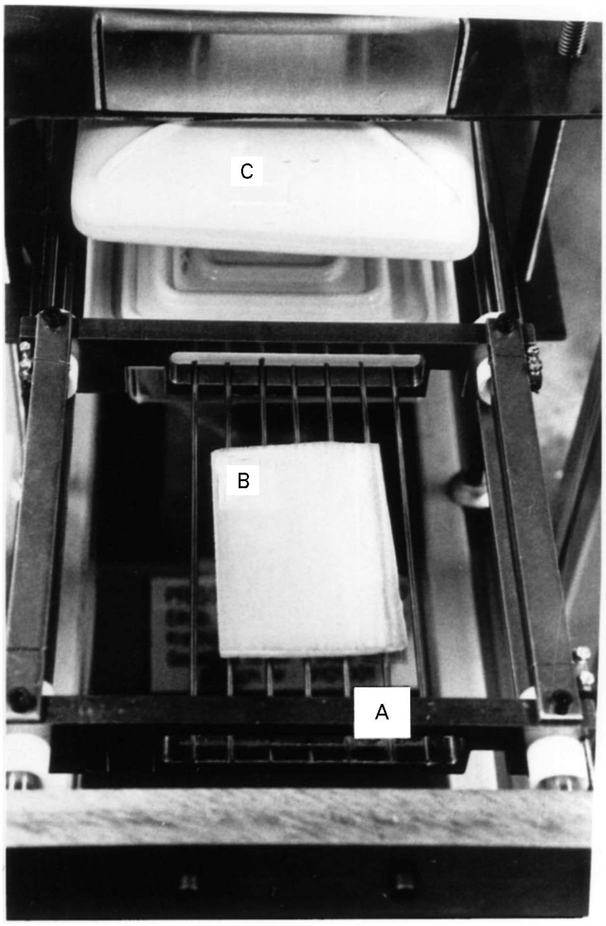

*Figure 4* Transport sledge (A) with flat laminate (B) and IR-heating plates (C).

## 3. Design of the themoforming apparatus

Fig. 3 shows the thermoforming apparatus (I), which had dimensions of 110 cm × 40 cm × 40 cm (length × width × height); it contained a transport sledge (II), an infrared heating zone (III), a needle-bed mould system (IV) and a temperature/transport speed control system (V). This apparatus was designed so as to allow the heating and transport procedure to be fully automatic. A cold pre-consolidated laminate panel, as the feed material, was placed on the transport sledge which could be moved along two parallel guiding steel rods fixed in the length direction of the apparatus (Fig. 4). The sledge was driven by a direct current electric motor connected via a steel wire. Transport speed and direction could be controlled by changing the current direction and intensity at the electronic motor. There were three heating stations in the heating zone; each station consisted of a pair of infrared heating plates with a capacity of 1200 W. The distance between two heating plates could be arbitrarily changed in each station. The pre-heating temperature could be controlled by either adjusting the input power of the infrared plates or the distance between them. When the transport sledge moved through these heating stations, the composite laminate on it could be gradually heated to a desired forming temperature. At

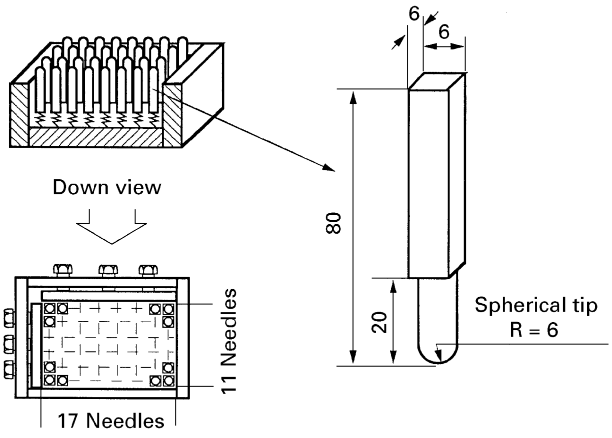

*Figure 5* Construction of needle-bed mould.

the end of the heating zone, the hot laminate was dropped into the needle-bed mould.

