

Effects of Calcium Carbonate, Talc, Mica, and Glass-Fiber Fillers on the Ultrasonic Weld Strength of Polypropylene

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ABSTRACT: The objective of this work was to study the differences in the ultrasonic weld strength of polypropylene compounds with different fillers. The fillers were calcium carbonate, talc, mica, and glass fibers. The welder parameters were varied to determine the optimum set. These welder parameters were the weld time, weld force, trigger force, and amplitude. The results indicated that the weld time had the greatest effect on the weld strength of each of the filled compounds. Unfilled polypropylene had the high-

est weld strength under the optimum welding conditions, which were used as the baseline welding conditions. For each given filler, the weld strength was reduced as the filler loading increased. © 2004 Wiley Periodicals, Inc. *J Appl Polym Sci* 94: 1986–1998, 2004

Key words: adhesion; fillers; interfaces; mechanical properties; strength

INTRODUCTION

There are many techniques available for joining thermoplastic materials to themselves. The major methods are mechanical fastening, adhesive bonding, solvent cementing, and welding. Mechanical fastening is suitable for all material types, but it introduces stress concentrators and fatigue problems. Adhesive bonding and solvent cementing both suffer the disadvantage of adding a third component to the two parts to be joined. Welding by heat, or thermal welding, has the advantage of not usually requiring a third component.

Thermal welding^{1–8} can be accomplished with many techniques, including hot-plate welding,⁶ induction welding,⁷ vibration welding, spin welding,⁸ and ultrasonic welding.^{1,2} Several factors must be considered to determine the best welding technique for a specific project. These factors include the strength required, the size and shape of the parts to be joined, the types of plastics, and whether or not the joint must be concealed. Because of these considerations, ultrasonic welding has become a widely used method.^{1,2}

Ultrasonic welding can be used on both filled and unfilled thermoplastic materials. Fillers are added to resins for a variety of reasons, such as cost reduction, increased impact resistance, increased stiffness, and the modification of mechanical, thermal, or electrical properties of the base polymer.³

In this work, a Herrmann ultrasonic welding machine was used to study the effect of fillers on the ultrasonic welding of polypropylene (PP). The fillers used in this study were calcium carbonate (CaCO₃), talc, mica, and chopped glass fibers. These fillers were chosen because of their wide use in plastic materials. The filler concentrations were 10, 20, 30, and 40 wt % for CaCO₃, talc, and mica. The glass fiber was added at 10 and 20 wt % concentrations. The effect of the filler type and filler percentage on the weld strength was investigated. The morphology of the fractured weld surfaces was correlated with the weld strength via scanning electron microscopy (SEM).

Ultrasonic welding

Ultrasonic welding is a widely used welding method.^{2,9} The advantages of the process include low cycle times, easy incorporation into automation, and low-to-moderate capital equipment costs. It uses high-frequency, low-amplitude vibrations to generate heat at the joint interface of the parts being welded. The two parts to be joined are held together under pressure during the process, and a bond forms upon the cooling of the molten polymer at the interface.

The basic equipment of an ultrasonic welding system includes a power supply, a converter,^{10,11} a booster, and a horn.¹² The power supply transforms 50/60-Hz electrical power into ultrasonic power at the desired frequency. The usual frequency levels are 20 and 40 kHz. Higher frequencies tend to be used with small, delicate parts because of the low-amplitude characteristics of high-frequency systems.

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The ultrasonic welding process results in dilational vibrations transmitted from the stack to the parts being joined. A stationary wave field forms in the joined parts. For a beam of constant dimensions, the points of maximum vibrational amplitude occur first at a length of $\lambda/4$, second at a length of $3\lambda/4$, and n th at a length of $n\lambda/2 + \lambda/4$ (where λ is the wavelength).¹³

Important process parameters in ultrasonic welding include the weld time, trigger force, weld pressure or force, hold force, hold time, power level, and amplitude. The horn down speed has also been shown to have an effect on the weld strength.^{14,15}

The weld time is the amount of time for which the actual welding process or ultrasonic vibration is active. Increasing the weld time generally increases the weld strength until an optimum time is reached.^{2,9,16,17}

The trigger force is the amount of force that must be developed by the horn pressing against the parts before the ultrasonic power is turned on. Higher trigger force settings result in higher levels of contact between the weld surfaces, facilitating diffusion. Higher horn descent speeds give similar results.^{14,15}

The weld force is the amount of force applied to the welded parts during the actual welding process (while the ultrasonic power is on). The weld force allows for the transmission of vibratory energy through the parts. Low weld forces can be expected to result in poor energy transmission, whereas high weld forces may result in increased melt volume and molecular alignment in the flow direction.^{9,16,18}

The hold force is the amount of force applied to the parts after the ultrasonic power is terminated. The parts are clamped at this force level for a predetermined amount of time, which is called the hold time. The purpose of the hold force is to keep the parts in contact while the molten plastic cools.

The power level available from the generator affects the success of the process. Selecting a generator with insufficient power causes excessively long weld times. Typical generator power levels are 1000, 2000, 3000, and 5000 W. Larger parts require larger power levels.¹¹

The amplitude is the physical displacement at the face of the weld horn during ultrasonic vibration.

The vibrational amplitude is proportional to the applied strain at the mating surfaces to be joined. The average heating rate (Q_{avg}) in the energy director (described later) is dependent on the strain (e_0), the frequency (w), and the complex loss modulus of the material (E'') through the following equation:

$$Q_{\text{avg}} = we_0^2 E'' / 2 \quad (1)$$

The complex loss modulus of thermoplastic materials is highly temperature-dependent. As the temperature

is increased, the loss modulus increases, and this results in a rapid rise in the weld interface temperature.^{9,16-21}

Joint design

Joint design is possibly the most critical facet of part design for ultrasonic welding. The requirements for a good joint design include a small contact area initially and a uniform contact area subsequently. A uniform contact area means that the mating surfaces should be in intimate contact around the entire joint. A small initial contact area concentrates the energy and reduces the time required to start the melting;^{11,13} it is called the energy director.

The simplest joint design is a flat butt joint. This design does not have a uniform contact area, but it does not have an energy director. Melting is not initiated in any prescribed location on the flat weld surfaces. Any high points occurring from the molding process (surface asperities) will melt first. This results in long weld times and somewhat inconsistent welds.^{9,11,13} An energy director is typically a triangular bead molded into the part interface. It usually runs the length of the entire joint. The apex of the energy director is under the greatest stress during welding and is the first area at which melting occurs.^{2,11} This offers an advantage over the flat butt joint, in that the energy director is more consistent than natural asperities. The use of an energy director also results in lower weld times.

PP

PP is a semicrystalline polymer characterized by regions of ordered molecular structure. Among polyolefins, it plays an increasingly important role, as shown by its high melting temperature, low density, and high chemical inertness. In addition, its low cost gives it an advantage over many other thermoplastic materials.

Fillers

The term *filler* describes any relatively inert material added to a plastic material to modify its mechanical, thermal, electrical, and flow properties, chemical resistance, or dimensional stability or to lower its cost.

