1-1-2020

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ABSTRACT*: Compression molding is used to produce tensile bars to determine the strength of plastics. Due to inherent variability in measurements, several bars must be tested to establish mean values, and it is beneficial to produce multiple bars in a single molding cycle. But consistent bars will result only if each mold cavity experiences the same temperature-time history. Thus, an actual three-cavity aluminum mold has been modeled with finite elements, and the temperature distributions throughout its body have been predicted for a one-minute cycle and a 165°C molding temperature. Results demonstrate that all three polyester bars have nearly an identical heating history. The bars' temperatures reach 177°C but quickly cool while the mold body remains near 165°C. This study was conducted by undergraduate students fulfilling their requirement to obtain the honor's distinction for a heat transfer course.*

KEYWORDS*: ANSYS, Compression molding, Mold temperature, Transient thermal analysis*

1 BASICS OF THE COMPRESSION MOLDING PROCESS WITH ASSOCIATED THERMAL ISSUES

Compression molding is a method of fabricating three-dimensional plastic parts. The process begins by placing a preheated mold with its resin (charge) on the bottom platen of the compression molder which is also known as a press or heated press. The press closes, compressing the charge between its mold halves. This is illustrated in Figure 1, and the molding force is usually applied with a hydraulic piston. The press remains closed during the curing stage, maintaining high pressure and heat, as the plastic hardens. The compression force is then released, the mold is cooled, and the part is removed from the mold.

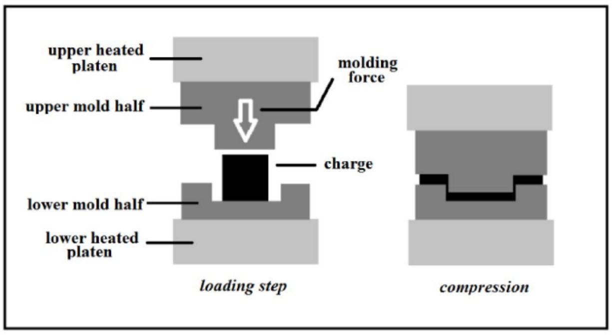

Fig. 1 Schematic view of the basic compression molding process

Unlike many conventional thermoplastic processing methods which utilize resin in pellet format, in compression molding the resin charge is available in several forms. Common are granules, a coarse powder, that when heated and pressurized liquefy and cure to harden. Pastes are combinations of a liquid thermoset with its filler. Various dough molding compounds are viscous pastes that are mixes of the resin, filler, and reinforcement as in a BMC (bulk molding compound). Other, more engineered compounds, are SMCs (sheet molding compounds) and GMTs (glass mat-reinforced thermoplastics) and are pre-manufactured in sheet form.

Compression molding most often employs thermosetting polymers, and it is the pressure and temperature combining to initiate and complete the polymerization reaction. The charge is composed of the monomer, catalyst, and a variety of additives and fillers. The polymerization itself is an exothermic reaction in which heat is released, and in some cases too much heat can lead to a defective final part.

One required course for all undergraduate mechanical engineering students at Northern Illinois University (DeKalb, Illinois, USA) is MEE 352 - Heat Transfer. This is a three-credit-hour, sixteen week, one semester course that covers the basics of conduction, convection, and thermal radiation. The Department of Mechanical Engineering is part of the College of Engineering and Engineering Technology, and its program is an applied one, focusing on bridging theory with practice and applications. The four-year degree requires 128 credit hours. In addition to the standard mechanical engineering curriculum, undergraduate students pursue one of two available emphases: Advanced Computing and Simulation or Sustainable Energy. Each emphasis has a set of core courses and electives.

Students may elect to complete MEE 352 with honors through extra assignment(s). To fulfill this requirement, a group of students was assigned to perform a thermal analysis of a mold used in processing plastics by compression molding. Their work is herein documented.

2 TEMPERATURE REQUIREMENTS IN COMPRESSION MOLDING

Common thermosetting plastics used in the compression molding process include polyesters, epoxies, phenolic molding compounds, and polyurethane resins. The required molding temperature is dependent on many factors, primarily on the material being molded, but the consensus is 150 - 200^{o}C for most resins.

