ADVANCES IN

AUTOMOTIVE PLASTIC COMPONENTS AND TECHNOLOGY

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Advances in Automotive Plastic Components and Technology

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PREFACE

The automotive industry is a rapidly changing environment. From the annual body styling and aesthetic changes to advances in mechanical technologies of powertrains and subassemblies, automotive designers and engineers are in a constant race to improve, optimize and economize. Just when no improvement seems possible, we are surprised by the latest development that opens new doors and ways of thinking.

Advances in plastic technologies are a prime example. Plastics and resins have long been used in automotive applications, yet every year some new production process, tooling technology, design or material leads to new applications that leave us wondering "what next?"

In any given year, a number of new technologies can be identified as "cutting edge." An even longer list would be the components resulting from these advances. The SAE has invited automotive industry innovators to present their advances in plastic components and technology at the 1995 International Congress and Exhibition. Although not all inclusive, the selection of papers for this SAE special publication, <u>Advances in Automotive Plastic Components and Technology</u> (SP-1099), is an attempt to sample a cross-section of these advances in the industry. It is our hope that by gathering these presentations in a single forum, we may help further the use of plastics in automotive applications and break new ground for future innovation.

T. Michael McCormack
Teknor Apex Company

Session Organizer

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An Evaluation of the Factors Affecting Circularity of Injection Molded Thermoplastic Underhood Components

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ABSTRACT

For a number of underhood applications such as throttle bodies, tight operating tolerances require dimensional stability of the entire assembly, including both the material and the part design, under a wide variety of chemical and temperature exposures. Using a prototype air conditioner compressor housing tool, a series of design of experiments (DOEs) were conducted to identify the key processing and material factors that effect final part out of roundness properties. The initial series of DOEs included both unfilled and glass filled polyetherimides and a glass filled polyphenylene sulfide. Thirty percent glass filled polyetherimide performed best dimensionally based on both low out of roundness characteristics as well as low variability. Conversely, the highest out of roundness and variability were evident with the glass filled polyphenylene sulfide. The key processing variables which seem to effect the polyetherimides' out of roundness were injection hold pressure and cure time. Polyphenylene sulfide was affected primarily by melt temperature. Additional DOEs were conducted to investigate a wider variety of materials (base resins, filler agents and levels) and evaluate the effects of post molding conditions such as thermocycling. Ultimately, this information can be utilized to optimize the combination of materials, design features and processing conditions with the goal of meeting or exceeding the application requirements while minimizing final piece costs.

INTRODUCTION

Many powertrain and chassis applications require tight tolerance circular features. Although data sheet properties are typically reviewed to assess a material's suitability for an application, the ability to mold round, consistent dimensions with the material is less often evaluated prior to final specification and design. For applications such as throttle bodies, these circular dimensions are critical to part performance. Given the stringent requirements for some applications, several designed experiments were performed to quantify differences between materials and their abilities to achieve a high degree of circularity. These experiments were not meant to be process capability or repeatability studies but rather an evaluation of overall capability of each material.

EXPERIMENTAL PROCEDURES

In order to both evaluate and predict the possible effects of base resin, filler type, filler concentrations, process variations as well as simple design features, the study was developed using the design of experiments (DOE) methodology. Due to the large number of variables, multiple DOEs were planned. The initial screening DOEs were designed to determine the key processing variables and examine the possibility of interactions between the variables for each type of material. Additional DOEs were focused on the in-depth evaluation of many different types of materials and the key process variables. Parts were evaluated via dimensional checks for out of roundness. Surface appearance issues such as weld lines, voids, sinks, burning at the vents and glassiness were not considered in this evaluation but would be important criteria in real applications.

Out of roundness, the difference between the longest and shortest radius of a part with a defined center point, is a commonly used test in a variety of applications (automotive and non-automotive) where circularity is a critical finished part property. For example, the inner cylinder of a throttle body must be circular to ensure a tight seal between the valve and sidewall. The functionality of the assembly will be adversely effected if the out of roundness exceeds the specified tolerances. There are many methods and types of equipment available to test out of roundness and cylindricity, an indication of circularity in different planes over the length of the cylinder. A radial measurement system was utilized for this series of screening DOEs. Cylindricity was not measured in this initial study.

The tool, a single cavity prototype compressor housing, utilized in this evaluation was chosen based on accessibility as well as design similarities to small plastic or metal automotive parts such as throttle bodies. The design is not optimal. There are large variations in wall thickness from 3.2 to 15.9 mm, promoting sink and void issues. The plastic is delivered into the part via a simple system of a cold sprue with five small sub-gates spaced radially into the center bore. A number of weld lines exist due to the gating arrangement and number of bores. The basic dimensions of the cylindrical style part are 101.6 mm diameter and 50.8 mm high (Figure 1).

