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Thermal stresses in aluminum 6061 and nylon 66 long fiber thermoplastic (LFT) composite joint in a tailcone

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Abstract The present paper involves a metal/polymer joint in a tailcone in a kinetic energy penetrator (KEP), one of the ammunition types used by the military. It is currently made of aluminum 7075 alloy, which could be partly replaced by long fiber thermoplastic (LFT) composite. Two different types of aluminum insert geometries were considered, viz., beaded and threaded. Thermal stresses set in during cooling of the tailcone from the processing temperature mainly because of the difference in the values of coefficients of thermal expansion and differential cooling between the aluminum and the LFT composite. Finite element (FE) modeling was done to predict the temperature profile during the cooling of the tailcone from the processing temperature. FE results showed that the LFT composite part of the tailcone cooled faster than the aluminum insert. Experimental verification of this temperature profile was obtained by infrared (IR) thermography. Based on the temperature profile, thermal stresses at the metal/LFT composite interface were estimated using an FE model. Different magnitudes of thermal stresses were present at the aluminum/LFT composite interface owing to the nature of distribution of fibers around the insert. Magnitude of thermal stresses in the case of a beaded insert was approximately 2.5 MPa whereas in the case of a threaded insert, it was approximately 12 MPa.

Introduction

This paper involves study of long fiber thermoplastic (LFT) composite/metal interface in a tailcone. The tailcone is an aerodynamic stabilizer of the kinetic energy penetrator (KEP), an ammunition type used in the military. Currently, the tailcone is made out of a single block of aluminum alloy 7075, which is an expensive machining operation. The main objective of this work is to replace a part of tailcone by long fiber thermoplastic (LFT) composite. Here, the objective is not of weight saving by replacing part of aluminum with the composite, but faster processing cycle, using low cost polymer based materials that will reduce the overall cost. The LFT composite used in this case is glass fiber reinforced nylon 66 composite. The tailcone was manufactured by extrusion–compression molding, which eliminated expensive machining operations, making it an economical part. Thus, the tailcones required for the training rounds would be expected to yield significant savings because of ease of processing and lower cycle time (Vaidya et al., unpublished work).

Metal/polymer systems are used extensively in the areas of automobile, aviation, electronic packaging, prosthetic devices, coatings, and many more. The most commonly used metal/polymer systems in structural applications such as automotive and aerospace industries are adhesively bonded dissimilar or similar metals where the adhesive used is generally a thermoset resin such as an epoxy or phenolic [1]. All of the above applications demand reliability of the part, prolonged life span, ease of processing, higher yield, and low cost. Thus, joining of polymer or polymer matrix composite (PMC) to metal is a very critical step. In polymer/metal joints, the interface consists of metal such as aluminum, which has a closed packed

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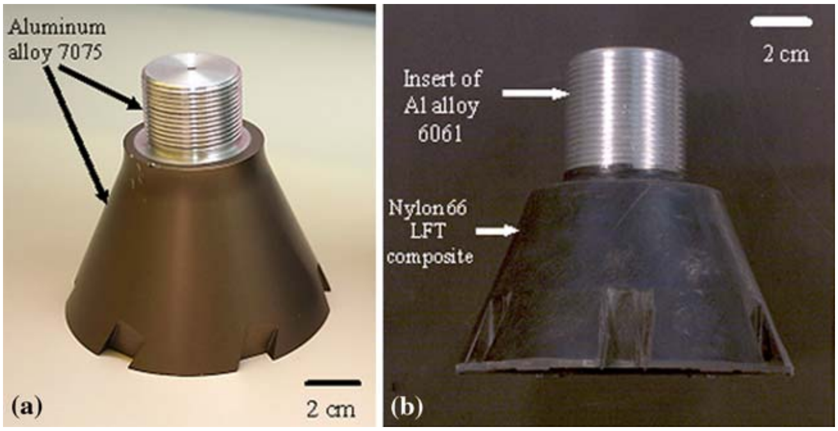

Fig. 1 Tailcones (**a**) Tailcone made from single aluminum alloy block via machining. The bottom part has a different color because of anodizing and (**b**) Tailcone made of aluminum insert and LFT composite

crystalline structure and a polymer, which has a long chain molecular structure.