Fillers comprise a broad range of particle sizes and shapes, and many undergo surface treatments before use. Surface treatments are usually in the form of wetting agents (surfactants) used to aid in the dispersion of the particles. Surfaces can also be treated with coupling agents to aid in the bond between the filler and the polymer matrix.²²

The shape of the filler can greatly influence the properties of the compound. Flakes or fibers have aspect ratios enabling them to act as reinforcements, improving strength anisotropically. Spheres have an

aspect ratio of one and produce composites with isotropic properties. The surface area of the filler particles can have a great effect on the properties of the compound, especially if surface modifiers are used or the matrix is a polar polymer. The uniform distribution of fillers is important, so that as many polymer chains as possible can be in contact with the filler surface.²³

The size of filler particles has been shown to have an effect on the mechanical properties of polymer compounds. For a constant volume, a decreasing filler particle diameter correlates with an increasing modulus, increasing tensile strength, and decreasing elongation.²⁴ It has been theorized that this expresses a dependence on the surface-to-volume ratio of the filler.

CaCO₃

CaCO₃ is the most abundant white mineral in the earth's crust. It is one of the most widely used fillers in thermoplastics. It is low-cost, nontoxic, odorless, white with a low refractive index, soft, dry [no water of crystallization], and stable over a wide temperature range.²⁵

Talc

There are several forms of ore from which talc can be made. The talc mainly used as a filler for thermoplastics is a finely ground platy material with the following composition: SiO₂ (40–62%), MgO (30–33%), H₂O (16–17%), Al₂O₃ (0.2–11%), and Fe₂O₃ (0.1–1.5%).²⁶ The unique features of talc are its softness (Mohr's hardness = 1.0–2.0), lubricity (due to weak van der Waals forces holding the layers together), and excellent wetting and dispersion properties.²⁷ Pure talc is the softest known mineral.

Composites filled with platy talc always exhibit higher stiffness and creep resistance, both at ambient and elevated temperatures, in comparison with compounds containing other particulate fillers.

PP is the largest volume plastic used with talc.²² Because of the platy geometry of talc (high aspect ratio), it is often classified as a reinforcing filler to distinguish it from other particulate mineral fillers.

Mica

Mica is an abundant class of minerals, including commercial varieties such as muscovite and phlogopite. Most micas are predominantly aluminum silicates of potassium, which may also contain various proportions of magnesium, iron, lithium, or fluorine. Mica is easily cleaved into thin flakes by ordinary grinding methods and is often delaminated into very thin flakes with special methods. These ultrathin flakes have very

high aspect ratios and impart a high level of reinforcement when used as fillers in thermoplastic materials.²⁸

In addition to high stiffness, mica imparts high dimensional stability and good dielectric properties to plastics. Its main use in the plastics industry is in electrical applications, although it has been used as an inexpensive substitute for glass fibers in PP parts.²⁷

Glass fiber

Glass fibers are the most commonly used reinforcements in the polymer industries. They are often modified with silanes to promote adhesion to the polymer matrix. Glass fibers favorably influence the modulus of elasticity and shrinkage.²⁶

Filled PP

PP is known to suffer from poor adhesion to fillers such as CaCO₃, talc, mica, and glass. In some cases, carboxyl groups have been grafted onto PP for enhanced adhesion with these common fillers.²⁹ This type of modification has not been implemented as widely as the incorporation of surface modifiers on the fillers themselves.

There are many types of surface modifiers for fillers designed to affect interactions with PP. Stearic acids are often used to reduce aggregation, resulting in better dispersion of the filler. Surface treatments with stearic acids have been shown to result in decreases in matrix–filler adhesion,^{30,31} although one source claims that they improve mechanical properties through increased wetting of the filler surface by polymer molecules.³²

Surface modifiers with silanes have had mixed results with PP. They have not worked well with talc.²⁶ Mica and glass fibers have occasionally shown improved bonding with PP when treated with silanes.³³

Polymer layers are rarely used surface modifiers for improved filler–PP interactions. Typically, maleic anhydride or acrylic acid modified PP is added to the filler surface during processing. Interdiffusion between this layer and the matrix results in increases in the strength.³⁴

PP readily accepts CaCO₃ with a particle size of less than 3 μm at loadings of up to 40%. CaCO₃-filled PP is often used in automotive panels and in PP films. Its high stiffness allows it to be used in load-bearing structural applications. Because of the low aspect ratio of CaCO₃, it often gives higher knit-line strengths than many other fillers.^{25,26,35}

The effect of the CaCO₃ filler concentration on the viscosity of PP compounds has been found to be positive. The viscosity increases with increasing filler concentration. The melt viscosity decreases with increasing temperature, and the effect of the temperature on the viscosity appears to be independent of the filler

concentration.³⁶ The addition of stearic acid can lower the viscosity in comparison with that of compounds involving an untreated filler.

There are many commercial grades of PP incorporating talc at loadings of up to 40%. The major applications are in the automotive and appliance industries because of the increased stiffness and high-temperature creep resistance.

The use of talc as a filler for PP results in a higher tensile yield strength and flexural modulus in comparison with those of CaCO₃-filled PP. The impact strength of PP is lowered by the addition of talc. Unfilled PP has a notched Izod impact strength of 0.58 ft-lb/in., 20% talc-filled PP has a strength of 0.47 ft-lb/in., and 40% talc-filled PP has a strength of 0.42 ft-lb/in.³³

The viscosity of talc-filled PP exhibits a dependence on the filler concentration similar to that seen for CaCO₃-filled PP.³⁷

Mica-filled PPs are less prevalent than CaCO₃-, talc-, and glass-filled PPs. One reason is that normal screw compounding of mica-filled PP leads to a decrease in the flake aspect ratio. Mechanical degradation of the mica flakes can also occur during processing, such as injection molding or extrusion.

The flexural modulus of mica-reinforced PP is greater than that of unfilled PP. PP with 40% mica resulted in 8 GN/m²; the modulus for unfilled PP was 1.7 GN/m².³⁸

The incorporation of mica into a PP matrix increases the viscosity of the polymer. At low shear rates, a loading of 20% mica increases the viscosity 1.09 times over that of unfilled PP, and 40% mica increases the viscosity 1.17 times over that of unfilled PP.³⁸

In the United States, glass-fiber-reinforced PP is the most widely used of all reinforced thermoplastics.²⁶ The glass fibers are available in a range of diameters and lengths. The addition of glass fibers imparts high toughness, high stiffness, and high tensile strength to PP over a wide temperature range. Disadvantages include the orientation effect, reduced impact strength, and abrasion on processing machinery.

The viscosity of glass-fiber-filled PP is increased by an increase in the filler concentration. The effects of the fillers on the viscosity decrease with an increasing shear rate.³⁹

Welding of filled polymers

There are many studies involving the remelting and reprocessing, or welding, of filled polymers.⁴⁰ Relatively few of these involve the ultrasonic welding of filled PP, possibly because of the difficulty in achieving strong bonds in PP through this method. Studies on filled PP usually involve other welding processes.