This molding temperature must be maintained by heated platens or by heating channels within the mold body. Temperature sensors with a minimum of one within each mold half, such as thermocouples, are of great assistance in monitoring the temperature of the mold. However, this only measures the temperature at a single point, rather than providing a full temperature profile throughout the mold, including at the cavity surfaces that are in contact with the charge. As this is difficult to achieve in practice, computerized simulations have the ability to predict mold temperatures, thus informing the curing reaction and ensuring parts that are more consistent in their properties and without defects or deformations.

3 BACKGROUND AND RELATED STUDIES

Even though compression molding has been a routine manufacturing process for thermosetting resins for over a hundred years, the heat transfer path between the press, mold (tool), and charge has not been extensively studied. Rather than heat transfer rates, it is the temperature distribution within the mold body and hence at the mold's surface cavities that is paramount as any temperature fluctuations can affect the curing mechanism and finished part quality.

Herman (1978) was one of the first to formally recognize the importance of the heat transfer process within the mold; specifically, uneven cavity surface temperatures create inferior part quality and/or slower production rates. Results of this FEA (finite element analysis) suggested to subdivide the mold into independently-controlled regions with which to improve the curing reaction and significantly decrease molding cycle time. Further stressing that a uniform mold cavity temperature is important when manufacturing SMC parts, Barone & Caulk (1980) have shown analytically that a 25^{o}C temperature variation in the cavity surface temperature exists in larger SMC-molded parts; using part dimensions, this variance is proportional to length^2/(thickness × cycle time). Therefore, the thermal inconsistency increases when molding thinner parts made with shorter cycle times. Such variance leads to surface quality problems and can be improved by better platen heating design.

It must be remembered that any required molding temperature is that of the entire mold. Also, this is not the same as the temperature of platens as there will always be a temperature gradient between the platens and mold. But since presses have programmable platen temperatures, in many cases it is the platen temperatures that are monitored. Thus, it is important to minimize the difference between platen and mold values. This difference arises from two factors: the mold material has a thermal capacity, and there is a time lag between the platen set-point and the actual mold temperature; also, unless the mold is well-insulated, both radiative and convective heat losses from the exposed surfaces of the mold to its surroundings exist. Tatara (2017) measured platen and mold body temperatures during a sample molding with a single-cavity steel mold. Here a thermosetting resin was compressed while at room temperature (cold formed), and then the platen heaters were engaged until the mold was brought up to its curing temperature of 171 - 177^{o}C. The results indicated that throughout this cycle there is relatively close agreement between the upper and lower mold sections' temperatures, within 5.6^{o}C. But each platen is 11 - 22^{o}C warmer than its corresponding mold half. Therefore any platen setting would not accurately represent the tool temperature, and it is useful to be able to directly monitor mold temperatures in addition to platen values.

Overall, heat transfer from the surface of each platen into and within the mold body is conduction while heat is lost continually from the sides of the closed mold to the surrounding air through convection and radiation. Kuczmarski & Johnston (2007) demonstrated that the convective losses constitute a more significant factor than mold body conduction when attempting to minimize the platen and mold temperature differential. Their numerical simulation indicated that reducing the exposed surface area by a redesign of the mold is a reasonable way to decrease the temperature variation, and more practical than utilizing a mold material having a higher thermal conductivity. To verify the numerical analyses, an actual mold was constructed, tested, modified, and again tested. The data demonstrated through reducing the height of the tool profile from 59.1 to 40.1 mm, while increasing the mold's radius to maintain the same weight, the mold's temperature variation decreased from 20^{o}C to 10^{o}C. Simultaneously, the temperature variation at the charge decreased from 8^{o}C to 2^{o}C.

Instead of indirectly heating the mold through platens, the mold may be equipped with embedded heating and cooling channels. Hot oil or steam is circulated within the channels providing thermal energy. Such an arrangement also leads to temperature variations at cavity surfaces. Moreover, this variation changes as the mold is cycled through ordinary production. Hu, et. al. (1998) simulated SMC manufacturing where the cavity surface temperature variance increased with the number of cycles, and at the end of 90 cycles portions of the mold's surface were 20^{o}C lower which meant that the charge here was only 80% cured. Barone & Caulk (1981), using numerical simulations, concluded that proper design of the location of heating channels, along with separate fluid temperature and flow control, is effective in minimizing temperature gradients when using embedded mold channels. For instance, during a molding time of one minute, the cavity surface temperatures between locations differed by as much as 24^{o}C under standard heating conditions using identical temperature and flow rates in all oil channels. For the same one-minute cycle, the temperature variance decreased to 6.6^{o}C when each oil channel featured independent temperature and flow control. Finally, with a repositioning of the channels, each having independent oil temperature and flow rate, this same variance was only 1.4^{o}C.

