SELF REINFORCED POLYMER COMPOSITES: COMING OF AGE

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SUMMARY

This paper discusses recent advances in Self Reinforced Polymer (SRP) composites. The paper details the results of a two and a half year research project. An introduction to SRPs is given, including the benefits and limitations of these materials. Novel forming and post-processing technologies will be discussed along with products developed for specific high performance applications.

Keywords: Self reinforced polymer, composite, processing, polymer

AN INTRODUCTION TO SELF REINFORCED POLYMER (SRP) COMPOSITES

As industries such as aerospace, automotive, construction and many others demanded lighter and lighter materials polymer composites and particularly thermoplastic composites are becoming much more common [1]. This trend is due to polymer composites offering high performance materials with minimal weight when compared with more traditional materials such as high strength steels.

This trend of increased usage means it is becoming much more important to be able to recycle components made from fibre reinforced polymer composites. Materials made of thermoplastics can be simply re-melted and re-moulded into new components, however this is not possible with the inclusion of fibres such as glass or carbon as these cannot be melted down. Thus, the composite materials must be shredded and used as lower performance short fibre reinforced polymer composites [1]. To meet the demand of recyclable fibre reinforced polymer composites, fibres which can be melted along with the polymer matrix and be compatible with that melt must be used; this has lead to the development of Self Reinforced Polymer (SRP) composites.

Self reinforced polymer composites, also known as self reinforced plastics and single polymer composites, are fibre reinforced composite materials. The fibre reinforcement in these materials is a highly orientated version of the same polymer from which the matrix is made. For example; a polypropylene matrix reinforced with highly orientated polypropylene fibres [2].

Self reinforced polymer composites are currently being developed using numerous different thermoplastic polymers such as polyamide [3], polyethylene [4-6], polyethylene terephthalate [7-9] and polypropylene [2,10-11], however by far the most mature of these materials are the polypropylene materials that are at present commercially available such as Pure® (http://www.pure-composites.com/), Armordon® (http://www.donlow.co.uk/static/wovens/srpp/srpp/) and Curv™ (http://www.curvonline.com/).

Properties

Numerous different polymers can be used in the manufacture of SRP composites and obviously result in a wide array of different properties ultimately achieved. However, all the self reinforced polymer composites offer significantly higher properties than the virgin polymers from which they are made; for example Cabrera shows that at room temperature the all-polypropylene material Pure® displays a Young's modulus of 5.9GPa [12]. This is significantly above the modulus of isotropic polypropylene which has a modulus of around 1.1GPa [13]. Cabrera is supported in his findings; Hine and Ward show that the modulus of Curv™ which is another all-polypropylene material manufactured using a different method to Pure® is also significantly higher than unmodified polypropylene and reaches 5GPa [13].

Self reinforced polymer composites made from materials other than polypropylene are much less mature and not yet commercially available. However, the properties they exhibit even in the development stage have been no less impressive. Hine demonstrates that self reinforced polyethylene terephthalate can be made showing a modulus of 5.81GPa [14] which is more than twice that of isotropic PET [14]. Also Rein gives figures between 10-12GPa for self reinforced polyethylene [6], a dramatic shift upwards in the stiffness of this material.

Stiffness is not the only property which is augmented as a result of turning a material into a self reinforced polymer composite. Strength, heat deflection temperature and impact performance are all increased while offering little increase in the density of the material [13]. It can be clearly seen from Hine's work that the most drastic increase comes in the form of impact performance [13]. It is suggested by Alcock that this dramatic increase in impact performance is due to interfacial failure between the polymer tapes/fibres and the matrix material around them [10]. This is a failure mechanism which does not exist in virgin unreinforced polymers as obviously there are no tapes/fibres and no interfacial bonds, and thus the materials react as they traditionally would. Although Alcock suggests that interfacial failure between tapes/fibres and matrix material is the main reason for the increase in impact performance there are of course other mechanisms within the material. As with all fibre reinforced composites, these materials gain their properties by transferring loads from the relatively low property matrix material into the high performance reinforcement fibres. Due to the very high level of molecular orientation within the reinforcements of self reinforced polymer composites resulting from high draw ratios (up to 20 for polypropylene) [12], the tape/fibre reinforcement within these materials has vastly higher properties than the unmodified material. Due to this, more traditional failure mechanisms such as tensile failure are delayed due to the transmission of load from the matrix to the tape/fibre reinforcement.