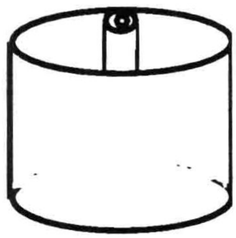

Figure 1: AC Compressor Housing

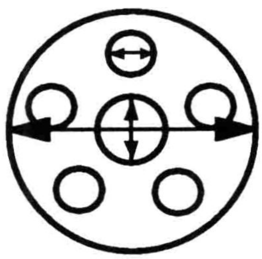

Figure 2: AC Compressor Housing (Top View)

For the initial DOE series, three different size bores (Figure 2) were tested for out of roundness. The diameters of the specified bores range from 17.8 to 101.6 mm. The two smaller bores are reinforced by the surrounding plastic. The part's outer diameter was measured in a non-reinforced area to reflect a "worst case scenario" or highest degree of out of roundness. A single boss is located in the part which has a significant effect on the outer diameter's out of roundness. To eliminate testing variation due to the taper or draft built into the tool, each of the individual measurements were made at consistent heights throughout the study. A more elaborate testing mechanism was utilized in the advanced evaluations to clearly differentiate between out of roundness due to material differences and out of roundness due to design features such as the boss.

The materials selected for this evaluation focus on the high performance amorphous and crystalline engineering thermoplastic polymers. The initial DOE included an unfilled amorphous polyetherimide (PEI), a 30 % glass filled polyetherimide and a 40 % glass filled crystalline polyphenylene sulfide (PPS). Advanced DOEs examined varying glass levels and type (fibers versus milled) in polyphenylene sulfide and polyetherimide bases, the addition of mica as a filler agent in a polyetherimide base, a glass filled polyphthalamide, glass and mineral filled crystalline polyesters and a glass filled amorphous modified polyphenylene ether/crystalline nylon alloy.

The initial screening DOEs represent the "worst case scenario." The processing variables included melt temperature, injection velocity, injection hold pressure, cure time and mold temperature (where possible). For the initial DOE series, the processing condition set points generally encompassed the extremes of the material suppliers' recommended ranges. For example, if the recommended melt temperature range was 350 to 415 °C, machine settings (such as barrel temperatures) were adjusted until the specific melt temperatures of 350 and 415 °C were achieved (within reason). Evaluation at the extremes resulted in out of roundness data which indicated the worst possible performance for each material but <u>not</u> necessarily the best. The use of extremes also made it easier to evaluate interactive effects between the variables as well as to determine which of the bores or circles should be measured in the advanced experiments.

A fractional factorial DOE matrix was utilized for each of the two polyetherimide materials (Tables 1 & 2). A full factorial DOE matrix was utilized for the polyphenylene sulfide material to improve the estimation of interactive effects (Table 3). Since the materials differ chemically, separate DOEs were planned. To maximize the amount of information gained and minimize the confusion, an individual DOE was utilized for each material. The absolute values of the factors (processing variables) differ with each type of material (amorphous versus crystalline/polyetherimide versus polyphenylene sulfide), thus the matrixes below specify levels rather than absolute numbers. The actual values are included in the results section of this paper (Table 4).

	FACTORS				
Run #	Melt Temp	Inject Velocity	Hold Press	Cure Time	Mold Temp
1	4	1	2	4	1
2	4	1	4	1	4
3	1	4	3	4	2
4	1	4	1	1	3

Table 1: Unfilled Polyetherimide DOE Matrix
Factor Level 1 => Low
Factor Level 4 => High
(3 replicates of each run)

FACTORS					
Run #	Melt Temp	Inject Velocity	Hold Press	Cure Time	Mold Temp
1	3	3	2	1	N/A
2	3	3	1	3	N/A
3	1	1	3	1	N/A
4	1	1	2	3	N/A

Table 2: Glass Filled Polyetherimide DOE Matrix
Factor Level 1 => Low
Factor Level 3 => High
(3 replicates of each run)

FACTORS					
Run #	Melt Temp	Inject Velocity	Hold Press	Cure Time	Mold Temp
1	3	3	1	1	3
2	3	3	3	3	3
3	1	3	3	3	1
4	1	1	3	1	1
5	1	1	1	3	1
6	1	3	1	1	1
7	3	3	1	3	1
8	3	1	1	1	1
9	3	3	3	1	1
10	3	1	3	3	1
11	3	1	3	1	3
12	3	1	1	3	3
13	1	1	2	3	3
14	1	3	1	3	3
15	1	1	1	1	3
16	1	3	2	1	3

Table 3: Polyphenylene sulfide DOE Matrix
Factor Level 1 => Low
Factor Level 3 => High
(3 replicates of each run)

All samples were dried according to the suppliers' recommendations and molded on a single standard injection molding machine by one operator to minimize variation. Further, a single operator was used in the testing phase. To maintain consistent overall cycle and barrel residence times, delayed injection was utilized on the shorter cure time runs. Occasionally, mold release spray was necessary to ensure part ejection due to varying material shrinkage properties and the resulting effects of increased hold pressure and temperatures. Mold temperature could not be included as a factor during the evaluation of the glass filled polyetherimide due to difficulties with the tooling.