To improve cure uniformity and maximize production rates, FEA was employed to analyze temperature distribution in a mold featuring embedded steam heating channels; then a finite difference technique modeled the charge cure dynamics at critical regions (Castro & Lee, 1987). One conclusion is that the mold body in the immediate vicinity of the charge should be heated to a higher initial temperature because heat is absorbed by the charge in this region when the mold is first closed. (The temperature of the charge increases as the charge is compressed outward until the mold and charge have come to equal temperatures.) This could be accomplished with hotter steam tubes in this region to achieve a more uniform cure. Furthermore, the heating channel separation distance was varied to observe its effect on temperature uniformity. Simulating separation distances of 203 mm, 102 mm, and 0 mm, showed that distances between adjacent channels of more than 102 mm yielded undesirable temperature gradients. Under 102 mm distances yielded little to no change in the uniformity. Additionally, the study concluded that adding insulation around the outside of the mold does not significantly improve the temperature gradients if the heating channels are closely spaced.

In another effort, researchers evaluated a compression mold used in manufacturing automobile panels (Barone, et. al., 1986). A computerized model optimized the mold to minimize the variation in temperature by modifying heating line temperatures and paths. Thermocouples in the original mold, as well as in an improved one, determined cavity surface temperatures. In baseline, multiple cycle molding with conventional heating, there was a temperature variation of 10^{o}C as, mostly, the model predicted temperatures to within 1^{o}C of the experimentally determined values. The study did note parts experiencing undercure and adhering to the mold cavity as the number of tests progressed. With the improved, optimal heating, the temperature variation was only 3^{o}C. This mold design clearly better maintained heating throughout the duration of the cycles compared to the previous, conventional heating pattern. Significantly, the issues of undercure and part release no longer occurred. It was recommended to increase the number of heating lines at specific locations so that the entire mold reaches equilibrium temperatures at the same time.

Lee & Cho (1995) used shape optimization to solve for the optimal position of a number of heating lines in a compression mold to maintain uniform temperatures of the mold cavity surface. Using a set-point of 150^{o}C, three lines were needed for uniform temperatures. A boundary element method, with a boundary integral for the temperature sensitivity, proved effective in finding the optimal number and positions of heating lines.

The previous research into thermal design of a compression mold demonstrates that simulations are useful, but due to the wide variety of molding conditions, it is problematic to generalize or extrapolate results. This necessitates modeling each specific case to better understand temperature distributions, especially in transient analyses.

4 THE THREE-CAVITY MOLD AND ANSYS THERMAL ANALYSIS

Tensile bars are routinely produced to determine the mechanical strength properties of materials, including plastics. Often these are of the "dog-bone" shape, measuring 165.1 mm long with width and thickness in the narrow (i.e., neck) region of 12.7 mm and 3.2 mm, respectively. Due to the inherent variability in experimental measurements, several bars must be produced and tested to establish average values for tensile strength, tensile modulus, and elongation, and it becomes beneficial to produce multiple bars in a single molding cycle. In this case, consistent samples will result only if each bar experiences the same temperature-time history. Figure 2 is a photographic view of a 7075-T651 aluminum, three-cavity mold used for compression molding tensile bars. It has a mass of 5.8 kg and when closed measures 191 mm in length, 152 mm in width, and 70 mm in height. Figures 3a and 3b are CAD drawings of the lower and upper mold halves, respectively. Accordingly, this mold has been modeled, and the temperature distribution throughout its body has been determined by FEA.

