EFFECT OF PRESSURE IN THERMOPLASTIC RIBBON THERMAL WELDING

J. A. Hinkley
NASA Langley Research Center
Hampton, VA 23681

B. C. Messier and J. M. Marchello
Old Dominion University
Norfolk, VA 23529

ABSTRACT

An inexpensive apparatus was designed to simulate some features of on-the-fly thermal welding in heated-head tow placement. Previous studies have shown how ply/ply weld strength depends on weld time/temperature history. The apparatus has been modified recently to apply higher contact forces. Welding at pressures up to 1.7MPa (250psi) produced more consistent welds and fewer intra-ply voids. This has permitted a study of the conditions required for achieving the limiting ply/ply cohesive strength in simulated tow placement of a polyimide oligomer.

KEY WORDS: Tow placement, thermoplastic composites, consolidation

1. INTRODUCTION

In-situ composite fabrication using heated-head placement of continuous-fiber reinforced ribbon or tape is still a developing technology [1]. Its degree of success depends on both process issues (e.g., How fast can the head move and still provide adequate heating?) and material issues (e.g., Is the polymer matrix viscosity low enough at the process temperature?)

Weld/peel experiments [2] were conceived to accelerate the development of both materials and processes. They do this by providing insight into the material response, by allowing rapid screening of small quantities of new materials, and by helping to optimize the

Previous investigations into the kinetics and mechanisms of *in-situ* bonding [2,3] focused on the initial wetting and polymer chain interpenetration at short times. At longer times, the strength of the welded interface would be expected to level off at the full cohesive strength of undamaged material [4]. In practice, however, the rapid heating required for an *in-situ* process introduces two complications. The first is the development of voids due to the rapid release of volatiles; the second is the potential for resin degradation, especially at the surface where heat is applied.

By considering the effect of pressure at both short and long bonding times, this paper addresses aspects of these two factors.

2. EXPERIMENTAL

The 6 mm-wide ribbon was fabricated at NASA Langley from Hercules IM7 fiber and a LaRC™ phenylethynyl-terminated polyimide oligomer [4]. The resin was supplied by Imitec.

Welds were produced using the apparatus sketched in Figure 1. Pressure on the ribbons was calculated from the pneumatic cylinder pressure and the areas of the cylinder and platen. Otherwise, procedures were similar to those described in Reference 2. Effective times were calculated using time-temperature superposition as before [2,3] and referenced to Tg.