DOE RESULTS & ANALYSIS

Due to material limitations as well as the procedures utilized in the experiments and analysis of the data, the DOE results and predictions are valid only within the tested processing ranges (Table 4). The properties of thermoplastic materials may be adversely effected if processed beyond the recommended ranges.

	Unfilled PEI	Glass Filled PEI	Glass Filled PPS
Melt Temp (°C)	670 to 790	685 to 790	585 to 645
Inject Velocity (%)	25 to 75	55 to 75	25 to 75
Hold Press (MPa)	5.52 to 12.76	2.76 to 11.03	5.52 to 11.03
Cure Time (sec)	40 to 60	40 to 60	40 to 60
Mold Temperature (°C)	198 to 265	N/A	272 to 290

Table 4: Screening DOE Ranges

A graphical representation of a typical out of roundness result is included (Figure 3). As expected, the outer unreinforced diameter with the single boss resulted in the highest degree of out of roundness for all three materials. The lowest out of roundness results were achieved with the center bore, the smallest diameter tested during this evaluation.

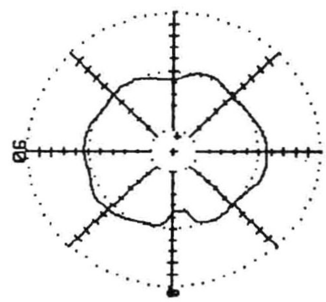

Figure 3: Out of Roundness Representation
(Glass Filled PEI)

Histograms of the outer diameter raw data indicate definite material differences (Figures 4, 5 and 6). The 30 % glass filled amorphous polyetherimide resulted in the lowest out of roundness as well as the smallest variation in out of roundness. Conversely, the 40 % glass filled crystalline polyphenylene sulfide resulted in higher out of roundness as well as a wider distribution of data.