Tailcone

It was proposed to manufacture a cost effective tailcone made of LFT composite and a metal insert used in training rounds of kinetic energy penetrators. A kinetic energy penetrator (KEP) is one of the ammunition types used by the military. The tailcone, which is aerodynamically designed to induce drag and stabilize the projectile by inducing rotation. The in-bore conditions for the tailcone are severe. The tailcone experiences a maximum acceleration of 434,140 m/s^2 for 6.15 ms and a maximum hydrostatic pressure of 406 MPa for 1.95 s. The tailcone is also subjected to a temperature of 1,970 K in bore.

Currently, the tailcone is made from an aluminum 7075 alloy block, which is fed to a computer numeric control (CNC) machine (Fig. 1a). The cost of manufacturing of the tailcone is high mainly due to long machining time and surface finishing operations required after machining. Compression molding of LFT composite around an aluminum alloy insert was chosen as the manufacturing process mainly because of low cycle time and near-net-shape molded parts. Figure 1b shows the tailcone with an aluminum alloy 6061 insert and nylon 66 LFT composite flare surrounding it. The LFT composite/aluminum interface necessitated characterization of joining between LFT composite and aluminum in terms of thermal residual stresses.

The term LFT composites represents a family of composites with reinforcing fiber lengths between 12 mm to 50 mm and a thermoplastic matrix such as polypropylene, nylon, polyurethane, etc. The main advantage of LFT composites is that they can be processed using traditional plastic molding operations such as compression molding, injection molding, or injection–compression molding. Therefore, the LFT composite parts can be manufactured at high volume rates with excellent consistency and repeatability [1–3].

The use of a plastic flare in the KEP was investigated earlier by Garner et al. [4]. They demonstrated that commercial polymers such as poly ether ether ketone (PEEK) could withstand extreme conditions encountered inside the barrel during firing and the pressure drop during the muzzle exit of the projectile. However, the cost of PEEK is prohibitively high ($96.8/kg). In this work, we have used nylon 66 matrix LFT composite containing 40 wt% of long E-glass fibers, which is relatively inexpensive ($4.4/kg).[1]

Thermal stresses

Joining of any two dissimilar materials results in thermal residual stresses with change in temperature which can arise either from cooling from the processing temperature or from the changes in the environmental temperature. The stresses are generated mainly because of their difference in coefficient of thermal expansion (CTE) values and hence differential expansion or contraction of the materials joined together [2, 5]. The problem of thermal residual stresses in the case of metal/polymer systems is severe since the CTE values of metals and polymer differ by a large magnitude. For example, CTE values (in units of 10^{-6}/K) of polymers such as PP and nylon 66 are 90 and 80, respectively whereas those of steel and aluminum are 13 and 24, respectively. The thermal stresses generated are also very important from the design and service point of view; these stresses (compressive or tensile) should be accounted for when applying an external load. Sometimes the thermal stresses generated can be so large as to cause delaminations or debonding in the joint or even plastically deform the thermoplastic polymer. Williamson et al. [6] used an FE model to simulate thermal residual stresses developed at the Al_2O_3/Ni interface during cooling. The FE model was

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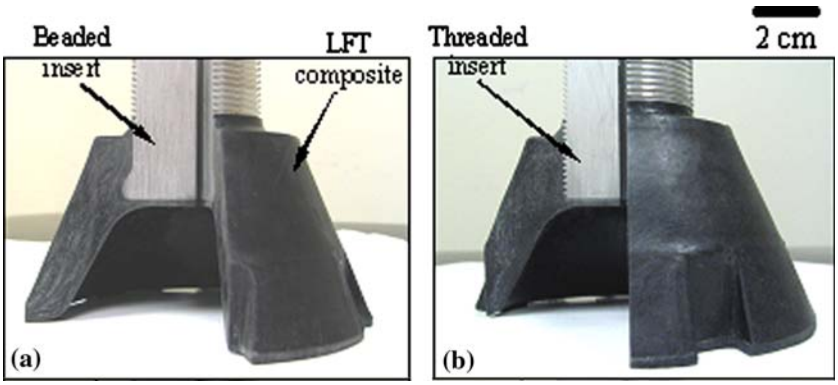
[1] www.plasticstechnology.com, as on 30 October 2006.