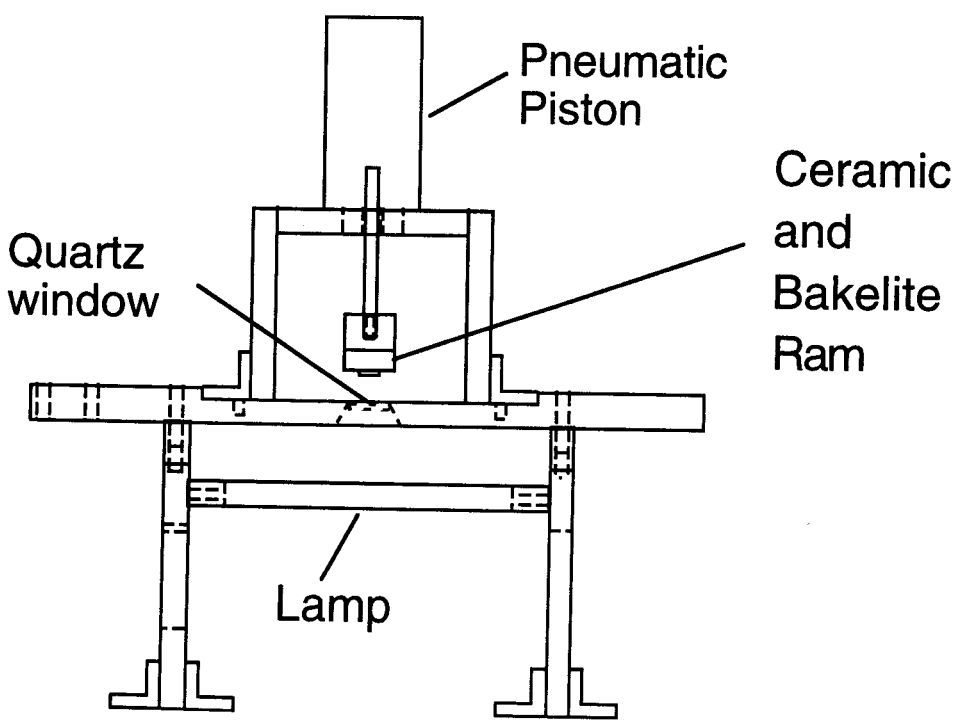

Figure 1. Schematic of welding apparatus. Overall height: 47 cm.

The stronger welds produced at longer times required a new approach to the peel test. An idea and analysis of Glessner *et. al.* [5] was adopted, using the simplified arrangement shown in Figure 2. The razor blade wedge was driven relative to the load cell at a crosshead speed of 1.3 cm/min. The wedge force divided by the specimen width is equivalent to a strain energy release rate.

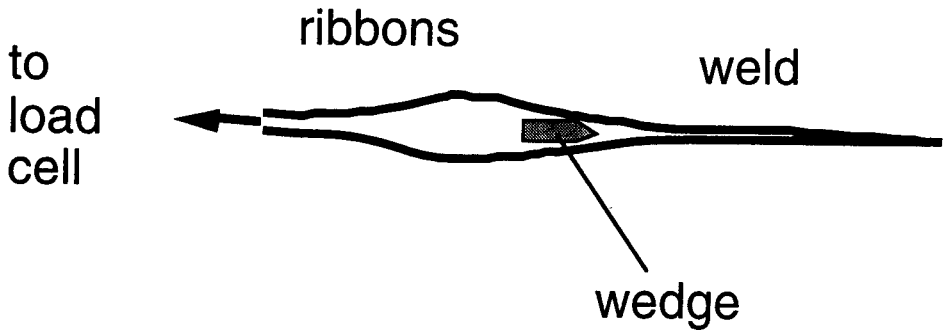

Figure 2. Wedge peel test geometry (not to scale).

Differential scanning calorimetry was performed in aluminum pans in air at a heating rate of 20°C/min. Optical microscopy of polished cross sections used an Olympus BH2 microscope with Cue2 image analysis system. Peel surfaces were coated with a nominal 8 nm of Au-Pd and observed with a Hitachi scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

An infrared heating time of 7 seconds was found to be just sufficient to adhere the ribbons. Using this as a starting point, the heating time was increased in 5-second increments.

It is assumed, first of all, that no welding takes place below the glass transition temperature, Tg. DSC thermograms obtained before and after welding revealed Tg's of 230.4 and 230.9°C, respectively, so no appreciable resin advancement (curing) occurred. Figure 3 shows the relevant portion of the temperature profiles for the four welding conditions. It may be seen that times spent above the glass transition temperature, Tg, ranged from 4 seconds to approximately 60 seconds. Much more important than this 15-fold *time* difference, however, is the difference in peak *temperatures*. For example, the WLF equation used to reduce the data [3,6] implies that welding should occur 10^{14} times faster at Tg+ 200 than it does at Tg.