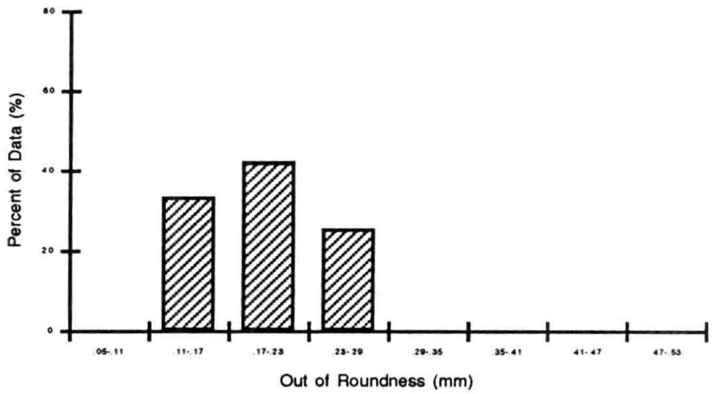

Figure 4: Histogram of Outer Diameter Data
Unfilled PEI

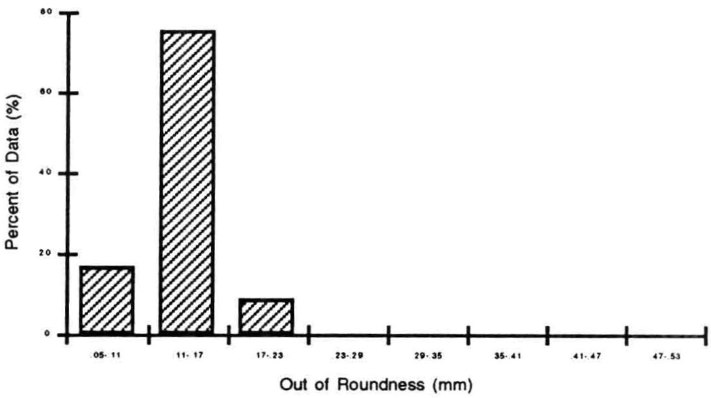

Figure 5: Histogram of Outer Diameter Data
Glass Filled PEI

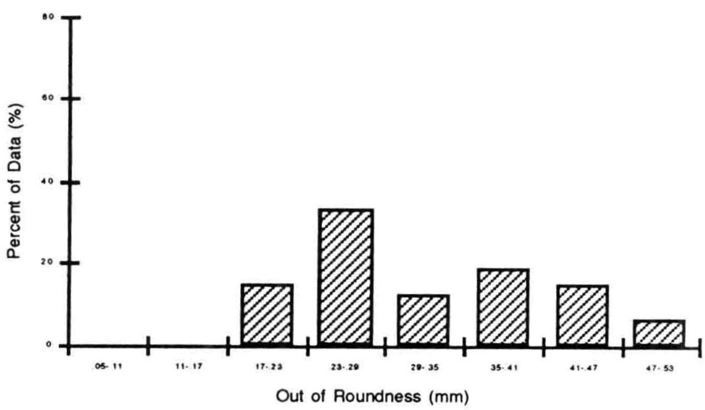

Figure 6: Histogram of Outer Diameter Data
Glass Filled PPS

Using confidence levels of 95 %, each set of material data was evaluated individually for identification of the key variables and interactive effects. The variables that had the most effect on out of roundness are hold pressure, cure time and melt temperature. The unfilled and glass filled amorphous polyetherimides were effected mainly by hold pressure and cure time whereas melt temperature had a very strong effect on the crystalline glass filled polyphenylene sulfide. For all three materials, interactive effects were found to be insignificant compared with the effects of the key processing variables. Finally, using a RS1 software package, the predicted effects of the processing parameters were determined (Figures 7, 8 and 9).

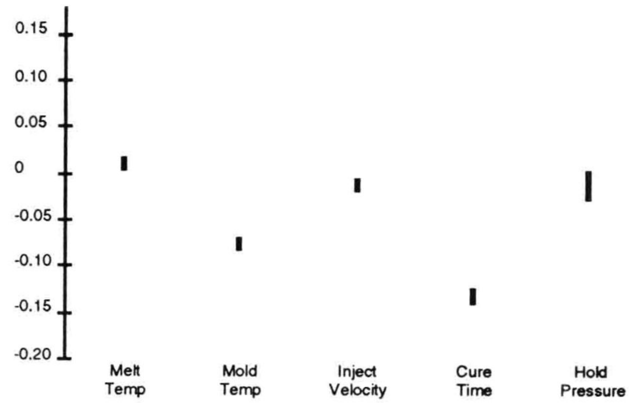

Figure 7: Processing Effects on Out of Roundness (mm)
Unfilled PEI

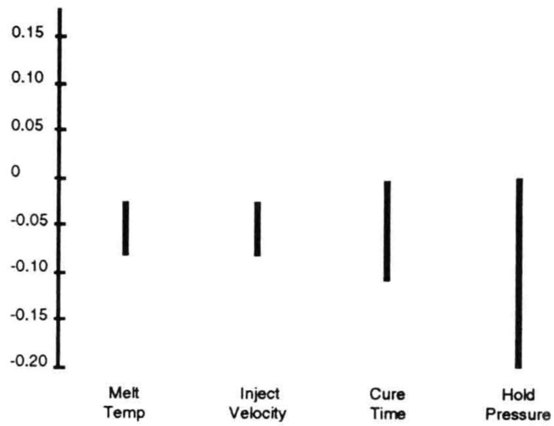

Figure 8: Processing Effects on Out of Roundness (mm)
Glass Filled PEI

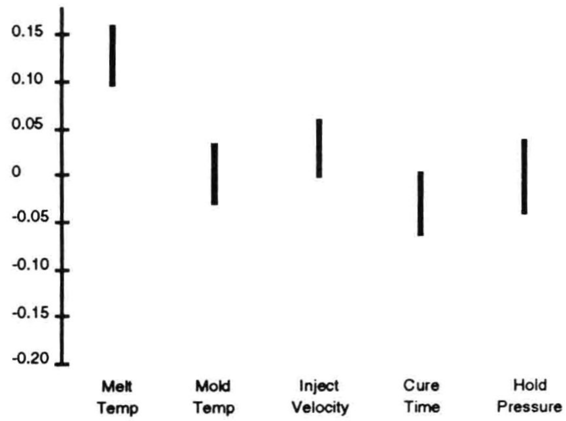

Figure 9: Processing Effects on Out of Roundness (mm) Glass Filled PPS

For the unfilled polyetherimide, increasing the cure time from 40 to 60 seconds (across the tested range) should decrease the out of roundness of the outer diameter by approximately 0.13 mm. Conversely, increasing the melt temperature from 307 to 341 °C of the glass filled polyphenylene sulfide could increase the out of roundness of the outer diameter as much as 0.16 mm. Thus, the predictions can be utilized for guidance on techniques to minimize out of roundness. Finally, when combined with cost, secondary operations and assembly considerations, the results can also be utilized to balance dimensional properties versus cost per finished piece.

CONCLUSIONS

The major findings from the initial series of DOEs are as follows:

1. Thirty percent glass filled polyetherimide performed best dimensionally of the three materials tested based on both low out of roundness characteristics and a high degree of consistency. Conversely, the highest out of roundness and variability were evident with the glass filled polyphenylene sulfide.