TABLE I
Physical Properties of Montell 6323

| | |
|-----------------------|-----------------------|
| Density at 23°C | 0.9 g/cm ³ |
| Tensile yield stress | 34 MPa |
| Tensile modulus | 1200 MPa |
| Hardness (Rockwell R) | 88 |
| Melting point | 165°C |

EXPERIMENTAL

Materials

The PP used in this research was a general-purpose homopolymer (grade 6323) from Montell USA, Inc. (Lansing, MI). It was an injection-molding-grade. The physical properties are given in Table I.

Four different types of fillers were used. The fillers were CaCO₃, talc, mica, and glass fibers.

CaCO₃ was supplied by Specialty Minerals, Inc. (New York, NY). Its trade name was Hi-Pflex 100. The average particle diameter was 3.5 μm, with a range of 0.5–11 μm. It was treated with 3% stearic acid. The specific gravity was 2.71.

The talc was supplied by Polar Minerals (Mt. Vernon, IN). Its trade name was Polar 9102. It was platy, and the average particle diameter was 2.5 μm, with particles as large as 10 μm. It was an untreated talc, and its specific gravity was 2.71.

The mica was supplied by Zemex Industrial Minerals (Atlanta, GA). Its trade name was Suzorite 200. It had a high aspect ratio, with the particles having a 45-μm diameter on average. It was an untreated mica, and its specific gravity was 2.73.

The glass fibers were supplied by PPG (Pittsburgh, PA). The trade name was Maxi-Chop 3298. The diameter was 13 μm, and the length was 1/8 in. It had a silane surface treatment, and its specific gravity was 2.54.

The filler concentrations chosen for this study were 10, 20, 30, and 40 wt % for CaCO₃, talc, and mica. The glass fiber was added at 10 and 20 wt % concentrations.

Compounding

PP was melt-blended with the four fillers with a Japan Steel Works (Tokyo, Japan) 30-mm corotating intermeshing twin-screw extruder.

In the case of the talc and CaCO₃ fillers, the filler was tumble-mixed with PP in the proper proportions before extrusion. The resulting mixture was then fed through the first hopper on the extruder.

The glass fiber and mica compounds were produced by PP being fed through the first hopper and by the filler being added through the second hopper at the appropriate percentage. This was done to minimize

TABLE II
ASTM Bar Molding Conditions (Boy 155 Hydraulic Injection-Molding Machine)

| | |
|--------------------|-------------------------------|
| Zone 1 temperature | 207°C |
| Zone 2 temperature | 207°C |
| Nozzle temperature | 100% rheostat |
| Injection time | 19 s |
| Cure time | 18 |
| Injection speed | High |
| Injection pressure | 42.5 MPa (4.69 MPa hydraulic) |
| Clamp pressure | 22 MPa |
| Screw speed | 200 rpm |

any mechanical damage to the large glass-fiber and mica particles during extrusion.

In all cases, the extrudate was discharged through a die plate and into a water bath. The quenched strands were then pelletized. The extruder processing temperatures were 200°C at the hopper, 235°C through the remaining zones, and 240°C at the die. The material was extruded at a screw speed of 100 rpm.

Injection molding

The injection molding of the compounds took place on two machines. A Boy (Neustadt-Fernthal, Germany) 15S hydraulic injection-molding machine was used to mold the tensile bars for the subsequent determination of the mechanical properties of the base compounds. A Van Dorn (Strongsville, OH) 120HT3 toggle-type injection-molding machine was used to mold the welding specimens.

The tensile bars were molded in a standard ASTM mold. The Boy 15S hydraulic machine had a 15-ton clamp capacity, three temperature zones, and a 24-mm

screw. The injection-molding conditions used with this machine are presented in Table II.

The welding specimens were molded in a two-cavity, two-plate mold, with cavity blocks fabricated to mold the parts to the dimensions shown in Figures 1 and 2. The Van Dorn 120HT3 machine had a 120-ton clamp capacity, four temperature zones, and a 30-mm screw. The injection-molding conditions used with this machine are presented in Table III.

The welding specimens were molded according to the dimensions proposed by the American Welding Society (AWS) as a standard for evaluating ultrasonic welds. Specimen 1 had an energy director that mated against a butt surface on specimen 2. The energy director was triangular, with a 0.61-mm base and a 0.38-mm height. The sharp angle on this energy director was reported to give better results with semicrystalline resins, such as PP.¹¹ The 0.610-mm energy director base was approximately $W/4$, W being 2.388 mm for this joint.

Ultrasonic welding

The ultrasonic welding took place on a Herrmann (Schaumburg, IL) model 2012 2000-W ultrasonic welder. The weld horn was a step type, with a flat face, which touched the top specimen (AWS specimen 1) on its top surface. The gain structure of the horn was 1:2.4, which meant that it increased the amplitude by a factor of 2.4 from that seen at the top face of the booster.

The amplitude seen at the bottom of the converter was 10.8 μm . Various boosters were used between the converter and the horn to achieve final amplitudes of 38.9, 45.6, and 51.8 μm for this study.

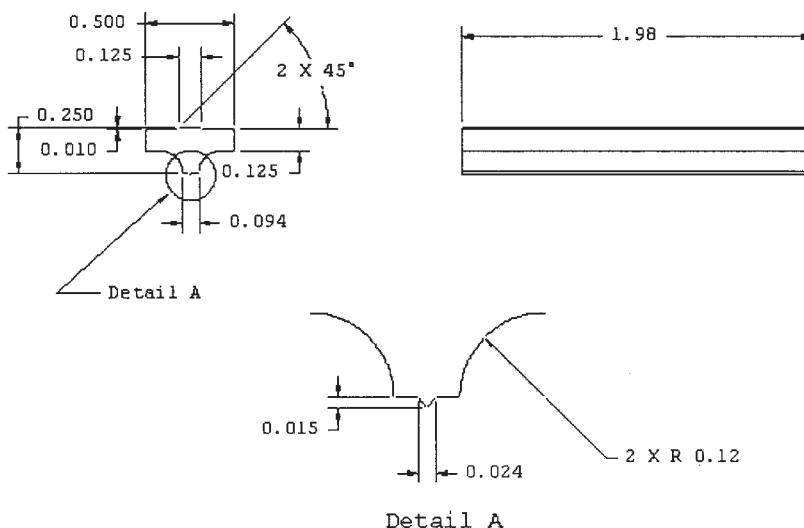


Figure 1 AWS ultrasonic welding specimen 1.

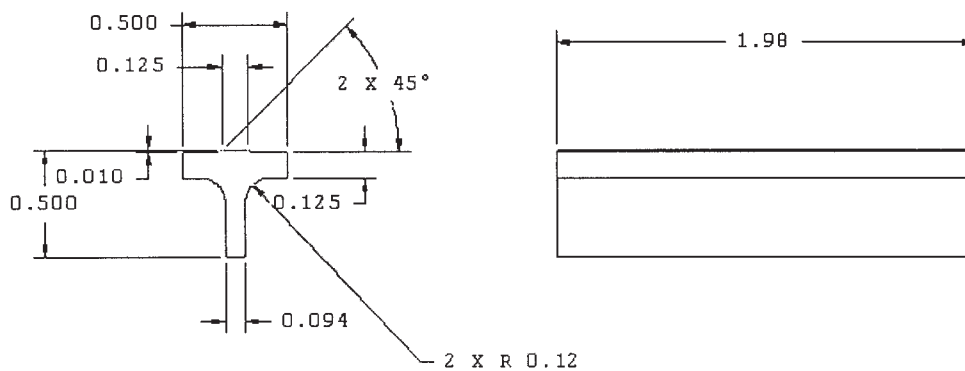


Figure 2 AWS ultrasonic welding specimen 2.

