# Development of Solar Energy Concentration for Plastic Joining

P. Yarlagadda and I. S. Kim

## Abstract

This paper presents development of a SEC(Solar Energy Concentration) utilizing the concentrated solar beam radiation for joining engineering thermoplastics such as Acrylonitrile/Butadiene/Styrene (ABS), Polycarbonate (PC) and Polymethylmethacrylate (PMMA). In addition, to study the joining of the materials, necessary experimentation with applying primer was performed. Tensile tests were conducted to determine the bond strength achieved at the specimen joint interface. Microscopic examinations of the fractured joints were performed in order to analyze the overall bond quality. Finally, the results in terms of bond strength achieved at the joint interface and energy consumed in the process was compared with those obtained with similar thermoplastic joining technique utilizing microwave energy.

**Key Words :** Solar beam, Solar energy concentration, Thermoplastic welding, Focussed microwave

## 1. Introduction

Joining of plastic materials and their composites can be broadly divided into mechanical fastening and bonding. Welding can be further categorized into thermal bonding, friction welding and electromagnetic bonding[1]. Some common aspects of current conventional and alternative plastic welding technologies under development are discussed[2]. While many of the above mentioned conventional plastics joining technologies have been used for years, some modern welding technologies are in fairly early stage of development. The microwave welding process uses electromagnetic interaction between the incident microwave radiation and the materials to be joined. Industrial applications for using microwave energy to join thermoplastic materials are still in research and development stage[3]. Potente et. al.[4] have reported the successful use of this technique for infrared welding of glass-reinforced polymer in very high weld strengths. Jones and Tailor[5] have reported a high-speed laser welding of polyethylene films using carbon dioxide and Nd-YAG lasers. Weld speeds of 50 m/min were achieved, and higher speeds were considered possible. Weld strengths were near parent material strength.

considered possible. Weld strengths were near parent materials strength. Many conventional and modern plastics joining technologies either use or are based on effects using different types of non-ionising electromagnetic radiation[6]. Some modern plastic joining technologies use artificial source of electromagnetic radiation. However, a source of electromagnetic radiation is needed, and the greatest renewable energy source available on earth is the sun. In the sun every second 657 million tons of hydrogen convert into 653 million tons of helium[7-8]. The essential attribute for the utilization of the concentrated beam solar radiation is its absorption by the irradiated material. The photoelectric effect is responsible for the absorption of the visible light. Not all electrons meet the criteria of accepting the energy from a photon. In general this is the reason that not all materials can accept the photon's energe[9]. Although the thermodynamic limit of concentration with a single ideal device is about 45,000, today very high solar flux systems (e.g. 20,000 to 100,000 times concentration) are being developed[10]. When thermoplastics are subjected to heat they pass through a phase in which they change from rigid or glassy to soft and pliable materials. The temperature at which this occurs is called glass transition temperature. The softening of the thermoplastics is due to the uncoiling and loosening of the molecular bonds of the large chain molecules in the material. When the dipole molecules are not directly attached to the main chain, segmental movement of the chain is not necessary for dipole polarization and dipole movement is possible below

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*P. Yarlagadda* is a Professor, School of Mechanical, Manufacturing and Medical Engineering QUT, GPO Box 2434, Brisbane Q 4001. Australia

*I. S. Kim* is an Assistant Professor, Department of Mechanical Engineering, Mokpo National University Muan-gun, Chonnam 534-729, Korea

E-mail : ilsookim@chungkye.mokpo.ac.kr

the glass transition temperature[11].

In this research, studies were undertaken to look into the bonding of thermoplastics with the use of adhesives. Samples were exposed and cured under the wide spectrum of wavelength radiation directly from the sun at 75°C and 250°C respectively. The three types of thermoplastic that were chosen in this feasibility study are Acrylonitrile/Butadiene/Styrene (ABS), Polymethylmethacrylate (PMMA), and Polycarbonate (PC). Comparison was drawn with ambient cured condition with and without surface roughening preparation. Besides, results were also compared with conventional methods such as microwave curing in the area of bond quality and process efficiency.