2. The dimensional stability of polyetherimide is affected principally by the processing parameters of injection hold pressure and cure time. Polyphenylene sulfide's dimensional stability is affected to the greatest degree by melt temperature.

Based on these results, additional DOEs evaluated:

1. A wider variety of materials including polyphenylene sulfides and polyetherimides with varying glass levels and type (fibers versus milled), polyetherimides with mica as a filler agent, glass filled polyphthalamide, glass and mineral filled polyesters and glass filled modified polyphenylene ether/nylon alloys.

2. The potential effects of post molding conditions such as thermocycling.

3. The differentiation of material and part design effects.

Alternate testing techniques such as profile testing were required to obtain the necessary information. Since the key processing variables have been identified, the DOEs were designed to include multiple factor levels to increase the confidence in the results. The data will also be useful in determining the optimum processing conditions, material combinations and design features to minimize final part out of roundness and maximize dimensional stability. Ultimately, this information can be utilized to choose the best combination of materials and design features needed to meet the applications requirements while minimizing component cost.

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Bolt Load Retention Modeling from Creep Performance Data

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ABSTRACT

Composite materials are replacing metals in a variety of engine and transmission components, including covers, manifolds, pumps and housings. In many applications, the cost and complexity of mounting boss inserts can be avoided by understanding composite creep performance and designing bolted joints for adequate bolt load retention.

A lumped element model of a bolted joint is presented. Based on empirical equations describing creep performance, the present model yields equations to predict clamp load retention in bolted joints. Load retention is aided by the elastic compliance in the fastener, and is reduced by creep compliance in the boss and gasket. To ensure adequate load retention, the fastener must provide adequate elastic compliance to compensate for creep in the boss and gasket. The present model provides a means of choosing composite material, process conditions and fastener type based on application clamp load retention requirements.

The creep performance of phenolic composites has been characterized by a method presented in reference (3). The present model has been verified in bolt load retention experiments on prototype phenolic composite pump covers. The model has been implemented in PC software to facilitate design calculations.

INTRODUCTION

To reduce engine weight, cost, noise and corrosion, composite materials are replacing metals in a variety of engine and transmission components. Many of these applications, including fuel and air induction components, oil and coolant pump housings, pulleys and covers, are fastened with bolted joints. The integrity of a joint depends on the stiffness and creep characteristics of mating components and seals. Under comparable fastening loads, composites deflect substantially more than metals.

To enable effective fastening and sealing of composite engine components, new design technology is emerging. In this paper, an original model of a bolted joint is proposed which yields predictive equations for bolt load retention based on composite material creep performance data.

DEFLECTIONS of JOINT ELEMENTS

In a traditional approach to joint design, loads and deflections are described by the balance between bolt tension and gasket compression, as illustrated in Figure 1[1]. In this traditional method, the compression of the component mounting boss or flange is neglected. When fastening typical iron or steel components, mounting boss compression is very small compared to bolt elongation, and can generally be neglected in joint design.

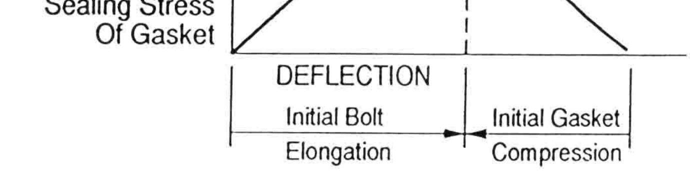

Figure 1. Bolt and gasket deflection under load

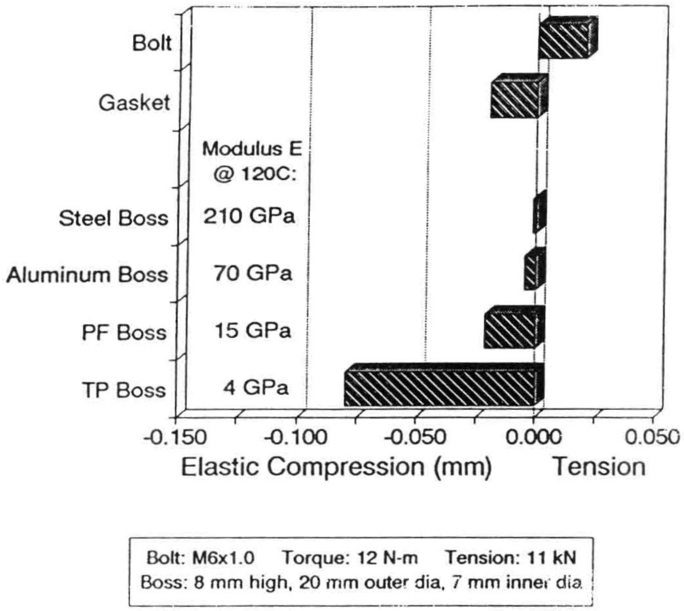

Figure 2. Typical deflections of joint elements

The deflections of joint elements can be estimated from Hooke's law[2]:

$$\delta = FL/EA \quad (1)$$

in which δ = deflection
F = force
L = stressed length
E = Young's modulus
A = stressed area