The construction of the needle-bed mould is shown schematically in Fig. 5. Both halves of the mould were made of many tiny round metal sticks in a metal frame and used as male and female part, respectively. When the mould was closed, the surface contour formed by the tops of these metal sticks acted as the forming surfaces to press the hot laminate to the desired geometry. As shown in Fig. 5, there were 187 metal sticks in each metal frame. Each stick has a spherical tip with a radius of 3 mm and a total length of 80 mm, of which 60 mm has a square cross–section (6 mm × 6 mm) and 20 mm has a circular cross–section (diameter 6 mm). All sticks were connected individually through a spring with the bottom plate of the metal frame giving a forming area of 102 mm × 66 mm. This needle-bed mould allowed one to copy any contour (smaller than this cross-section) by pushing it slightly on the spring fixed-needles. The position of these sticks could be fixed by forcing the side plates of the metal frame together through 12 screws. The needle-bed mould was designed according to the criterion that the forming surface could resist a press load of 30 kN. The unique properties of this needle-bed mould lie in the fact that it can be repeatedly used and can copy any complex surface contours by simply adjusting the needle positions. The thermoforming apparatus was mounted in a hydraulic press (HY-Power OP 2MI-TR8-115/30, Italy). The press had two working strokes, i.e. an opening/closing and a compression stroke. The characteristic of the press was that it allowed the needle-bed mould to be rapidly closed on the hot laminate panel in the opening/closing stroke; then it closed more slowly in the compression stroke to build up high pressure and to promote consolidation of the material in the mould [15].

*Figure 6* Saddle-form models.

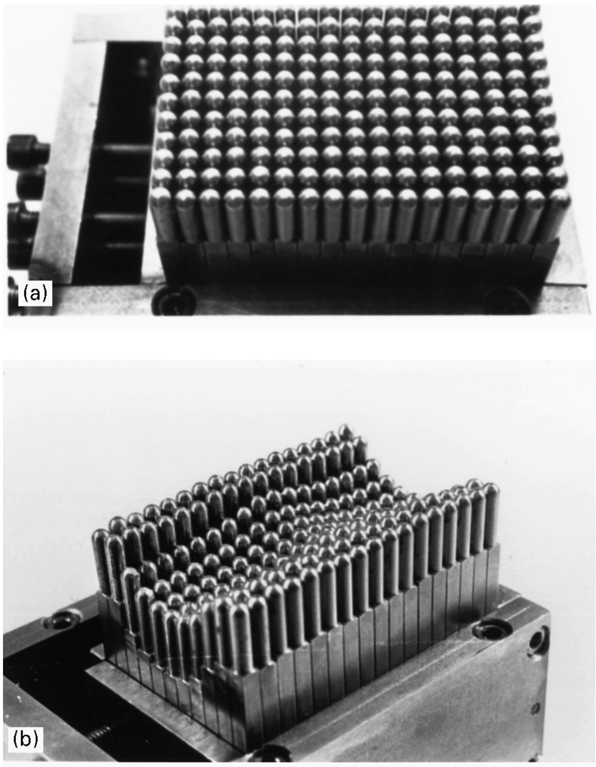

*Figure 7* Needle-bed mould: (a) initial flat surface; and (b) saddle-form contour.

## 4. Forming of saddle-shaped model samples with GF/PP and CF/PP composites

Two saddle-form models (Fig. 6) made of porcelain clay with different curvature profiles were chosen to demonstrate the copy and forming features of the needle-bed mould. Fig. 7 shows the initial flat surface and the saddle-form contour of the needle-bed mould. Continuous glass fibre (GF) and carbon fibre (CF) reinforced polypropylene (PP) pre-consolidated laminate panels with different stacking sequences were used as feed material. GF/PP and CF/PP composite panels had a thickness of 3 mm and fibre volume fractions of 33% and 20%, respectively. The melting temperature of PP was determined by differential scanning calorimeter (DSC) as 163 °C.

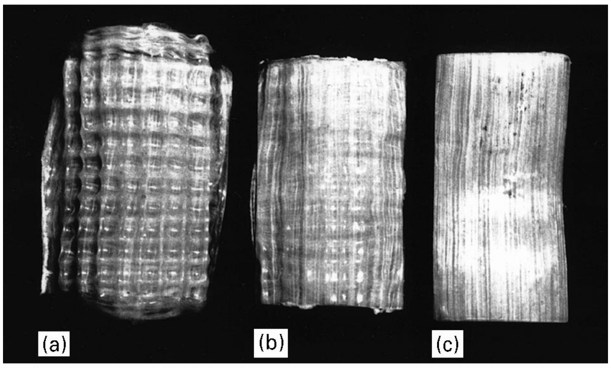

*Figure 8* Effect of silicon rubber pad thickness on surface quality of saddle composite samples. Pad thickness: (a) 0; (b) 1 mm; and (c) 2.5 mm.