Fixtures were designed and fabricated to hold the parts during the welding cycle. The parts were held in place in the fixture by slides that were fastened into the fixture base. The fastening bolts were tightened before each weld cycle to ensure that the parts were held tightly in a consistent manner.

The welder settings of the weld time, weld force, trigger force, and amplitude were varied during the study to determine the effects that they had on each compound. These variables were chosen on the basis of the literature, which showed them to be the most influential on the process, with the replacement of the horn down speed by the trigger force.^{9,13,15,16,41} The horn descent speed cannot be expressly set on a Herrmann ultrasonic welder. The trigger force setting actually changes the descent speed for Herrmann machines. This is a fundamental difference between Herrmann units and most other machines, such as those manufactured by Branson, Dukane, and Sonics.

A preliminary study was conducted to determine the baseline welding conditions. The baseline welding conditions were chosen according to the combination of process variables that resulted in the highest weld strength for unfilled PP samples. The strategy used in arriving at the baseline conditions involved first determining the optimum weld time for unfilled PP while all other variables were held constant. The am-

plitude, weld force, and trigger force were then optimized in that order.

The weld depth and weld energy were noted from each trial. The weld depth is the horn displacement seen during welding (from the moment at which the trigger force is achieved until the moment at which the ultrasonic energy is terminated). This value was measured with a linear transducer next to the weld stack.

Tensile testing

The welded samples were tested for the strength of the weld with an Instron (Canton, MA) 4204 testing machine. The tensile test fixtures were built specifically for these parts. The tensile load cell used in performing these tests was a 50 kN load cell. The crosshead speed was 10 mm/min. The gauge length was 50.8 mm for the tensile bars and 6.4 mm for the welded samples. The mechanical properties of each compound were also determined by the tensile testing of molded ASTM bars.

SEM

The welded samples, broken at the weld plane, were used to study the fractured surfaces with SEM. SEM was also performed on unwelded samples to determine the dispersion of the fillers in the joint area. The samples were submerged in liquid nitrogen to bring them below the glass-transition temperature, and they were fractured perpendicularly to the weld plane.

RESULTS AND DISCUSSION

Determination of the baseline conditions

Before the ultrasonic welding of each compound, the baseline welding parameters were determined through a preliminary study with unfilled PP. The weld time was first varied from 0.05 to 0.75 s,

TABLE III
AWS Specimen Molding Conditions (Van Dorn 120 HT3 Toggle)

| | |
|--------------------|------------------------------|
| Zone 1 temperature | 194°C |
| Zone 2 temperature | 194°C |
| Zone 3 temperature | 194°C |
| Nozzle temperature | 200°C |
| Injection speed | 51 mm/s |
| Cure time | 20 s |
| Hold pressure | 117 MPa (11.7 MPa hydraulic) |
| Hold time | 16 s |
| Screw speed | 200 rpm |
| Back pressure | 0.34 MPa |

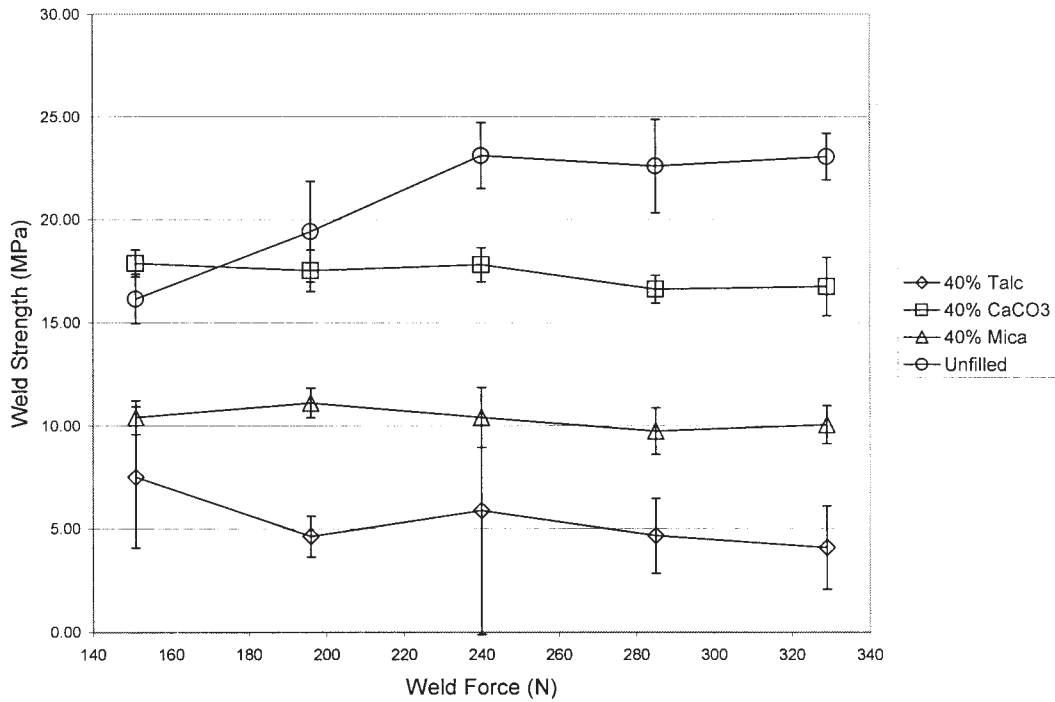


Figure 3 Effect of the weld force on the weld strength at a 40% filler concentration and a comparison with unfilled samples.

whereas the other settings were kept constant (amplitude = 51.8 μm , weld force = 196 N, and trigger force = 80 N). The welded specimens were then tested to determine their weld strength. On the basis of these results, the baseline settings were determined to be a 0.25-s weld time, a 240 N weld force,

a 93 N trigger force, and a 51.8- μm amplitude. The effects of the weld force and amplitude on the weld strength at a 40% filler concentration are compared with those for unfilled PP in Figures 3 and 4 to illustrate the baseline conditions for the weld force and amplitude and to show the resulting reductions