In a typical engine joint, an M6x1.0 bolt is torqued 12 N-m, providing a clamp load of 11 kN onto a mounting boss of inner diameter 7 mm, outer diameter 20 mm and height 8 mm. Under these conditions, the 8 mm stressed length of the bolt is stretched about 20 μm, and a typical paper gasket is compressed about 20 μm. According to equation (1), a typical iron or steel mounting boss (E = 210 GPa) in this joint would compress 1.5 μm. This deflection is small enough to be safely neglected in joint design.

When lower modulus materials are used, boss compression is greater. Typical joint element deflections for various boss materials are summarized in Figure 2. These element deflections have important implications:

- Elastic compression in iron or steel bosses can generally be neglected.
- Elastic compression in aluminum bosses can sometimes be neglected.
- Elastic compression in phenolic composites is comparable to bolt stretch and cannot be neglected. However, the deflection can be accomodated in joint design, and phenolic engine component joints are widely used without metal inserts.
- Elastic compression in typical thermoplastic composites is much greater than bolt stretch; mounting bosses in thermoplastic components typically require metal inserts.

Traditional joint design calculations are based on two compliant elements, bolt and gasket, as shown in Figure 3(a). Composite component joint design should accomodate the compliance of the mounting boss, as shown in Figure 3(b).

The initial deflections of joint elements are governed by elastic compliance, and can be estimated from equation (1). But the long term performance of a bolted joint is governed by creep compliance.

After assembly, the load in a bolted joint decreases in response to any creep in the bolt, boss or gasket. In traditional joint design, only gasket creep is considered, as the creep in steel bolts or in iron or steel mounting bosses is negligibly small. Aluminum creeps substantially more than iron or steel. While the elastic compression of aluminum bosses can usually be neglected, aluminum creep cannot always be neglected. Composite creep can rarely be neglected.

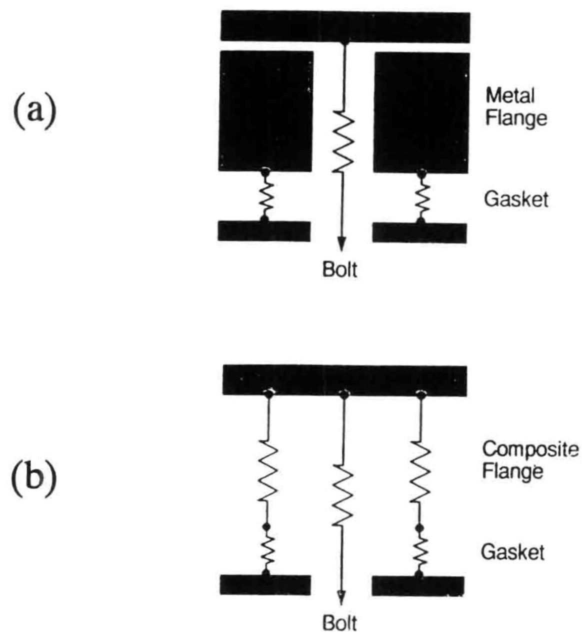

Figure 3. Models of bolted joints

In this paper we present a method to predict bolt load retention at elevated temperatures from laboratory creep data and fastening design variables. Two assumptions enable a complete analytical description of load relaxation in the bolted joint due to compressive creep in the boss:

- The loaded boss or flange section is idealized as a lumped element under uniform, uniaxial compression;
- The fastener behaves elastically.

JOINT DESIGN ANALYSIS

The relationship between the torque applied to a bolt and the initial tension developed in it is given by[1]:

$$T = K*D*F_0 \tag{2}$$

in which T = applied torque
K = friction factor
D = nominal bolt diameter
F_0 = tensile force

Reference (1) cites friction factor values of 0.11 - 0.20 and recommends a typical value of K = 0.17 for steel bolts. The initial load F_0 compresses the boss and stretches the bolt:

$$H(0) = H_0 - F_0 * C_0^b \tag{3}$$

$$L(0) = L_0 + F_0 * C^f \tag{4}$$

in which H_0 = free height of boss (t<0)
L_0 = free length of bolt (t<0)
H(0) = compressed boss height (t=0)
L(0) = stretched bolt length (t=0)
C_0^b = elastic compliance of boss (t=0)
C^f = elastic compliance of fastener