Fig. 2 Three-cavity, aluminum 7075-T651 tensile bar mold in open position; dimensions = cm

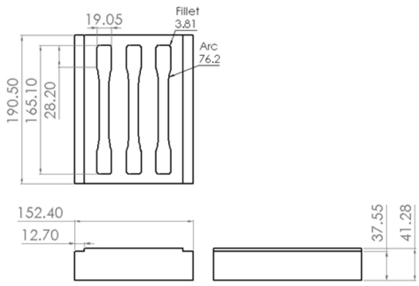

Fig. 3a Schematic drawing of lower mold half; dimensions = mm

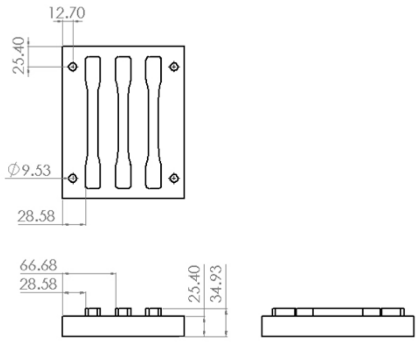

Fig. 3b Schematic drawing of upper mold half; dimensions = mm

ANSYS (Ansys, Inc., Canonsburg, PA, USA), finite element analysis software, was used to simulate the thermal performance of the subject mold. ANSYS is a well-known, commercial software package that specializes in mechanical stress and thermal analyses. It can simulate a wide variety of system constraints, including steady-state and transient conditions. For instance, Fan, et. al. (2011) simulated, using ANSYS, the heat transfer in rapid heat cycle molding during injection molding. To minimize heat losses, a combination of a mold insert with an insulation layer was included. This did conserve thermal energy, reducing heating time by 36% with a 25% reduction in cooling time.

The current problem is transient since the temperature of the mold changes throughout the molding cycle. Thermally, the analysis is depicted by Figure 4 which represents the mold with its corresponding boundary conditions. (It should be noted that thermal symmetry is present, and it would be possible to model only one-quarter of the mold. However, the number of finite elements needed to accurately represent the molding cycle was not excessive so the full mold was used for easier viewing and interpretation of the results.) The three-dimensional model was constructed using SOLIDWORKS (Dassault Systèmes, Vélizy-Villacoublay, France) from measurements of the physical mold. The mold does not feature embedded heaters, but rather relies on heat transfer from upper and lower press platens; this is simulated with the constant platens temperature, T_p. All four exposed sides of the mold release heat to the surroundings via free convection and thermal radiation boundary conditions. Additionally, the exothermic curing reaction within the charge is represented as a heat generation term, $\dot{e}_{gen}$. Under these boundary conditions, ANSYS solves the Fourier-Biot Equation in three dimensions at specified time intervals. Table 1 presents properties as well as initial and boundary conditions. The molding resin's properties are that from a polyester-based sheet molding compound (Barone, et. al., 1986).

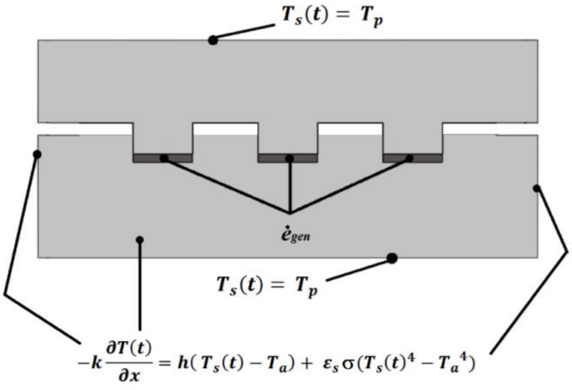

Fig. 4 Thermal representation of the mold with boundary conditions: T_s=surface temperature, T_p=platen temperature, T=mold body temperature, T_a=ambient temperature, t=time, $\dot{e}_{gen}$=heat generation, k=thermal conductivity, h=convection coefficient, ε_s=surface emissivity, σ=Stefan-Boltzmann constant, and x=dimension

Table 1. Input Property Data with Initial and Boundary Conditions

Parameter	Value
Mold Material	7075-T6 aluminum
Resin Material	polyester SMC
Resin Density	1850 kg/m^3
Resin Specific Heat	1000 J/kg
Resin Thermal Conductivity	0.53 W/m-^{o}C
Resin Heat of Reaction	80 kJ/kg
Initial Resin Temperature	165^{o}C
Initial Mold Temperature	165^{o}C
Platen Temperatures	165^{o}C
Molding Cycle Time	60 sec
Resin Curing Time	35 sec
Convective Heat Transfer Coefficient	9.6 W/m²-^{o}C
Emissivity of Aluminum Surfaces	0.25
Ambient Temperature	20^{o}C