Fig. 2 Insert geometries in the Tailcone (**a**) Beaded insert and (**b**) Threaded insert



generated using ABAQUS software. They observed strong geometrical influences on thermal stresses developed at the interfaces. Yao and Qu [7] estimated the thermal residual stresses generated at the interface of aluminum and epoxy filled with silica particles. Various volume fraction of silica powder were used to modify CTE values of epoxy adhesive. CTE value of epoxy decreased as the volume fraction of silica powder was increased. A commercial FEM code ABAQUS was used to quantify the thermal stresses between aluminum and different levels of silica filled epoxy. It was observed that thermal stresses decreased as silica content of the adhesive increased because the addition of silica decreased the CTE mismatch between aluminum and silica/epoxy composite.

Materials and procedures

Materials

LFT composite

The LFT composite used in this work consisted of nylon 66 matrix reinforced with E-glass fibers of about 12.5 mm (1/2 inch) in length. The LFT composite had 40 wt% (23 vol%) of glass fibers.

Metal insert

Metal insert used was an aluminum alloy 6061, the composition being Mg: 0.8–1.2, Si: 0.4–0.8, Cu: 0.15–0.4, Cr: 0.04–0.35 (all wt%). In the processing of the tailcone, two geometries of aluminum alloy inserts were used, namely, beaded and threaded as shown in Fig. 2. The properties of the constituent materials[2,3] are summarized in Table 1.

Procedures

Processing of the tailcone

The processing of the tailcones was done at National Composite Center (NCC), Kettering, Ohio. The tailcones were made by extrusion–compression molding with the aluminum alloy used as an insert. In this process, LFT composite pellets were fed into the hopper of a single screw extruder or a plasticator. For compression molding a 400 metric ton press was used. The mold was heated to 121 °C, insert was preheated to 110 °C, and the plasticator temperature was set to 287 °C. The plasticated or semi-molten LFT composite charge was transferred from the extruder to the compression molding press. The charge was placed in the mold cavity and the mold was closed. A load of 300 metric ton was applied to consolidate the LFT composite charge around the aluminum insert. After consolidation, the mold was opened and the tailcone was demolded. The cycle time was approximately 60 s. The demolded tailcone was cooled in air down to room temperature from a temperature of approximately 100 °C.

Determination of thermal stresses at the LFT composite/aluminum interface

In the tailcone made out of single aluminum block, residual stresses were not of concern because of uniform CTE, since it was made from a single material. In the new design, residual stresses arise because of joining of two dissimilar materials, viz. aluminum alloy and LFT composite, having different CTE values [2]. Even though the tailcone as a whole was at the same temperature after compression molding, differential contraction of LFT composite and aluminum during the cooling was expected to rise to residual stresses at the interface. A commercially available finite element (FE) code, ANSYS (version 8.0), was used to evaluate the differential cooling between LFT composite and aluminum and also to estimate magnitude of the thermal stresses based on temperature profile.

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[2] www.rtpcompany.com, as on 30 October 2006.

[3] www.matweb.com, as on 30 October 2006.

Table 1 Important properties of neat nylon 66, nylon 66 LFT composite, and aluminum (see footnotes 2 and 3)

Property	Neat nylon 66	Nylon 66 LFT	Al-6061
Density (kg/m^3)	1,140	1,460	2,700
Specific heat (kJ/gK)	1,700	2,200	900
Thermal conductivity (W/mK)	0.25	0.5	180
Coefficient of thermal expansion (10^{-6}/K)	80	31	25
Tensile strength (MPa)	95	221	130
Elastic modulus (GPa)	2.7	13.8	70

Distribution of fibers in the nylon matrix was also given due consideration when modeling the thermal stresses. In the case of beaded insert, it was observed that there existed fairly uniform distribution of fibers all over the matrix, including near the insert edges (Fig. 3a). On the other hand, in the case of threaded insert, it was observed that the LFT composite in the threads was highly resin rich while fairly uniform distribution was observed in the rest of the LFT composite volume (Fig. 3b). This uneven distribution of fibers was incorporated in the model by considering three different material properties, viz., LFT composite, neat nylon, and aluminum alloy.