Similar equations could describe the initial deflection of any gasket or washer in the fastened joint. The compliances C can be calculated from Hooke's law:

$$C = \frac{\delta}{F} = \frac{L}{EA} \tag{5}$$

$$C_0^b = \frac{H_0}{E^{boss} * A^{boss}} \tag{6}$$

$$C^f = \frac{L_0}{E^{bolt} * A^{bolt}} \tag{7}$$

Equations (3) and (4) could be solved independently for H(0) and L(0), as the right hand sides of these equations contain only known quantities. By introducing two unknowns F(t) and $C^b(t)$, equations (3) and (4) can be extended to describe the time-dependent deflections:

$$H(t) = H_0 - F(t) * C^b(t) \tag{8}$$

$$L(t) = L_0 + F(t) * C^f \tag{9}$$

in which H(t) = boss height vs time
L(t) = bolt length vs time
F(t) = bolt load vs time
$C^b(t)$ = boss compliance vs time

The tensile force in the bolt equals the compressive force in the boss, and geometric compatibility requires bolt and boss to move together:

$$H(t) = L(t) \tag{10}$$

If $C^b(t)$ were known, the three equations (8-10) in three unknowns (H(t), L(t) and F(t)) could be solved simultaneously for bolt load:

$$F(t) = F_0 * \frac{C_0}{C(t)} \tag{11}$$

in which C_0 = initial total joint compliance
$= C^f + C_0^b$

C(t) = total joint compliance vs time
$= C^f + C^b(t)$

The boss compliance $C^b(t)$ is the sum of its initial elastic compliance C_0^b (equation 6) and its creep compliance. If the creep performance of the boss material were characterized and expressed as an apparent modulus versus time $E^{boss}(t)$, the boss compliance would be known:

$$C^b(t) = \frac{H_0}{E^{boss}(t) * A^{boss}} \tag{12}$$

CREEP CHARACTERIZATION

The creep performance of phenolic composites has been characterized versus time, temperature, stress and degree of cure (T_g)[3]. For a given temperature and T_g, the apparent modulus versus time has been shown to follow a primary creep model:

$$\frac{1}{E^{boss}(t)} = A + B * t^{0.25} \tag{13}$$

The coefficient A is the measured elastic compliance, the inverse of the elastic modulus; $B*t^{0.25}$ is the time-dependent creep compliance. In reference (3), this model is shown to provide a good fit to phenolic composite creep data over a wide range of conditions. The coefficients A and B are shown to be independent of stress, and to depend on temperature and T_g only through the reduced temperature variable (T_g-T). Empirical equations for A and B versus (T_g-T) are given for a phenolic composite, as shown in Figure 4[3].

Substituting equation (13) into equation (12), the time-dependent boss compliance is given by:

$$C^b(t) = \frac{H_0}{A^{boss}} * (A + B * t^{0.25}) \tag{14}$$

Substituting equation (14) into equation (11) gives an expression for load relaxation in the bolted joint due to compressive creep in the boss:

$$F(t) = F_0 * \frac{C^f + (H_0/A^{boss}) * (A)}{C^f + (H_0/A^{boss}) * (A + B * t^{0.25})} \tag{15}$$

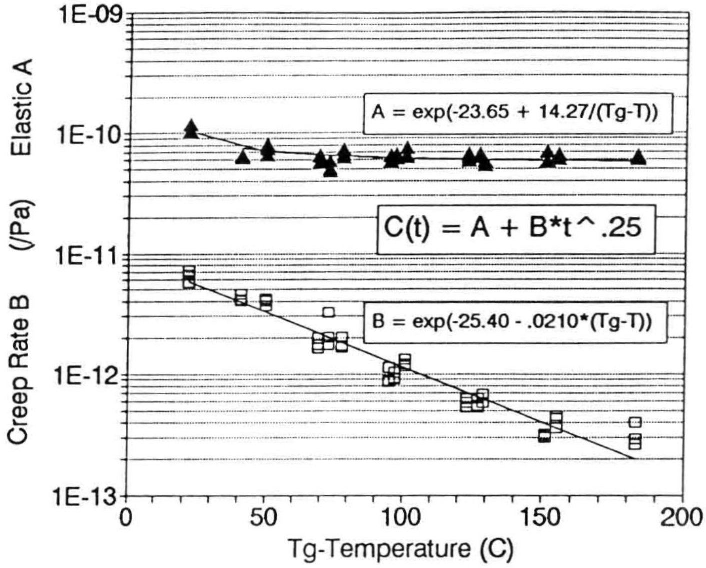

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Figure 4. Phenolic composite creep characterization

PREDICTION OF JOINT PERFORMANCE

Equation (15) quantifies the effect of phenolic composite boss creep on bolt load retention. It also quantifies the important role played by the elastic compliance of the fastener. Note for example that in the limit $C^f >> C^b(t)$, $F(t) = F_0$: if the elastic compliance of the fastener is large enough, it will experience no load loss.