The entire mold is assumed to be preheated to the cure temperature of 165°C. The resin as well as the top and bottom platens are set to this temperature at the start of the molding cycle (time=0 sec) with the press closed and the platens contacting the top and bottom mold surfaces. The platen temperatures remain at this value throughout the entire molding cycle. The heat of reaction is assumed to be evenly distributed over a 35 sec cure time that begins 15 sec into the molding cycle and stops 10 sec before the cycle's end when the press opens. The sum total volume and mass of the three tensile bars is 2.42×10^{-5} m^3 and 4.48×10^{-2} kg, respectively, which yields 0.102 kW of heat released during the 35 sec curing time. The emissivity represents a heavily oxidized aluminum surface while the convective coefficient is computed from laminar free convection from a vertical surface (the height of the closed mold). For the convective coefficient, the film temperature of 92.5^{o}C equals the arithmetic mean of 165^{o}C and the ambient. The thermal properties of the aluminum mold are the default values from the ANSYS properties library.

With these parameters, several preliminary ANSYS runs were conducted to establish a suitable meshing, i.e., number of elements. Results of this study indicated that reasonable, accurate numerical results became available with a total number of 55,477 elements. This required about 45 minutes of computing time. Figure 5 shows the closed mold body with this element meshing.

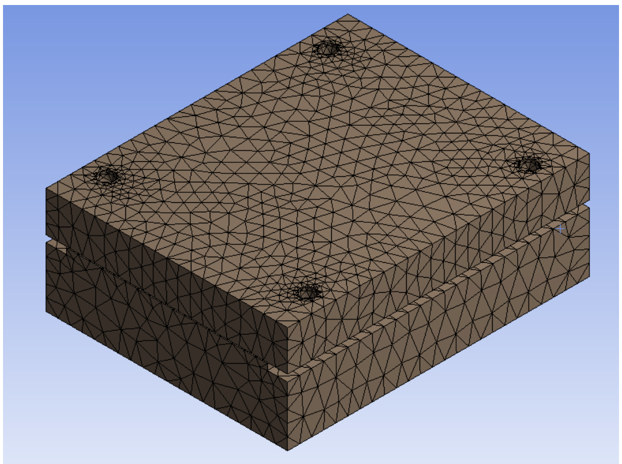

Fig. 5 Finite element meshing of mold body with 55,477 elements: ANSYS resolution=4 and span angle center=medium

5 RESULTS OF THE TRANSIENT ANALYSES WITH CONCLUSIONS

With the infinite number of temperature profiles available in the ANSYS post-processing files, four representative ones were selected to examine for isothermic behavior. Figure 6 is an outline view presenting the four selected temperature responses. Two temperature trends through the mold's width are plotted. One is through the exact midpoint of the mold, 95.3 mm from each end, and through the center of the thickness of each bar. Thus it begins at one edge; spans the aluminum up to the first bar; continues through the neck region of the first bar; and repeats until reaching the other edge of the mold. The path of the other temperature trend is very similar, except that it is located 14.1 mm from one edge of the bars' grip end. This places it through the center of each tensile bar's grip region. The last two trends are similarly located along the mold's length. One of which is through the exact midpoint of the mold's width, 76.2 mm from each mold edge, and again through the center of the thickness of the middle bar. The other spans the aluminum up to an end bar; continues through the center of this bar; and repeats until reaching the other edge of the mold. This path is 38.1 mm from the side edge of the mold.