Finite element (FE) modeling

FE modeling was used to predict thermal stresses at the LFT composite/aluminum interface after the tailcone was demolded and kept in air till it cooled down to room temperature. As mentioned earlier, the temperature of the tailcone after it was demolded was approximately 100 °C. ANSYS version 8.0 was used for modeling. The analysis was done in two steps, also referred to as coupled analysis. In the first step, thermal analysis was done to obtain the temperature profile while the tailcone was being cooled from 60 °C (333 K), the glass transition temperature (T_g) of nylon 66 LFT composite to room temperature, 27 °C (300 K). The temperature profile would show a differential cooling between the LFT composite and aluminum. The T_g of nylon 66 in LFT composite was chosen as the initial temperature because the thermal stresses generated while cooling from 100 °C to its T_g will be relaxed due to the leathery nature of the nylon 66 matrix. In the second step, thermal stresses were obtained based on the temperature profile obtained from the thermal analysis.

Material properties used in FE analysis are listed in Table 1. For the thermal analysis, PLANE 55 element type

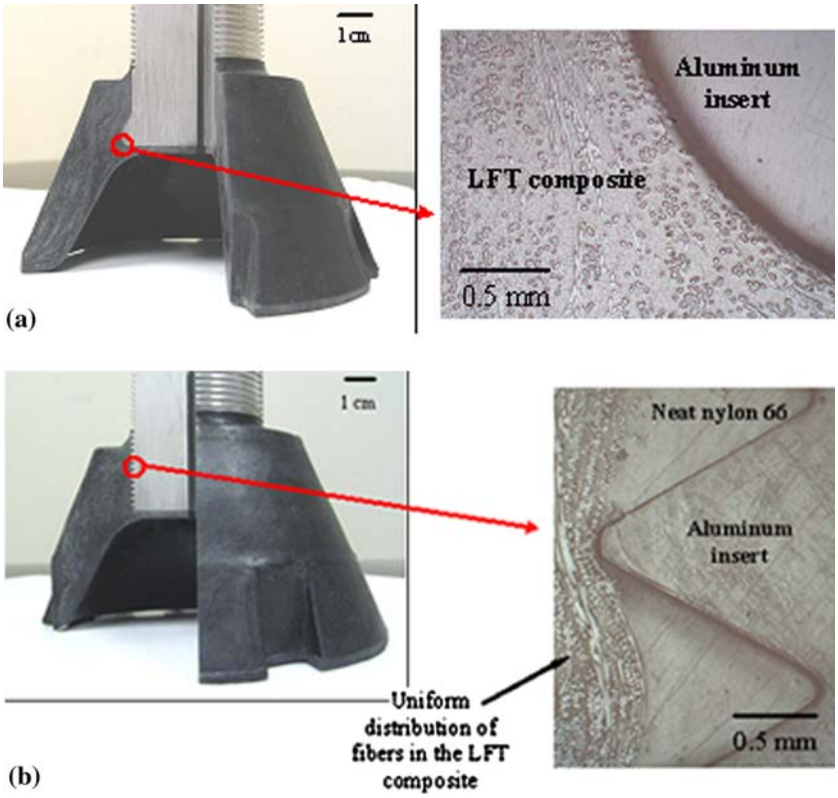

Fig. 3 Fiber distribution around the inserts in tailcones (**a**) The arrow indicates uniform distribution of fibers around the beaded insert and (**b**) Non-uniform distribution of fibers in the LFT composite surrounding a threaded insert. Note the nylon 66 rich area near the threads

was used which is a 2D element that possesses thermal conduction capability and temperature as single degree of freedom. The modes of heat transfer were conduction and convection. The analysis was done as transient analysis and the total time of the analysis was 1 h (3,600 s). The initial temperature of 60 °C (333 K) was applied to each node and reference temperature was chosen as 27 °C (300 K). The convection heat transfer coefficient, *h*, used in the modeling was that of still air; *h* in this case was equal to 7 W/m^2 K [8].