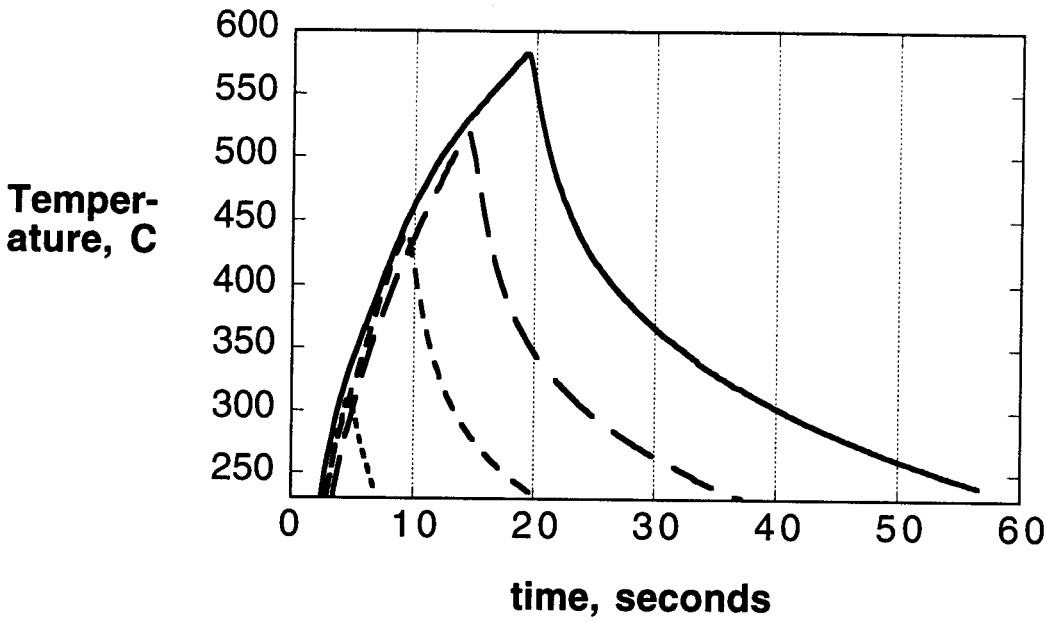

Figure 3. Temperatures recorded during welding experiments

Figure 4 summarizes the peel strengths obtained at three different pressures. The three curves are similar in shape. At short times, the peel strengths are low, and are attributed to wetting. Near 10^{14} sec, the strengths rise by a factor of more than 2. This upturn was documented in the previous reports [2,3,7] and is attributed to chain interdiffusion.

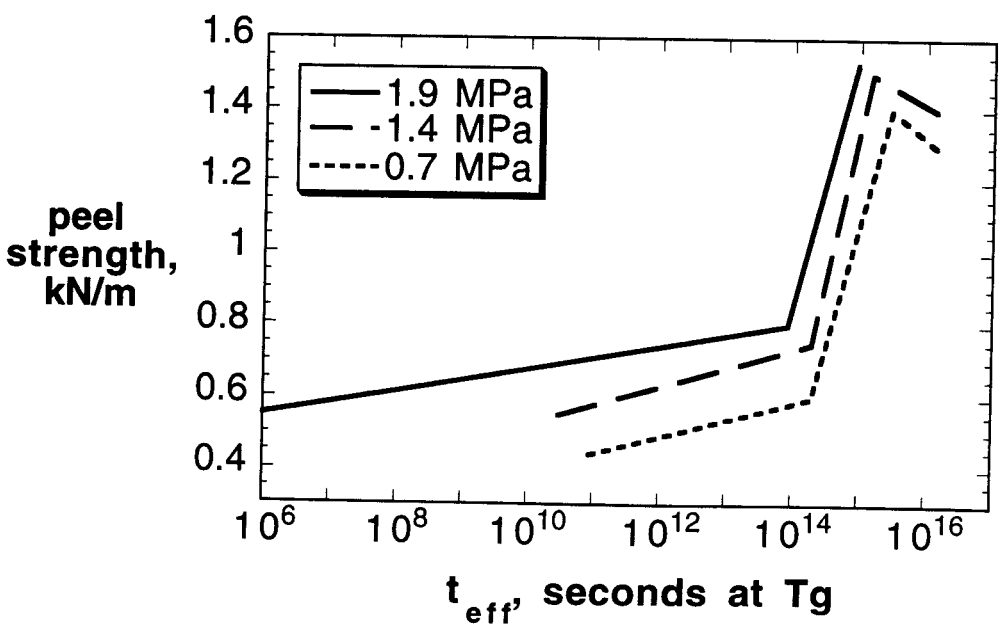

Figure 4. Peel strength as a function of effective time (referred to Tg)

At the longest weld times, the strengths decreased slightly again. This effect has not been seen before in our experiments. In a related filament winding study, however, Mazumdar and Hoa [8] found that excessive time at their highest laser power produced lower strengths. A possible cause is degradation of the resin or weakening of the fiber/matrix interface. This degradation is not easy to detect in our experiments; there were no gross changes in resin Tg or reflectance infrared spectrum. Although the drop in strength in Figure 4 is not large, this result certainly signals a need to pay attention to this upper limit on the process window. One should particularly be aware that highly localized heat sources may damage the ribbon surface just where diffusion is most critical to a good bond.