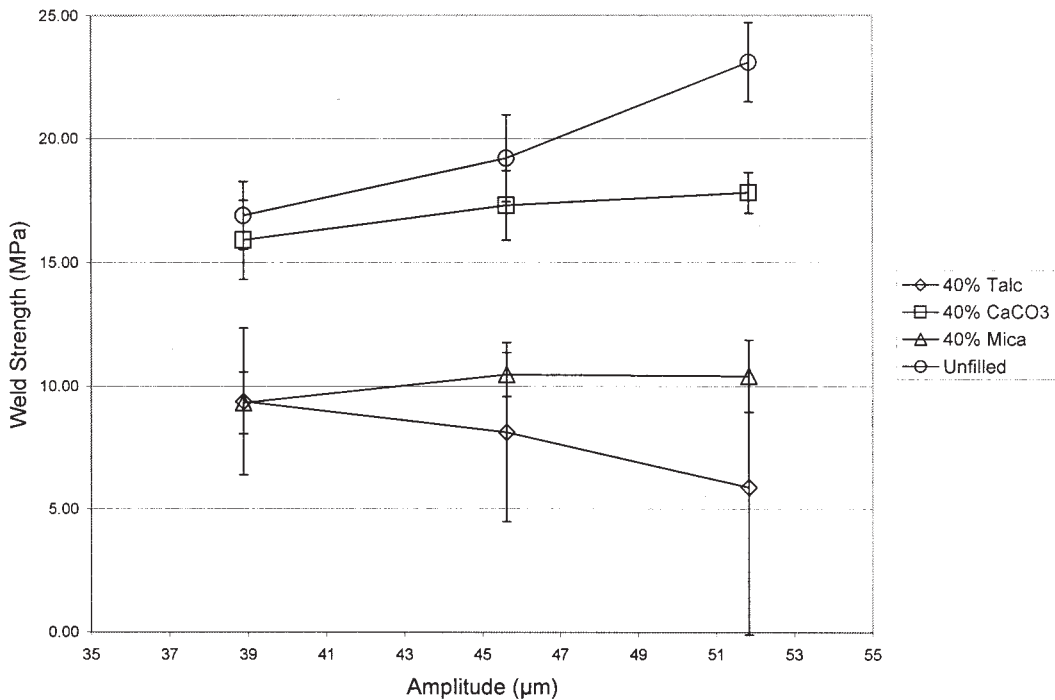


Figure 4 Effect of the amplitude on the weld strength at a 40% filler concentration and a comparison with unfilled samples.

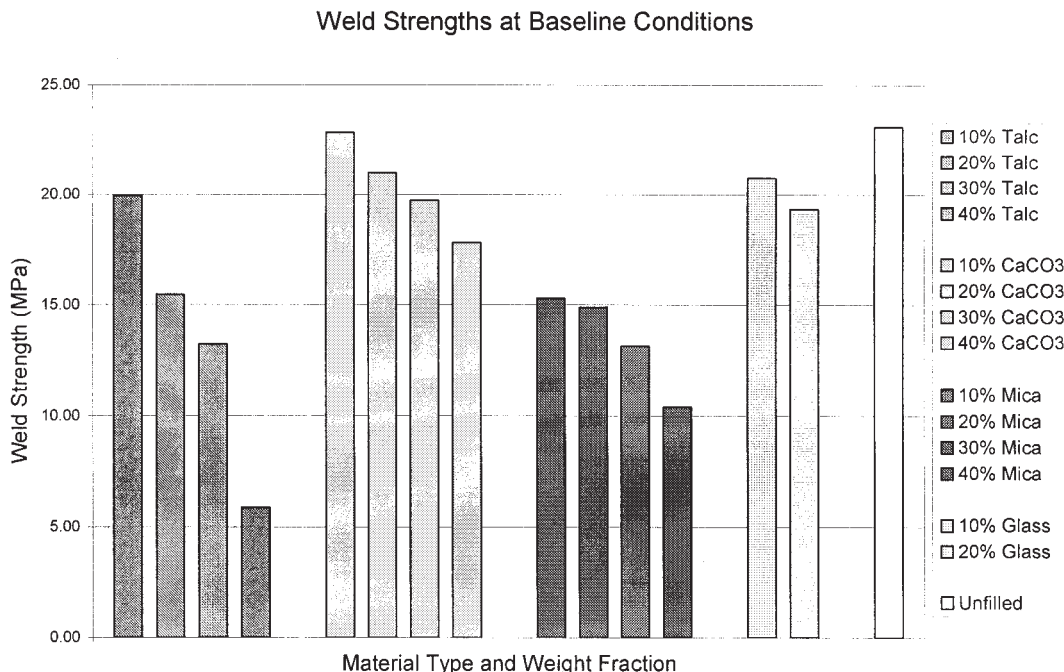


Figure 5 Weld break strengths under baseline conditions.

in the weld strength from those values as a result of filler addition at such a high level.

Effect of the filler type and level on the weld

Strength under the baseline conditions

Specimens molded from each of the compounds (including unfilled PP) were ultrasonically welded with

the baseline welding conditions. Five trials were conducted per compound. The weld break strengths, as determined through tensile testing, are shown in Figure 5. The elongation-at-break values for the same samples are shown in Figure 6.

The unfilled PP had the highest weld break strength at 23.10 MPa. The next highest strengths were achieved with 10 and 20% CaCO₃ (22.84 MPa and

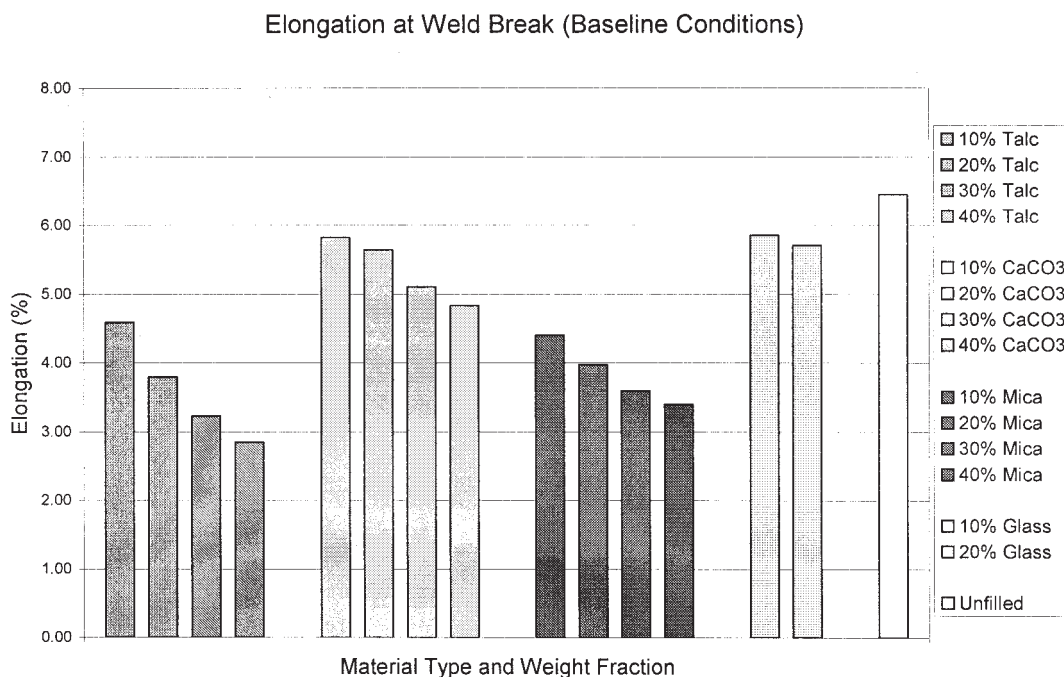


Figure 6 Elongation at break under baseline conditions.