## 2. Design of solar energy concentrator

The experiments were performed with a solar energy concentrator (SEC) facility, as shown in Fig. 1, which includes a small modified Cassegrainian telescope employing primary and secondary mirrors to focus the sunlight on a lens for delivering and further concentration of the light onto the specimen surface. The main component of the system is the modified two-mirror Cassegrainian telescope supported in a standard altitude-azimuth mounting. The primary mirror is with outer diameter 600mm and radius of curvature 4267mm. It is coated with electro-plated nickel with not less than 80% reflectivity in wavelength range 400 – 1200mm. The secondary mirror has a diameter of 240mm and radius of curvature 7433mm. The mirror surface is enhanced aluminum coating on E3 glass substrate with grater than 80% reflectivity in the same wavelength range. This combination has an overall focal length of 2778mm. The solar image in the Cassegrainian focus is 25mm. To transfer the concentrated flux to the workpiece, the system is designed to use magnifying unit, canister and periscope optics and additional auxiliary optics. The initial testing experiments of the optical and thermal characteristics of the SEC facility have revealed that, the use of conventional periscope and additional auxiliary optics lead to a substantial loss of power and additional limitations on the spectral range use imposed by the optics used. For the purposes of this feasibility experiments, direct system employing a single lens has been employed instead of the proposed conventional optics in order to decrease the optical and thermal loses in the system.

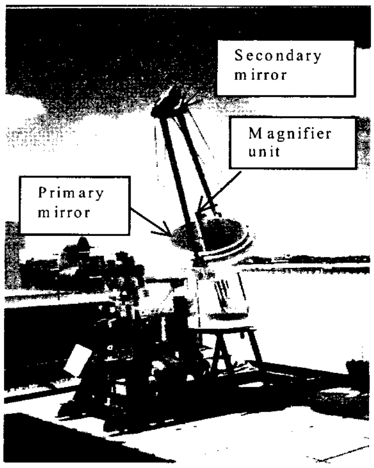

**Fig. 1** Solar energy concentrator

## 3. Experimental procedure

Polymethylmethacrylate (PMMA), Acrylonitrile-Butadiene Styrene (ABS) and Polycarbonate (PC) were chosen for the experiment because of their superior polymer structure and feature of ease in shaping. The operating temperature and strength of the three types of adherends used in the presentation investigation are shown in Table 1. The 3mm thick adherends were sized into 50x10mm. The adherend were clamped in the fixture and bonded in a lap joint on a 100mm$^2$ section.

In this study, wo types of adhesives namely: RS High Strength Epoxy and Rapid Araldite were used to bond PC adherends. In order to standardize, the results four samples were study in each experiment. Each two-part

**Table 1** Operating temperature and strength of adherends

| Parameters | PMMA | PC | ABS |
|---|---|---|---|
| Glass Transition Temperature $T_g$ | 105°C | 150°C | 106°C |
| Melting Temperature $T_m$ | 160°C | No Definite | 190°C |
| Parent Material Strength N/mm$^2$ | 54.04 | 59.44 | 32.07 |

**Table 2** Average strength of the weld with monitoring the welding parameters

| Material | Welding Duration (sec) | Temperature on idle running (°C) | Intensity of Direct Solar Radiation (W/m$^2$) | Wind Velocity (m/s) | Applied Tensile Force (N) | % of Parent Material Strength | Elongation (mm) |
|---|---|---|---|---|---|---|---|
| ABS | 18 | 549 | 898 | $\leq 2$ | 248 | 38.77 | 0.66 |
| PC | 27 | 565 | 922 | $\leq 2$ | 327 | 27.28 | 0.67 |
| PMMA | 50 | 555 | 888 | $\leq 1$ | 313 | 31.76 | 0.55 |

adhesive was prepared using syringe in order to ensure equal amounts of reaction product (bisphenol A) and epoxy resin (epichlorohydrin). The mixtures were mixed well, 15 seconds for Rapid Araldite and 1 minute for RS High Strength Epoxy, as recommended by the manufacturer. The adherends were bonded using lap joint on a 100mm$^2$ section with a bond thickness of 1mm. Bondline thickness was maintained using 1mm diameter glass beads. Four glass beads were used for each sample, in order to maintain consistency of bondline thickness and bond area. Weights were then placed on the specimen to achieve the desired bond thickness. Adherends were then mated using teflon tape to hold the adherends together and to prevent adhesive leakage prior to and during solar radiation The samples were then left to cure for 24 hours, shear tested and peak bond strength recorded. Two different types of adhesive were used to bond PMMA and PC. Five batches of four samples from each type of adherend, were initially subject to a temperature of 75°C for two minutes. The samples cured were then shear tested and peak bond strength was recorded. The experimentation was repeated under similar conditions, however, the samples are cured under a temperature of 250°C and the exposure time is 60 seconds.

## 4. Results and discussion

The SEC employed in this research utilizes primarily the visual range of the entire solar spectrum available at given time. In order to determine the suitability and measure the availability of a particular microwave wavelength (or range), spectrometric measurements of the available solar radiation at given time are needed. Since the intensity and the spectral distribution of the solar radiation available on the primary mirror are uncontrollable variables, in this feasible study only the intensity of the direct solar radiation at given time has been measured. The results obtained from the two techniques for measuring the intensity of the beam insolation on the primary mirror surface were consistent. The average intensity of beam solar radiation measured during each of the 6 days of the experiment between 8.30 AM and 3.30 PM was 872 W/m$^2$. The fluctuation of the intensity of the direct solar radiation measured between 9.30 AM and 2.30 PM was less than 10%. Therefore, the experiments were carried out during this period of time.