One purpose of this study was to determine the ultimate bond strength. The other was to explore the effect of pressure. An increase in pressure may have two kinds of effects. On the one hand, it should prevent the release of dissolved gases and the expansion of bubbles. It may also promote intimate contact between the plies.

In earlier experiments [2,7], in which welds were produced at 21kPa applied pressure, void contents as high as 50% were common. In contrast, the micrograph in Figure 5 shows that voids were successfully confined by increasing the pressure to 1.4 MPa (200psi). The effects of heat and pressure on void content are summarized in Table 1.

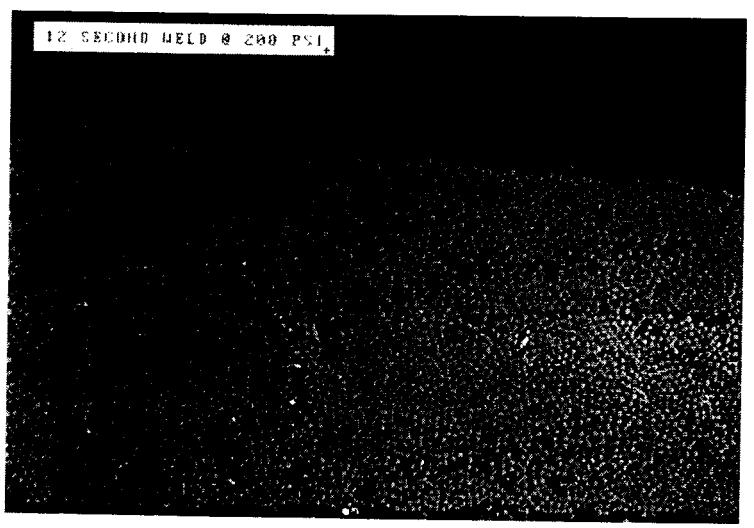

Figure 5. Cross section of weld produced at 1378 kPa pressure and 22 second lamp time. Scale: specimen thichness corresponds to 0.3 mm.

Table 1. Void contents (percent) obtained by image analysis.

	pressure, kPa		
total IR time, sec	689	1378	1874
7	1.8	2.7	2.1
12	1.4	2.1	2.1
17	1.6	2.9	4.0
22	18.7	4.2	--

It is apparent from these results, as well as a comparison with those reported earlier [2,7] that strength does not correlate well with void content. To explore the pressure effect further, some data interpolated from Figure 4 are replotted against pressure in Figure 6. The curves do not seem to level off with increasing pressure.