Equation (15) provides a mathematical explanation of two common tricks of joint design:

- Bolt load retention can be improved by using Belleville spring washers, which increase the elastic compliance of the joint; and

- Bolt load retention can be improved by using large integral washers, which increase the area of the boss or flange loaded in compression, and thereby decrease boss compliance.

The benefit of decreased boss compliance can be seen more directly by rearranging equation (15). For example, setting $F(t) = F_0/2$ and solving for t provides an expression for the time (seconds) to 50 percent load retention:

$$t_{50\%} = [(1 + \frac{C^f}{C_0^b})(\frac{A}{B})]^4 \qquad (16)$$

The term $(1 + C^f/C_0^b)$ will be large if the boss elastic compliance is small compared to the fastener elastic compliance C^f. Typical values for $(1 + C^f/C_0^b)^4$ are given in Figure 5, based on the joint geometry summarized in Figure 2.

Figure 5 also shows the effect of a typical Belleville washer used with 6 mm bolts, which increases C^f by about 10 μm/kN.

The term A/B will be large if the boss material creep compliance is small compared to its elastic compliance. Typical values of A and B for a phenolic composite are given in Figure 4. In phenolics, this ratio is controlled by postcuring, which raises T_g. Values of $(A/B)^4$ for the phenolic characterized in reference (3) are given in Figure 6.

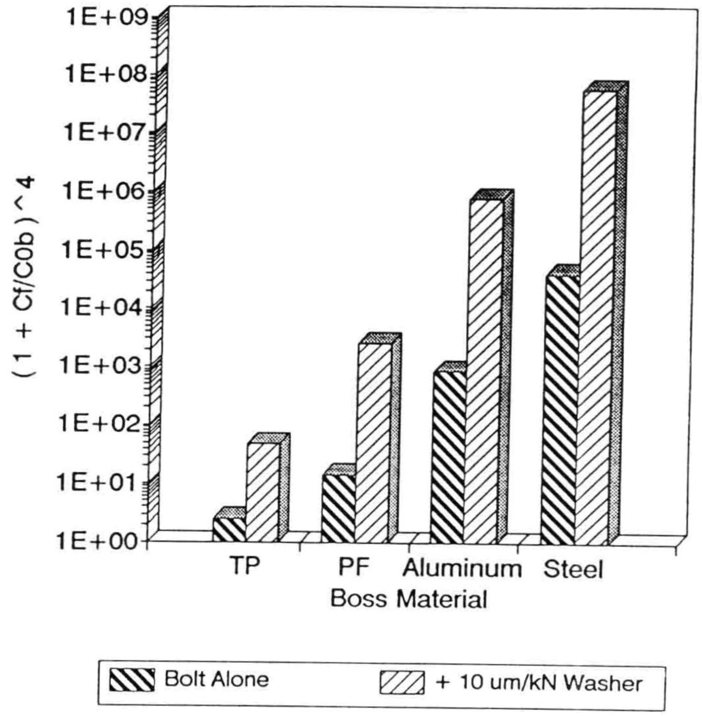

Figure 5. Effect of boss material on joint lifetime

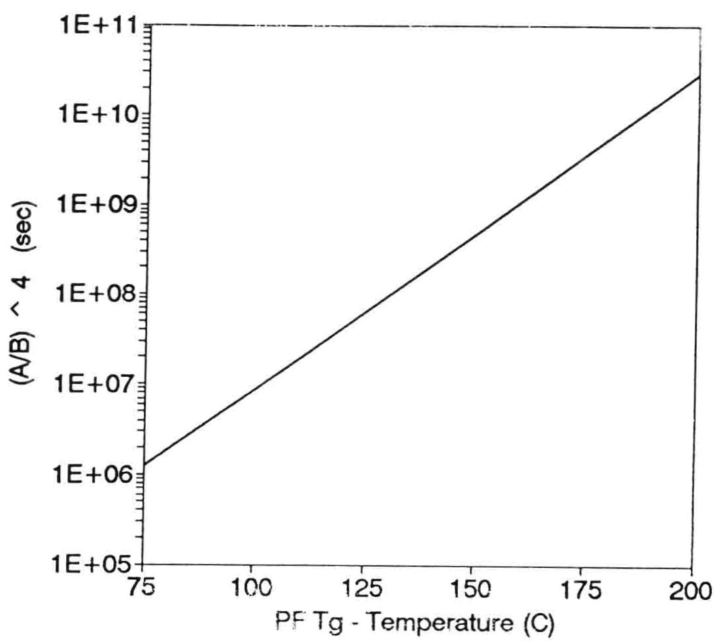

Figure 6. Effect of PF boss temperature & T_g on joint lifetime