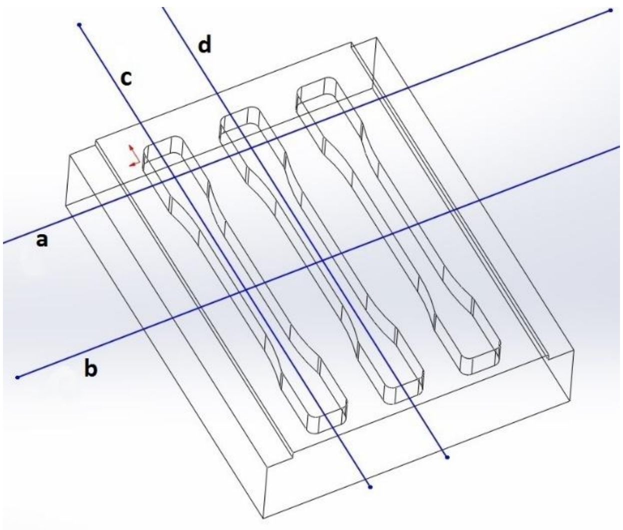

Fig. 6 Geometrical locations of the four temperature response lines

The resulting ANSYS temperature profiles displayed a "sawtooth" behavior. This could have been eliminated by using a larger number of finite elements and/or modeling only one-quarter of the mold (via symmetry) but would not numerically change the temperature values. The accuracy and stability of the solution was verified by a parametric analysis where the number of finite elements was increased until the temperatures at key locations remained unchanged. In order to improve the display of temperature plots, the data were processed by MagicPlot smoothing software (Magicplot Systems, LLC, St. Petersburg, Russia). The results shown in Figures 7 and 8 represent such processed data.

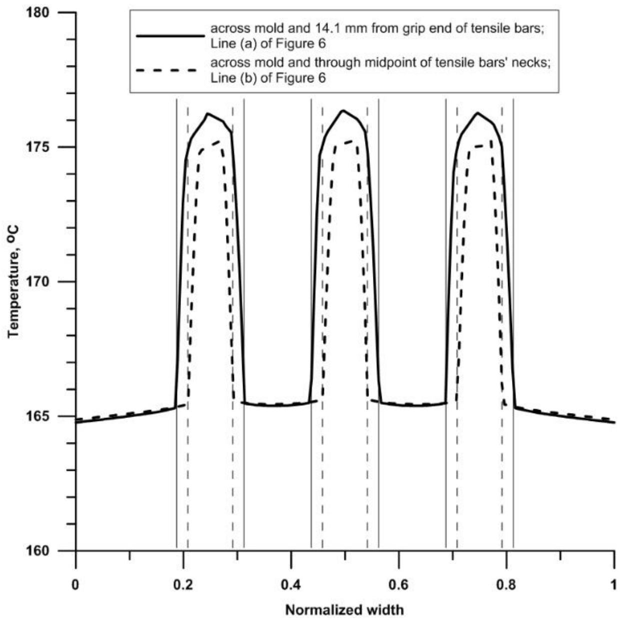

Fig. 7a Temperature response through the normalized width, set-point=165°C, time=48 sec

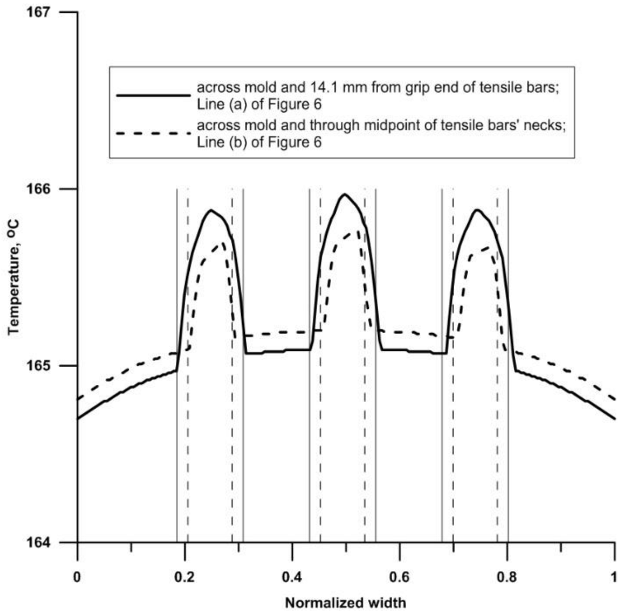

Fig. 7b Temperature response through the normalized width, set-point=165°C, time=60 sec

Figures 7 and 8 summarize the thermal distribution (as located by Figure 6) within the mold at 48 sec (2 sec before the end of the curing and equal to the global maximum temperature levels) and at 60 sec (the end of the molding cycle), respectively. Figure 7a shows the thermal response along the width of the mold. Here, the width has been normalized by dividing each location by the mold's overall width (152 mm). The figure shows the three temperature peaks as the temperature is traced from mold's edge to edge. Note that the figure displays the boundaries of the nominal, grip width of each bar, shown as solid, vertical lines. The width of the neck region of each bar is also indicated with vertical, dashed lines. Overall, each resin bar experiences the same temperature profile while within the heat-conductive aluminum, the temperature is near 165°C. The highest temperature levels are within the grip regions. Here lies the largest volume of resin with its heat generation; and, compared to aluminum, the resin is an insulating material further increasing temperatures. The difference between the peak neck and peak grip end regions is only about 1°C; such a small amount is not significant in the molding process. Similar behavior is illustrated in Figure 7b, although the middle bar retains a slightly higher temperature level (~0.1°C). The figure also indicates that the temperature rise during the heat of curing has been almost dissipated at the cycle's end.