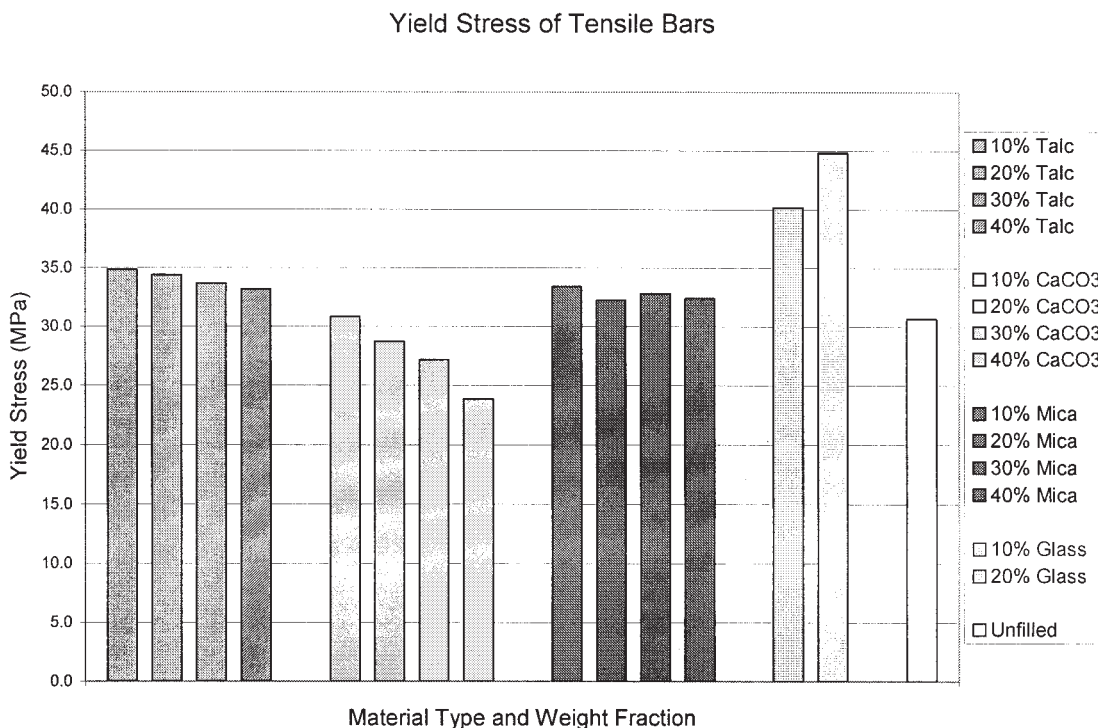


Figure 7 Yield stress of tensile bars.

21.00 MPa, respectively). The specimens with higher weld break strengths showed higher elongation at break in general.

The lowest break strength of 5.88 MPa was seen with the 40% talc compound. The top specimens molded from this material developed cracks and fractured during welding under the baseline conditions. In some cases, the bottom specimen fractured as well. This was a chronic problem for this material during the study because of the brittle nature of the compound. The elongation at break for this material was the lowest of all the compounds. None of the specimens molded from the other compounds exhibited any cracking.

For each filler type, the weld strength was at its maximum when the filler concentration was at its lowest. This was most likely due to the amount of PP available for welding at the joined surfaces. As more filler volume was added, less PP volume existed at the joining surfaces.

The highest strengths were achieved with CaCO_3 -filled and glass-filled compounds in general, whereas the talc-filled and mica-filled compounds exhibited much lower strengths. This may be partially due to the stronger adhesion between the fillers and PP in the CaCO_3 -filled and glass-filled compounds in comparison with that of the talc and mica compounds. The CaCO_3 filler was treated with stearic acid, and the glass fibers had a silane treatment, whereas the talc and mica were untreated. We must also note,

however, that the yield stress for the CaCO_3 compounds was the lowest of all the fillers, as shown in Figure 7.

A likely reason for the low weld strength with the talc-filled and mica-filled samples was the platy geometry of these fillers.

SEM study

SEM images of the fractured (by tensile testing) weld surfaces showed the orientation of these plates in a direction parallel to the joining plane. The glass fibers aligned in this fashion as well, but they were cylindrical and did not have a projected area equivalent to that of the flat platelets. The SEM images for the fractured weld surfaces of specimens welded under baseline conditions are shown in Figure 8. The images were all made at a magnification of $300\times$ and are listed by the weld break strength in descending order.

At this magnification, the large mica platelets were clearly visible, and the effects of their orientation could be seen. There was very little area within the weld plane available for the PP material to bond to itself. Very thin tendrils of the polymer rose from the fractured surface around the edges of the mica. This was the point at which the PP specimens bonded.

The talc platelets were much smaller than those of mica (2.5 vs $45 \mu\text{m}$) and were not as visible at $300\times$. When viewed at a magnification of $1000\times$ (Fig. 9), the talc platelets could be seen aligning themselves paral-