The thermal analysis was followed by structural analysis. The element type used was PLANE 42 which is a 2D element having capability of modeling of solid structure and having two degrees of freedom, viz., translations in *x* and *y* directions at each node. For the structural analysis, temperature profile obtained from the thermal analysis was provided as an input to obtain the thermal stresses. Figure 4 shows meshed axisymmetric section of the tailcone.

For the heat transfer problem, we assume that, at any point in a body, the rate of heat transfer by conduction into a unit volume plus the heat generation rate in the unit volume is equal to the rate of change of thermal energy stored within the volume. Alternatively,

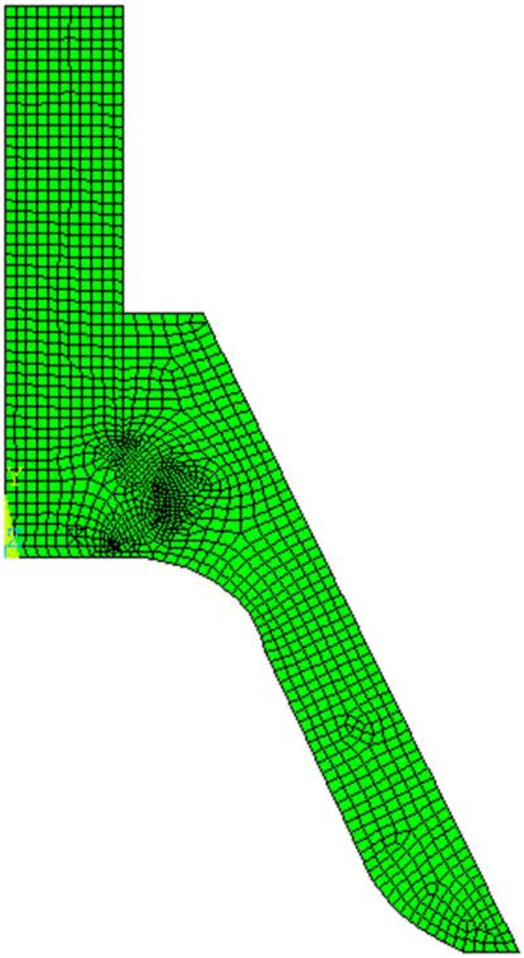

Fig. 4 Meshed axisymmetric section of a tailcone for FE analysis

$$\begin{aligned}&\text{Rate of heat transfer by conduction}\\&+\text{rate of heat generation}\\&=\text{rate of change of thermal energy}\end{aligned}$$

Mathematically, heat transfer within the LFT composite and aluminum can be expressed as [8]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+q=\rho c\frac{\partial T}{\partial \tau} \quad (1)$$

where k = thermal conductivity, $\partial T/\partial x$ = temperature gradient in the direction of heat flow, q = heat generation rate per unit volume, ρ = density of the material, c = specific heat of the material, τ = time. From the above equation we can obtain the temperature distribution in a body as a function of time.

Dissipation of heat takes place at the surface via free convection. Rate of heat dissipation via convection (q) is given by Newton's law of cooling [8].

$$q=hA(T-T_\infty) \quad (2)$$

where h = convection heat transfer coefficient, A = surface area, T = surface temperature, T_∞ = temperature of the surrounding fluid.

Thermal stresses were computed in the structural part of the analysis based on the temperature profile obtained from the thermal analysis. According to the finite element code used (ANSYS 8.0), the thermal stresses were calculated using the principle of virtual work, which states that a very small change in the internal strain energy must be compensated by an equal change in the external load [9–13]. The external load in this case would be thermal load. Thus, the governing equation to calculate thermal stresses is given by [10]:

$$[K]\delta=F \quad (3)$$

where $[K]$ = stiffness matrix, δ = nodal displacements due to temperature change, F = thermal force. The total thermal force (F) is given by the summation of the thermal forces acting on each element [10]:

$$F=\int[B]^T[C][B]\alpha\Delta T dV \quad (4)$$

where $[B]$ = strain–displacement matrix, $[C]$ = elasticity matrix, α = CTE of a material for a given element, ΔT = difference between the initial and final temperatures.