Advantages and Disadvantages

SRP composites offer a range of advantages over traditional fibre reinforced composites such as GRP and CFRP. These advantages include greatly improved recyclability, very low density and very high impact performance.

First and foremost of these advantages is that of recyclability. As SRP composites are 100% thermoplastic, recycling is a very simple process. Unlike more traditional fibre reinforced composites, SRP composites to do require the reinforcement to be separated from the matrix before effective recycling can take place, as with glass and carbon reinforced materials. At the end of product life a component can simply be re-melted and re-granulated. These granules can then be reprocessed into new components.

The second obvious advantage is that of density. SRP composites are reinforced with the same polymers from which the matrix made. This means that although gaining a significant increase in properties there is no increase in density of the material. This means extremely light weight materials can be manufactured and so very significant weight savings on finished components can be achieved.

Although SRP composites have many significant advantages they are not without their disadvantages. The first of these disadvantages is temperature sensitivity. During processing, temperature must be controlled very accurately in order to melt only the matrix material while keeping the reinforcement un-damaged by the heat. This is very difficult due to the relatively small processing windows these materials present.

Secondly, these materials are 100% thermoplastic, and as such they cannot be used for high temperature applications as they would lose properties very rapidly.

Processing Routes

There are two main processing routes for the manufacture of SRP composites; Hot Compaction and Co-extrusion.

Hot Compaction is a method by which highly oriented polymer tapes are very accurately heated (±0.5°C). This heating allows approximately 10% of the polymer tapes to melt.

With the application of pressure this molten polymer flows throughout the lattice work of tapes to form a continuous matrix. The sheet is then cooled while still under pressure to solidify the matrix. This process results in a rigid sheet which can then be thermoformed. Propex Fabrics use this process to mass produce a self reinforced polypropylene sheet called Curv™ .

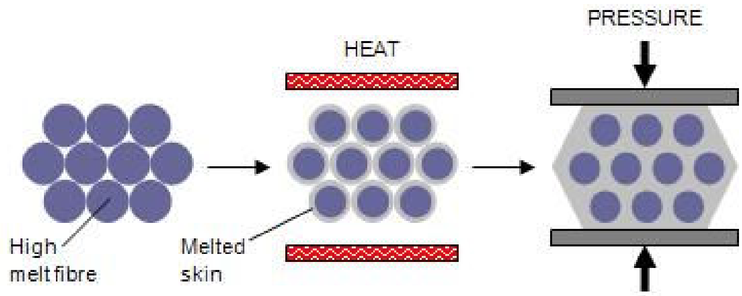

Figure 1. The Hot Compaction process

The second main method by which SRP composites are produced is Co-extrusion. Highly oriented polymer tapes are extruded from a high melting point grade of the chosen polymer. During this process a low melting point grade of the same family of polymers is extruded on the surface of the tape. These tapes can then be woven to form a fabric. During post processing into shaped components the outer layer of the tapes melts before the inner core of oriented polymer. Under pressure this low melt grade flows throughout the fabric. On cooling this low melt grade of polymer re-solidifies to form the composite matrix. This method is used to produce self reinforced polypropylene fabrics and sheets by Don & Low, Milliken and Lankhorst.

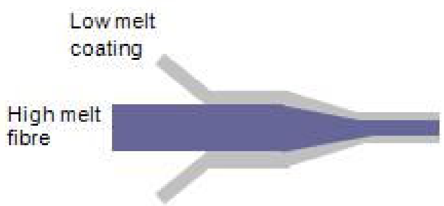

Figure 2. The Co-extrusion Process

SMARTPRESS 2

SmartPRESS 2 was a two and a half year research project undertaken by NetComposites with a grant for research and development from EMDA. This project followed on from earlier research work carried out at NetComposites on the forming of self reinforced polypropylenes including Curv™ and Pure® as well as a self reinforced polyethylene terephthalate fabric developed specifically for the project. Completed in 2008, the project made significant progress in a wide range of areas centred on enabling technologies such as painting and joining of components. The project also had a large focus of novel and efficient methods for forming the materials both from pre-consolidated sheet and unconsolidated fabrics.