### 4.1 Joining of thermoplastics with monitoring the welding parameters

The duration, power and temperature are important parameters that control the quality of the weld. Since the quality of the weld in this experiment depends entirely on the manual skill of the welder, it is thus not possible to directly compare the weld strength achieved with each material used unless the same percentage of human error is assumed. In order to investigate the feasibility of the solar energy concentrator to join thermoplastic materials by using concentrated solar radiation, the initial experiments were performed with monitoring the welding parameters such as direct insolation, temperature at the focus point and duration of the welding process. During the welding, due to presence of wind and clouds, the temperature was unsteady and fluctuated in the range of ±100°C. The data obtained during the initial experimentation is shown in Table 2. The tensile strength of the ABS joint ranged from 9.08% to 89.83% of the parent material strength. The tensile strength of the welded PC material ranged from 18.38% to 42.11% of the parent material strength. The percentage of parent-material strength for the welded PMMA material ranged from 4.67% to 55.23%. The average weld strength of the ABS, PC and PMMA specimens compared to their parent material was 38.77%, 27.28% and 31.76% respectively. Table 1 illustrates these results and shows that the PMMA had the slowest welding time, whereas the ABS had the fastest.

### 4.2 Joining of thermoplastics with controlling the welding duration

In order to obtain more data with less fluctuations of the intensity of the solar radiation, the experiments for specific welding duration were carried out between 9.30 AM and 2.30 PM. In this period, as discussed previously, the intensity of direct solar radiation was without major fluctuations during each experiment duration. The specimens of each material were welded once every hour at the average duration obtained. It can be seen that the strength of the welded joint of the ABS and PC materials

### 4.3 Joining of thermoplastics with the aid of adhesive

From the test results obtained, it was concluded that the type of adhesives introduced during welding did not contribute to the improvement of the overall bond strength and increased significantly the welding duration instead. The tests conducted by applying adhesives to the ABS, PC and PMMA specimens only revealed a low proportion of the parent material strength i.e. 19.09%, 4.29% and 10.19% respectively. When an adhesive is used, it is evident that part of the energy of the photons is absorbed by the adhesive itself, thus less energy is propagated into the specimen interface surface. Also, the generated temperature is obviously too high for achieving optimal performance of the adhesive.

### 4.4 Comparison with thermoplastic welding by means of focused microwave energy

The results obtained in the above experiments were compared with the results of the welding of the same materials (i.e. ABS, PC and PMMA) by using focused microwave energy. These thermoplastics were welded with and without the presence of primer at three different power inputs of 600 W, 800 W and 1000 W3). The comparison between both welding processes were based on the energy consumption (kJ) required performing the welding and the output results (strength of the welded joint). Assuming no energy loss, for the microwave welding process the energy consumption was obtained by multiplying the power input in (J/s) by the welding duration (s). Considering the average reflectivity in the visible wavelength range for the both primary and secondary mirrors as more than 80%, the energy consumed, $E_c$, iscalculated by using the following:

$$E_c = \eta_p \eta_s \pi/4(D_p^2 - D_s^2) I_s \tau \qquad (1)$$

where $\eta_p$ is the reflectivity of primary mirror, $\eta_s$ is the reflectivity of secondary mirror, $D_p$ is the diameter of primary mirror, $D_s$ is the diameter of secondary mirror, $I_s$ is the intensity direct solar radiation, and $\tau$ is the welding