The corresponding thermal stresses (σ_{th}) are then calculated by following equation [10]:

$$\sigma_{\text{th}} = [C]\varepsilon_{\text{th}} \tag{5}$$

where thermal strain (ε_{th}) is given by [10]:

$$\varepsilon_{\text{th}} = [B]\delta = [B][K]^{-1}F \tag{6}$$

Thus, the expression for the thermal stresses becomes [10]:

$$\sigma_{\text{th}} = [C][B][K]^{-1}F \tag{7}$$

Infrared (IR) thermography

The results obtained from the thermal analysis were verified by the thermographic inspection. Sections of tailcones with both the insert geometries viz. beaded and threaded were used for IR thermography. The bright reflecting surface of an aluminum insert was cleaned with acetone and painted with carbon black to match the surface emissivites of the LFT composite and the insert. The section of the tailcone was heated to about 60 °C in an oven and clamped to a stand. The tailcone was cooled in still air at room temperature. While the tailcone was being cooled, the temperature changes on the surface of the tailcone were observed by means of ThermaCAM Merlin camera (FLIR Systmes, Wilsonville, OR) and recorded as a video file.

IR thermography is a two dimensional non-contact technique for measurement of a surface temperature [14–16]. The electromagnetic radiation emitted by a body in the infrared region (IR radiation) is detected by an infrared detector. The IR detector is a transducer, which absorbs the IR radiation and converts it into an electrical signal. The temperature measurements made by thermographic cameras are based on Planck's law. According to Planck's radiation law, the blackbody radiation intensity ($E_{\lambda b}$) is given by the following expression [14]:

$$E_{\lambda b} = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \tag{8}$$

where C_1 and C_2 are the first and second radiation constants, respectively; λ is wavelength of the radiation being considered, and T is absolute temperature of the blackbody.

Results and discussion

Temperature profile

FE analysis

The temperature profile obtained from FE modeling of beaded insert tailcone is shown in Fig. 5. It was observed that while cooling of the tailcone after demolding, LFT composite cooled faster than the aluminum. Similar results were obtained in the case of the threaded insert. Because of the high thermal conductivity of the aluminum (180 W/mK), compared to the LFT composite (0.5 W/mK), the aluminum acted as a heat sink, i.e., aluminum absorbed the heat from the LFT composite. During the cooling, the heat in the LFT composite was continuously conducted from the LFT composite through the interface into aluminum. The aluminum insert attained a uniform temperature because of its high thermal conductivity. Thus, there existed a temperature gradient in the LFT composite where the temperature near the interface was higher compared to the far end.

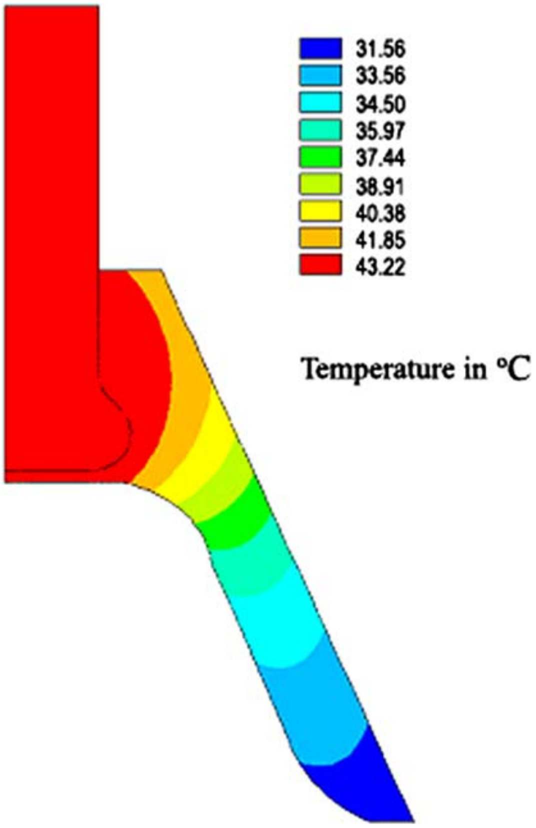

Fig. 5 Temperature profile obtained from the FE analysis showing LFT composite cooling faster than the aluminum insert. The temperature scale is in °C

IR thermography

Results obtained from thermography also showed that the LFT composite in the tailcone cooled faster than the aluminum insert. As explained earlier, this was because the aluminum acted as a heat sink because of its high thermal conductivity (180 W/mK) compared to that of the LFT composite (0.5 W/mK). The heat from the LFT composite was conducted by the aluminum insert and because of this the LFT composite cooled faster than the insert (Fig. 6). The thermography results confirmed the temperature profile obtained from the FE model that there existed differential cooling between the LFT composite and aluminum insert.