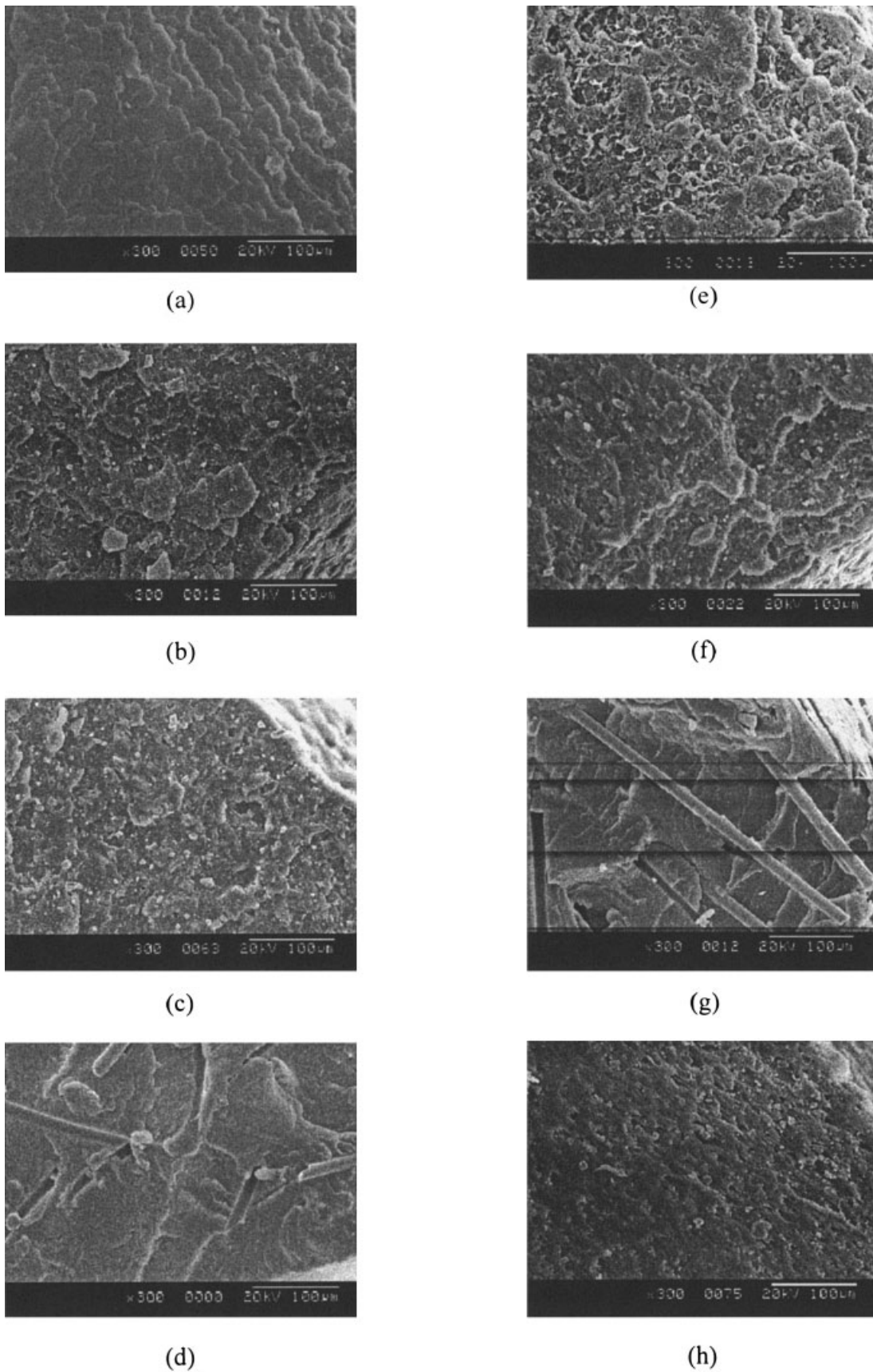
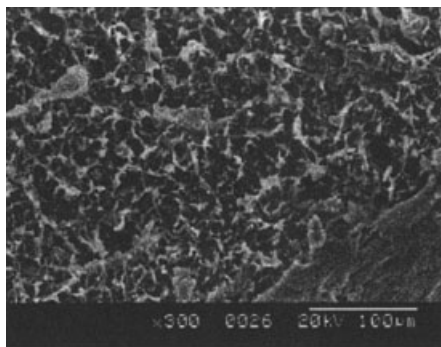
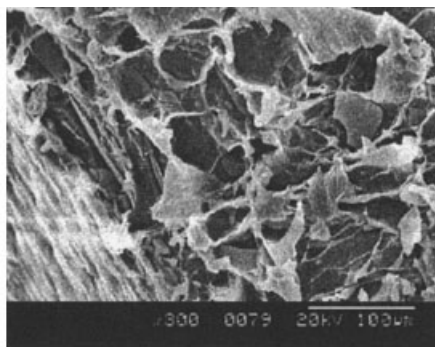


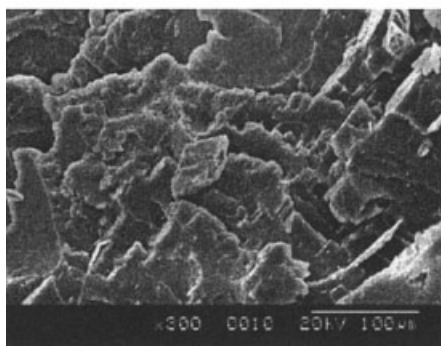
Figure 8 SEM micrographs at a magnification of 300× for postfractured surfaces of samples welded under baseline conditions: (a) unfilled, (b) 10% CaCO₃, (c) 20% CaCO₃, (d) 10% glass, (e) 10% talc, (f) 30% CaCO₃, (g) 20% glass, (h) 40% CaCO₃, (i) 20% talc, (j) 10% mica, (k) 20% mica, (l) 30% talc, (m) 30% mica, (n) 40% mica, and (o) 40% talc.



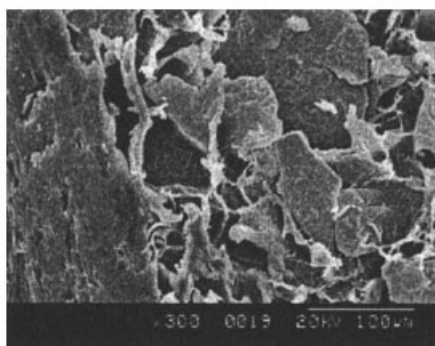
(i)



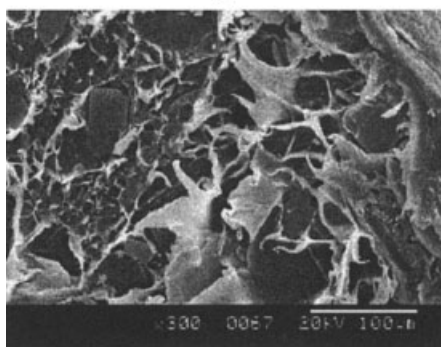
(m)



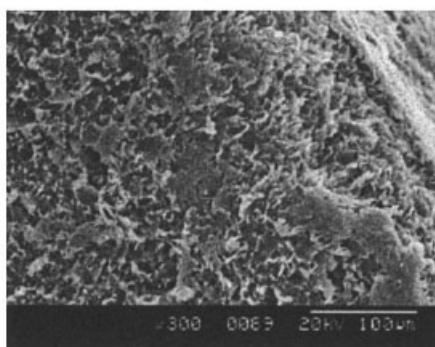
(j)



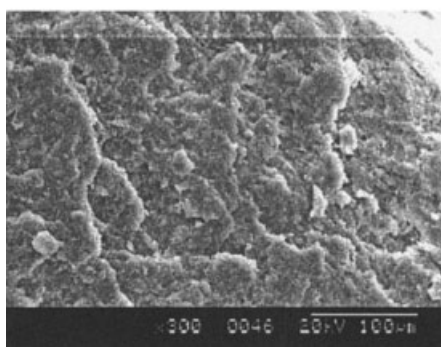
(n)



(k)



(o)



(l)

Figure 8 (Continued from previous page)