Project Areas

The project focused on a number of different areas, all of which related to the manufacturing and finishing of components. The project covered the forming of complex shapes, effective trimming of components to achieve good quality trim lines, finishing components to a high quality using various painting and coating technologies and joining components together using a variety of techniques.

Forming

The SmartPRESS 2 project dealt with self reinforced polypropylene in both pre-consolidated sheet form and as an unconsolidated woven fabric. These two types of material obviously need significantly different methods in order to form them into shaped components. Within the project both high volume and low volume processes were investigated for each material type.

Figure 3. Example of sheet and fabric forms of self reinforced polypropylene

Using the Curv™ and Pure ® sheet material, a relatively high pressure process was required in order to form highly detailed components. Compression moulding was chosen as the method of choice using matched metal tooling. In order to successfully form the material the sheets required pre-heating to a temperature at which they became malleable. Finding the optimum temperature for this was a priority as; due to the nature of the material structure, the temperature at which it becomes formable is naturally very close to the temperature at which the material is damaged. It was also found that if the tool is also heated this allows the material to be pre-heated to a lower temperature and still be formed successfully. This is due to the fact that when the tool is cold the material in turn cools very rapidly when contact is made and so a higher temperature is required to begin with. With the finding that the critical factor in moulding this sheet material was the moulding temperature verses the pre-heating temperature a method of deducing the time between heating and moulding was needed.

In initial investigations the material was pre-heated in an oven and manually removed and placed in the mould. A system was developed to allow the material to be heated, and transferred to the mould very rapidly. The system incorporated two heated plates which were accurately temperature controlled. The material was place between these plates which closed to ensure good contact on both sides of the sheet for rapid heat transfer. Upon reaching the correct temperature the plates opened and a carriage shuttled back over the material. This carriage picked up the material using vacuum and shuttled forward over the compression tool. On reaching the end of the run the carriage dropped the material onto the compression tool and shuttled back out of the way. The compression tool then closed and the part was moulded. This system enabled the material to be transferred from the heaters to the compression tool in just over 2 seconds, whereas previously this figure had been approximately 15 seconds. This significant reduction in time meant a significant reduction in heat loss during transfer. With the material at a higher temperature during moulding, more extreme shapes are able to be moulded without risk of damage to the material from overheating. Other advantages this system showed were a reduction in cycle times and a decrease in energy requirements for the heating of the sheet.

In order to mould the fabric material a much lower pressure is required. Vacuum forming was investigated as a low volume, low cost method of manufacturing components. It was found that vacuum consolidation is an effective method of manufacturing relatively simple shapes which do not contain very deep draw sections or sharp concave corners. It was found that vacuum pressure was not sufficient to completely stop the highly oriented tapes within the fabric from shrinking when exposed to the moulding temperatures. To this end if the material is required to mould into a sharp concave corner as the material shrinks slightly it will pull away from the mould and form a larger radius than was desired. The self reinforced polypropylene fabric showed considerably more shrinkage that the self reinforced PET. Vacuum consolidation has been shown itself to be a good method for manufacturing low cost prototype or low volume components which do not include very extreme shapes.

A second method for forming the self reinforced fabric materials was also investigated. This also took the form of compression moulding, however in a significantly different guise to that used for forming the sheet material. As the fabric material is unconsolidated, the highly oriented reinforcement is not constrained in anyway and is free to shrink when subjected to high temperatures. Due to this fact, the fabric material cannot be pre heated and formed in the same way as the sheet and therefore must be heated while constrained within the closed tool. This method of forming requires a pack of fabric to be placed onto the compression moulding tool. The tool is then closed to constrain the material and give it the required shape. The entire assembly is then heated to the moulding temperature and cooled in order to solidify the component. Extensive investigation was carried out on ascertaining the optimum moulding temperature and pressure to achieve a high quality component while retaining a realistic cycle time.

Trimming

Trimming is an important part of the manufacturing process. It is very important, especially in industries such as automotive and aerospace, for components to be accurate in size and shape. A variety of cutting methods were investigated within the project. These materials have proved traditionally quite difficult to trim and achieve a good quality trim line on. Methods trialled were:

- Water jet cutting
- Laser cutting
- CNC machining with both abrasive and shear cutters

Water jet cutters tended to cause delamination between the layers of the material. Laser cutting proved to be very accurate and very repeatable; however a melted burr was left around the trim line which in itself needed cutting off the part. CNC machining gave the best results overall. Using several passes with different cutters a neat, accurate and repeatable trim line was achieved. This was first trialled on thin sheets but through the project has been scaled up to cutting material of up to 9mm thick whilst still achieving the same quality of trim as on the thinner initial tests.