Thermal stresses

Based on the temperature profile, thermal stresses were calculated by the FE model (Fig. 7). In the case of the beaded insert geometry, there was a uniform distribution of fibers in the LFT composite. In the case of the threaded insert, the threaded regions were resin rich areas. Figures 8a and b show the stress state comparison between resin-rich region and uniform distribution of fiber in the LFT composite, respectively in the case of threaded insert. Note the higher magnitude of stresses in the regions of resin rich threads.

Thus, besides the differential cooling between the aluminum insert and the LFT composite, the difference in CTE values between the two cause thermal stresses. Because the LFT composite cooled faster than the aluminum insert and since the LFT composite had a higher CTE value (31×10^{-6}/K) than the aluminum insert (25×10^{-6}/K), the LFT composite contracted at a higher rate than the aluminum insert. This resulted in tensile stresses on the LFT composite side of the interface and compressive stresses on the insert side. The effective or von Mises stresses are shown in Figs. 7 and 8. From the modeling, the magnitude of the thermal stresses was calculated. In the case of the beaded insert, the magnitude of the von Mises stresses was approximately 2.5 MPa whereas in the case of the threaded insert, the magnitude was approximately 12 MPa considering the non-uniform distribution of fibers in the threaded regions. If it was assumed that the fiber distribution was uniform in the threaded regions similar to the case of beaded insert, the magnitude of thermal stresses reduced to approximately 7.4 MPa from 12 MPa (Figs. 8a and b).

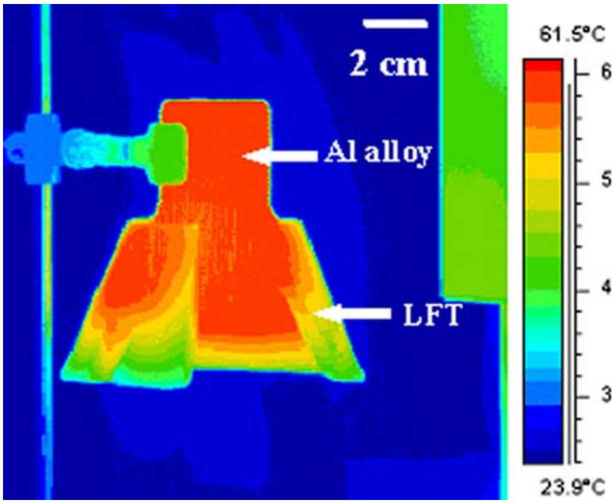

Fig. 6 Temperature profile obtained from IR thermography. Note that the LFT composite cooled faster than the aluminum insert