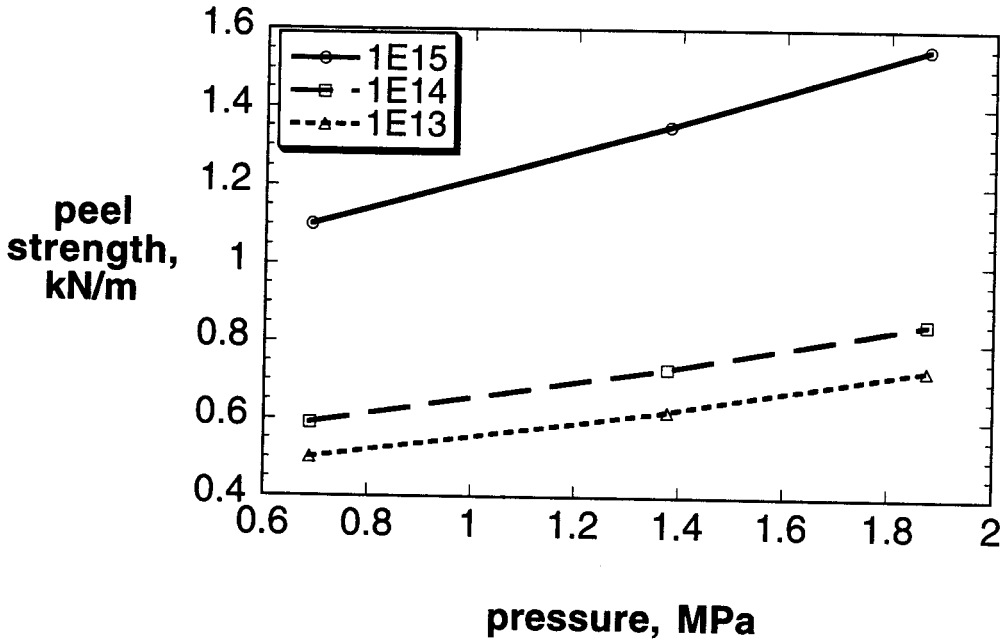

Figure 6. Peel strengths at three effective weld times

It is hypothesized, therefore, that increased pressure improves contact between the plies. In fact, some areas of the peel surfaces are far from planar, even though the ribbon surfaces were smooth to begin with. The SEM (Figure 6) is consistent with the idea that fiber nesting may be contributing to the measured strength. At the longest times, in fact, there was considerable splaying of the fibers. A practical implication of this is that ribbon and substrate surface roughness and fiber movement may strongly affect the efficiency of tow placement.

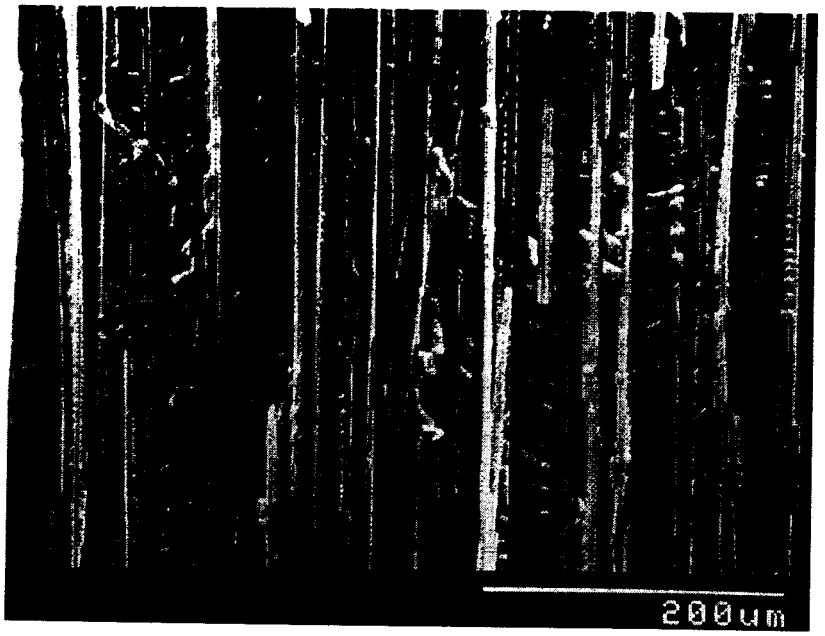

Figure 6. SEM of weld surface after peeling. (Weld produced at 1.4MPa for 22 seconds lamp time).

4. CONCLUSIONS

Void contents can be controlled by pressures of 0.7 Mpa (100 psi). Peel strength increases linearly with weld pressure, suggesting that other factors such as fiber movement affect the apparent weld quality.

At any pressure, the strength of welds increases with effective time, leading to maximum fracture toughnesses of ca. 1.5 kJ/m^2 before decreasing again at longer times. Resin degradation at the highest effective times is suggested. This hypothesis may be tested in the future by varying weld time while limiting peak temperatures.

5. REFERENCES

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