Figure 8 demonstrates similar trends as the temperature rise is contained within the resin, and aluminum temperatures are near the initial, set-point of 165°C. (The figure displays the boundaries of the bar's length, shown as solid, vertical lines.) During the curing time (Figure 8a), there is little difference in the middle bar's response compared to the temperature profile of an end bar. Likewise, at 60 sec, about 0.1°C temperature difference exists between the middle and the end bars (Figure 8b).

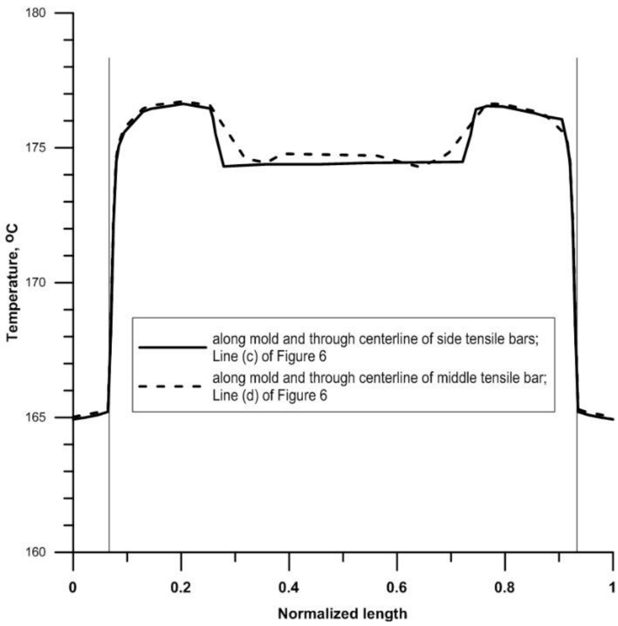

Fig. 8a Temperature response through the normalized length, set-point=165°C, time=48 sec

Figures 7 and 8 demonstrate that all three bars have nearly an identical heating history during their molding. The bars' temperatures reach nearly 12°C higher than the molding set-point, but quickly cool. The aluminum body of the mold largely remains at its initial temperature of 165°C. This result is important in that all three tensile bars can be considered identical for the purposes of testing their mechanical properties.

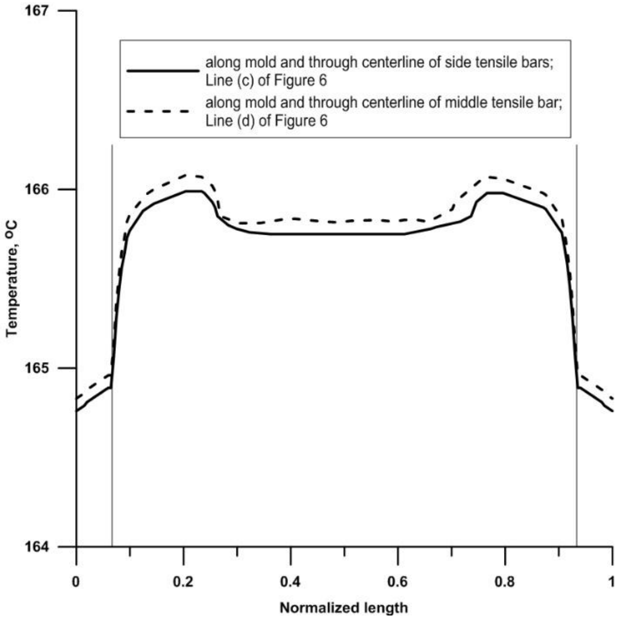

Fig. 8b Temperature response through the normalized length, set-point=165°C, time=60 sec

6 ACKNOWLEDGEMENT

The authors wish to thank Mr. Ian J. Kidd of the Department of Mechanical Engineering for his contributions.

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