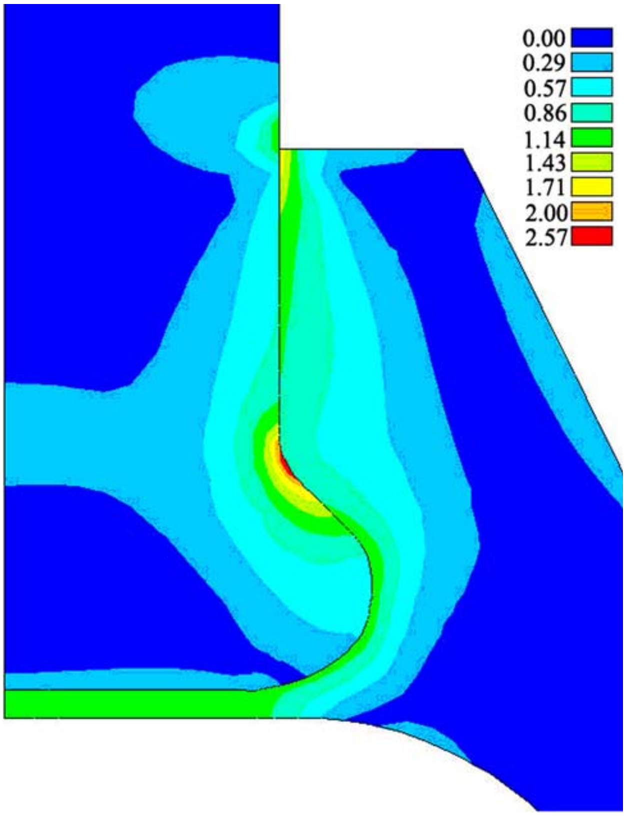

Fig. 7 Thermal stresses developed at the interface based on the temperature profile shown in Fig. 6. The stresses shown are von Mises stresses in MPa

Conclusions

The tailcone made of aluminum 7075 alloy was replaced by one made of long fiber thermoplastic (LFT) composite and aluminum alloy 6061. The LFT composite consisted of glass fiber reinforced nylon 66. The new design of the tailcone did not intend to save on the weight of the tailcone but the main purpose of the new LFT composite tailcone was cost reduction. To serve this objective, extrusion–compression molding process was chosen, where semi-molten LFT composite charge from an extruder was compression molded around aluminum alloy 6061 insert. The insert molded LFT composite would replace a tailcone made of single aluminum block. Two types of insert geometries were considered viz. beaded and threaded. Fiber distribution in the LFT composite was

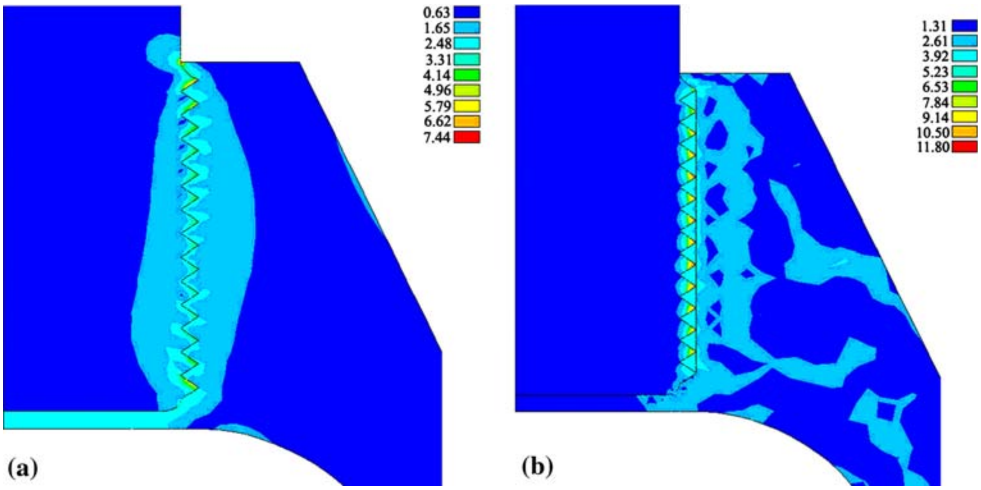

Fig. 8 Thermal stresses developed at the interface in the threaded insert tailcone. The stresses shown are von Mises stresses in MPa. (**a**) It was assumed that fibers are distributed uniformly in the threaded region and (**b**) It was assumed that the threaded region is a resin rich area. Note that the magnitude of thermal stresses is higher in the resin rich threaded region

found to be uniform around a beaded insert while resin (nylon 66)-rich areas were observed near the threaded insert.

Both, finite element thermal analysis and IR thermography results showed that the LFT composite cooled down faster than the aluminum insert. This was because of the large difference between the thermal conductivities of LFT composite (0.5 W/mK) and aluminum (180 W/mK) and hence the metal insert acted as a heat sink. Thermal stresses were estimated at the LFT composite/aluminum interface based on the temperature profile obtained. It was observed that in the case of beaded insert, the magnitude of stresses was approximately 2.5 MPa, on the other hand owing to the non-uniform distribution of fibers around a threaded insert, magnitude of stresses was approximately 12.0 MPa.

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