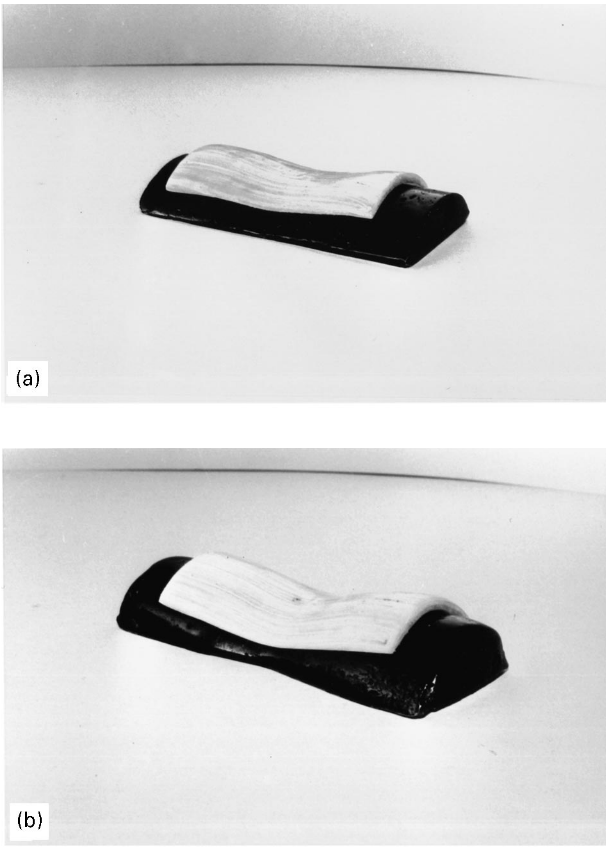

*Figure 9* GF/EP [0]6 saddle samples and their corresponding models, (a) right model on Fig. 6; (b) left model on Fig. 6.

CF/PP $[0]_8$

CF/PP $[0,90]_{4s}$

*Figure 10* CF/PP saddle samples and their corresponding models, (a) CF/PP [0]8; and (b) CF/PP [0, 90] 4s.

The stamp forming conditions used in the demonstration, i.e. forming temperature, pressure and velocity, were chosen based on previous experimental results [15]. Because the forming surface of both male and female needle-bed moulds were formed by stick-tops, it was not surprising to find that there existed serious press-marks of sticks on the surface of the composite. To prevent these press-marks, a series of trials were made in which both forming surfaces of the needle-bed mould were covered with flexible silicon rubber pads of different thickness. Fig. 8 demonstrates the effect of pad thickness on the quality of GF/PP [0] 6 composite saddle-form parts. It was found that rubber with a thickness of 2.5 mm could effectively reduce the depth of the press marks, and the contour of a saddle-form model could be copied at the same time. The copy ability of the needle-bed mould was examined by putting the saddle-form composite part back onto its original model, as shown in Fig. 9. It could be seen that the composite part did match fairly well with its corresponding model, i.e. there was almost no gap between them. Finally Fig. 10a and b show saddle-formed CF/PP composite samples with their corresponding models. The different contours of the model samples shown in Fig. 6 as well as different material stacking sequences ([0] 8 versus [0, 90] 4s) were realized without any problem.

## 5. Conclusions

Stamp forming of continuous glass fibre and carbon fibre reinforced polypropylene (GF/PP) composites with complex surface contours was successfully performed using a needle-bed forming system. A thermoforming apparatus was designed which allowed the thermoforming procedure to be fully automatic, i.e. a cold pre-consolidated laminate was heated in an infrared heating zone and then transferred into a cold mould system. The forming surfaces of the mould were built up by the tops of many tiny round metal sticks, which allowed one to copy any contour by pushing it slightly onto the spring-supported sticks. To prevent any press mark of the needle tops on the composite, i.e. to achieve smooth surfaces of the thermoformed

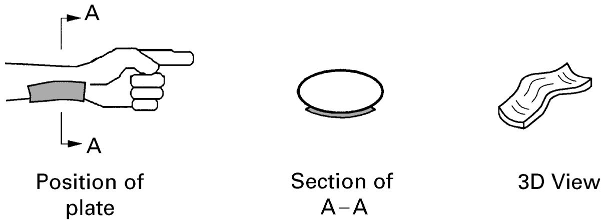

*Figure 11* Fixation plate for broken hand joint. The manufacturing steps are: (1) Imprint of broken hand joint area in the needle-bed. (2) Fixing of the needles. (3) Stamp forming of fixation plate.

composite parts, flexible rubber pads with a thickness of 2.5 mm were used to cover the mould surfaces. The surface profile of CF/PP and GF/PP composites formed by the needle-bed mould reproduced fairly well the complex surface contour of a saddle model sample. The technique demonstrated could be useful for many orthopaedic procedures, in which internal bone plates, external fixation supports or prostheses have to be rapidly formed, exactly adjustable to the individual surface contours of the various patients (Fig. 11).

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