**Table 3** Results from thermoplastic welding by utilizing of concentrated solar energy and focused microwave energy

| Welding by means of focused microwave energy | | | | Welding by applying concentrated solar radiation | | | |
|---|---|---|---|---|---|---|---|
| Power input (W) | Welding duration (s) | Energy consumed (kJ) | Weld strength compared with parent material (%) | Power input (J/s) | Welding duration (s) | Energy consumed (kJ) | Weld strength compared with parent material (%) |
| ABS Material (without primer) | | | | | | | |
| 600 | 46 | 27.6 | 26 | 134.4 | 13 | 1.747 | 31.99 |
| 800 | 38 | 30.4 | 28 | 124.8 | 18 | 2.246 | 32.8 |
| 1000 | 34 | 34 | 16.4 | 143.4 | 23 | 3.298 | 48.83 |
| ABS Material (with primer) | | | | | | | |
| 600 | 24 | 14.4 | 23.4 | 120.3 | 28 | 3.368 | 19.09 |
| 800 | 17.7 | 14.16 | 33.1 | (Ave) | | | |
| 1000 | 11.5 | 11.5 | 41.1 | | | | |
| PC Material (without primer) | | | | | | | |
| 600 | 140.5 | 84.3 | 11.5 | 134.4 | 22 | 2.957 | 18.01 |
| 800 | 66 | 52.8 | 28.2 | 124.8 | 27 | 3.370 | 22.39 |
| 1000 | 44.5 | 44.5 | 20.3 | 144.6 | 32 | 4.672 | 33.52 |
| PC Material (with primer) | | | | | | | |
| 600 | 35 | 21 | 14.7 | 118.4 | 47 | 5.565 | 4.29 |
| 800 | 20.6 | 16.48 | 50.2 | (Ave) | | | |
| 1000 | 17.3 | 17.3 | 63.3 | | | | |

From the data in Table 3, it is noticeable that in terms of the energy consumption the solar energy welding process consumed much less energy than the microwave energy welding process, moreover it has been free delivered. The joining process by applying concentrated solar radiation appears to be more favorable process in duration.

terms of energy consumption and output results.

## 5. Conclusion

A feasibility study and initial experimental results of joining three different types of engineering thermoplastics by utilizing concentrated solar flux is reported. The tensile strength of the parent materials were determined, then the welding of such materials was performed with and without the application of epoxy based primers. Finally, tensile tests were conducted to study the bond strength achieved at the joint interface. Compared to the parent material strength, minimum bond strength of 4.67% and a maximum of 89.83% were measured. Even though in the experiments using average welding duration the bond strength as a percentage of the parent material strength has not been significantly higher than that from the experiments with variable welding parameters, it could be considered relatively consistent. The quality of the weld could be improved should the power input remains constant and the compressive force is applied only when the whole joint is in its flow state.

Solar concentrating systems seem to offer some unique opportunities for high temperature transformation of thermoplastic materials. It appears that for small-scale feasibility study and experimental demonstration of concentrated photon utilization for materials processing a Cassegrainian solar concentrator can offer some advantages. Although solar energy is considered inexhaustible resource it is diffuse compared to other sources, and intermittent and unreliable source of energy. It is largely in the visible and near-infrared regions (which is mostly collected by the SEC facility) and in general, is not directly suitable for most photo-electro chemical reactions. Only about 4% of the solar spectrum is in ultraviolet region (energies greater than 3 eV).

Additional work is already in progress to improve the tracking control by implementing a sun tracking sensor and controller for the SEC facility. Future research in the field of materials processing by utilizing concentrated solar beam radiation could focus on improving the ability of transparent thermoplastics to absorb the photons from the visible spectral range, and joining of transparent and translucent or opaque to the visible solar photons thermoplastics.

## References

1. K. S. Vijay: Joining Methods for Plastics and Plastic Composites: *an Overview, Polymer Engineering and Science*, Vol. 29, No. 19 (1989), pp.1310-1324
2. L. A. Stoynov, P. Yarlagadda and K. D. Prasad: A Feasibility Study into Joining of Engineering Thermoplastics Utilising Concentrated Beam Solar radiation, *Renewable Energy Journal*, Vol. 21 (2000), pp.333-361
3. P. Yarlagadda, K. D. V. Prasad and C. C. Tan: An Investigation into Welding of Engineering Thermoplastics Using Focused Microwave Energy, *Journal of Materials Processing Technology*, Vol. 74, No. 3 (1998), pp.99-212
4. H. Potente, J. Natrop, T. Pedersen, Klit and M. Uebbing: A Comparison on three Methods for Welding Glass-fiber Reinforced PES, Conference Proceedings, *Society of Plastics Engineers ANTEC*, Vol. 1, No. 5 (1994), San Francisco, pp.1274-1279
5. I. A. Jones and N. S. Tailor: High Speed Welding of Plastics Using lasers, Conference Proceedings, *Society of Plastics Engineers ANTEC 94, San Francisco*, Vol. 1, No. 5 (1994), pp.1360-1363
6. The Hutchinson Encyclopedia, 11th Edition (1998)
7. J. K. Wagner: Introduction to the Solar System, Saunders College Publishing (1991)
8. F. Kreith and J. F. Kreider: Principle of Solar Engineering, McGraw-hill, U.S.A (1987)
9. J. A. Brydson: Plastics Materials, Butterworth Heinemann, 5th Edition, Oxford (1989)
10. A. W. Birley and M. J. Scott: Plastics Materials, Leonard Hill, Glasgow (1982)
11. G. Gruenwald: Plastics, How Structure Determines Properties, Hanser, New York (1993)