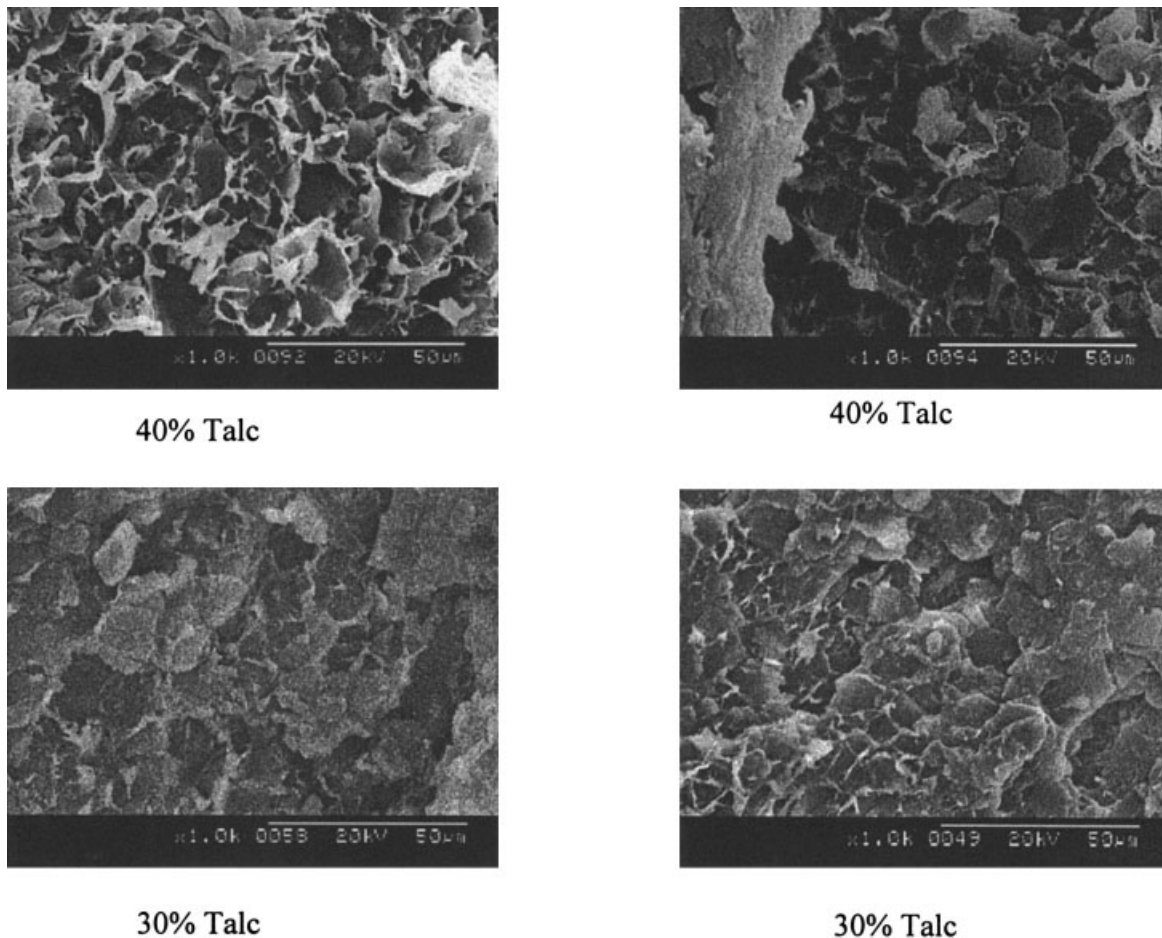


Figure 9 SEM micrographs at a magnification of 1000 \times for postfractured surfaces of samples, with 30 or 40% talc, welded under baseline conditions.

lel to the joining plane. As in the mica images, tendrils of PP could be seen coming out of the fractured surface around the edges of the talc particles.

By the filler concentration, the basic hierarchy of the weld strength in decreasing order was unfilled PP, CaCO_3 -filled PP, glass-filled PP, talc-filled PP, and mica-filled PP. The weld strength of the mica compound with the lowest percentage of the filler (10% mica) had a lower weld break strength than the CaCO_3 compound with the highest percentage of the filler (40% CaCO_3), even though the highest filler concentration resulted in the lowest weld strengths for any given filler type. This was possibly due to the platy nature of the mica versus the irregular (cube to sphere) shape of the CaCO_3 particles. The CaCO_3 particles did not orient in any particular direction and therefore did not block off the polymer from the weld plane to the same extent as the platy fillers.

The talc compounds had weld strengths that were not quite as diminished as those of the mica compounds by filler addition, with the exception of the 40% talc samples, which resulted in cracked specimens during welding. This was possibly due to the smaller plate diameters,

which resulted in more filler particles per unit of volume, so that more PP could bond between the samples around the particle edges. This difference could be seen in the 300 \times images of talc and mica.

A similar argument could also be made for the high strength of the glass-filled compounds. There was a large area at the weld plane available for the PP material, as the glass fillers had a low projected area while aligned parallel to the weld plane.

The ratio of the weld break strength to the bulk yield stress of each material is shown in Table IV. The weld strengths of the unfilled PP and CaCO_3 -filled samples were roughly three-fourths the yield strengths of these materials. The other filled compounds had markedly lower weld strengths (expressed as the percentage of the bulk yield strength).

CONCLUSIONS

The welding parameters were optimized for unfilled PP samples. The weld time had the greatest effect on the weld strength. As the weld time increased, the strength increased up to a plateau, after which further

TABLE IV
Weld Strength Versus Bulk Yield Stress

| Material | Yield Stress (Bulk; MPa) | AWS break strength (MPa) | Ratio |
|-----------------------|--------------------------|--------------------------|-------|
| Unfilled | 30.67 | 23.10 | 0.75 |
| 10% CaCO ₃ | 30.84 | 22.84 | 0.74 |
| 20% CaCO ₃ | 28.73 | 21.00 | 0.73 |
| 30% CaCO ₃ | 27.18 | 19.74 | 0.73 |
| 40% CaCO ₃ | 23.85 | 17.81 | 0.75 |
| 10% talc | 34.88 | 19.95 | 0.57 |
| 20% talc | 34.42 | 15.46 | 0.45 |
| 30% talc | 33.72 | 13.23 | 0.39 |
| 40% talc | 33.21 | 5.88 | 0.18 |
| 10% mica | 33.42 | 15.28 | 0.46 |
| 20% mica | 32.25 | 14.90 | 0.46 |
| 30% mica | 32.83 | 13.15 | 0.40 |
| 40% mica | 32.43 | 10.41 | 0.32 |
| 10% glass | 40.15 | 20.77 | 0.52 |
| 20% glass | 44.82 | 19.34 | 0.43 |

increases in time did not raise the strength or perhaps lowered it slightly. The optimum weld time for unfilled PP was 0.25 s.

The weld force increased the weld strength of unfilled PP up to a plateau at a 240 N weld force, after which further increases did not increase the strength. The trigger force had almost no effect on the weld strength. Increasing the amplitude resulted in increased weld strength for unfilled PP.

The highest weld strengths were seen for unfilled PP, followed by CaCO₃-filled and glass-filled compounds. The talc-filled and mica-filled compounds exhibited the lowest weld strengths. This was due to the platy nature of these materials. Thus, particle shape had a great impact on the strength of the welds achieved through ultrasonic welding.

The addition of fillers to PP affected the weld strength and elongation at break. With each filler type, increasing the filler level generally reduced the weld strength and elongation.

The decrease in the weld strength seen with an increased filler concentration was attributed to the lower polymer volume fraction available for welding at the weld interface. The filler particles prevented PP from bonding to itself.

The mica particles and talc particles had the greatest impact on decreasing the weld strength of PP. This was attributed to the possibly acquired orientation of the platelike particles in the direction parallel to the weld plane. This interfered with the cross diffusion of polymer chains across the weld interface.

A decrease in the elongation with filler addition was found in the tensile testing of both the bulk specimens and welded specimens. This was due to the acquired brittle nature of the compounds as the filler level was increased. The highest weld strengths were generally seen for the specimens exhibiting the greatest elongation.

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