Painting/Coating

Many applications in various industry sectors require components to have specific surface finishes, whether they are purely for aesthetic reasons or something more technical such as wear resistance. Polypropylene is traditionally a very difficult material to apply an additional surface finish too due to its very low surface free energy. This project aimed to achieve the following surface effects on moulded self reinforced PP components:

- Abrasion Resistance
- UV Stability
- ‘Soft’ Touch Finish
- Electromagnetic Transparency or Conductivity
- Heat reflection

Several methods of achieving adhesion between polypropylene substrate and the coatings were trialled, the most successful of which were using an aggressive solvent wipe before coating, which is of course undesirable, and adding a nylon veil to the surface of the material during moulding. The nylon veil promoted good adhesion to applied coatings to its much higher surface free energy. All the desired surface finishes were achieved. We developed a particularly successful way of colouring components by using in-mould films and sheets (figure 4). This has the additional advantage of not requiring an additional operation in the form of coating the already moulded component.

Figure 4. A selection of coated SRPP samples

Joining

The ability to join different components together is fundamental to the assembly of systems from multiple components. As with the painting of PP and thus SRPP it is very difficult to join components together using adhesives. This project performed lab tests on a variety of different adhesives coupled with different surface preparation techniques such a solvent wipes and plasma treatment. Good adhesion was achieved on all types of SRPP supplied using an acrylic based adhesive developed by a small but established adhesives company.

Demonstrator Components

SmartPRESS 2 involved the manufacture of two demonstrator components which were specified by external companies. These specifications were taken and the components and tooling designed. Moulded components were manufactured and put through performance tests as required by each specific application. The two components chosen to act as the demonstrators were:

- A Ballistic Cap
- An Aerospace Component

Ballistic Cap

The ballistic cap was a challenging component first and foremost as it had to provide protection against a ballistic attack. The shape of this component was challenging to mould in itself as it incorporates deep draw depths, complex curvatures and undercuts. This component was required to be very accurate in size as it was designed to affix on top of an existing helmet already in production.

The part was manufactured to 9mm thickness to meet the ballistic requirements. Due to the thickness of the components and the deep draw depth it was decided that the part would be manufactured using self reinforced polypropylene in fabric form. As such, the tooling was designed with a complex system of pipes within it for the purpose of independently heating and cooling the tool and material quickly and efficiently. After several iterations the component was successfully moulded using a complex pack of material with 4 different shaped blanks within it.

The part has been moulded and trimmed using the CNC machining technique developed within the project. The component has been designed to meet NIJ 0106 level 2 (US body armour) specification, providing protection against 9mm full metal jacket rounds.

Figure 5. Prototype ballistic cap in situ on a helmet

Aerospace Component

The aerospace component was a very large component (950mm diameter) with a very deep, almost vertical draw. This component had very high tolerance requirements in both thickness and overall dimensions. As with the ballistic cap, fabric was chosen over sheet material for this component due to the very deep draw required. The tooling for this moulding was particularly complex due to its large size coupled with the high tolerance requirements. This tool again was a cast tool with a system of heating and cooling pipes within it. Thermal expansion of the tool had to be factored into the design. The tool included internal stops for accurate thickness control. This tool also featured a previously untried pneumatic clamping plate to restrain the fabric pack while the mould is closing. The last feature of this tool was a pre-loading plate, this allowed the fabric to be laid onto a rigid plate and then placed in the press, loading a pack of fabric of the size and thickness required would have been almost impossible without this feature.

This part moulded very well due to the careful consideration that was put into the tooling design. The part has met all specifications for tolerances as well as performance tests carried out both independently and when assembled within the complete system for which it was intended.

Figure 6. Prototype aerospace component

CONCLUSIONS

The self reinforced polymer composites industry is growing at a high ratey with increasing interest and usage. The SmartPRESS 2 project has developed effective forming techniques for both fabric and sheet forms of SRP composites. The project has also developed suitable post processing technologies in trimming, joining and paining/coating of moulded SRP composite components. Finally the project demonstrated that SRP composites can be used to produce high quality high performance components for a wide variety of different industrial sectors.

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