Eliminating Distortion by Internal Surface Cooling of Thermoplastics Vacuum Pulled on Polyurethane Molds to Manufacture Ankle-Foot Orthoses

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ABSTRACT

The purpose of this study is to determine a process that will allow for copolymer ankle-foot orthoses (AFOs) to be cooled in a relatively short period while eliminating the distortion associated with force-cooling thermoplastics. This is accomplished by force-cooling the internal surface of the AFO using tap water. The results of this study show copolymer AFOs manufactured using a polyurethane mold could be cooled in 10 to 15 minutes with time starting the instant the thermoplastic is removed from the oven. By dramatically decreasing the amount of time it takes to cool the AFO and strengthening the internal surface, manufacturers are able to offer patients a turnaround time of less than 3 hours.

In the preparation of this experiment, a pipe is placed inside a polyurethane mold with a 1-inch hollowed center. The pipe has a 3/16-inch bored hole in its side. The hole is located on the pipe to ensure it will be positioned inside the polyurethane mold to prevent the thermoplastic from clogging the hole. Three nylon stockinets are placed over the mold to prevent the thermoplastic from sticking to the mold. During this experiment, two companies, Fillauer (Chattanooga, TN) and Friddles Orthopedic Appliances, Inc. (Honea Path, SC), manufactured the thermoplastics. Both are natural 3/16-inch copolymer.

The thermoplastics are heated to a thermoforming temperature using an infrared oven at 390°F until the copolymer is translucent. The temperature range for the thermoplastic exiting the oven is approximately 305°F to 330°F. The temperature is measured using an Extech type K thermometer (Extech Instruments, Waltham, MA) with a K type thermocouple. The accuracy of the thermometer (64.4°F to 82.4°F ambient) is ±(0.3 percent rdg + 2°F) for a range of -58°F to 2,000°F. Once the thermoplastic is translucent, it is removed from the oven and vacuum pulled over the polyurethane mold at approximately 12 psi vacuum. After 3.5 minutes, the plastic has returned to opaque, the toe is removed using a cast saw, and the orthosis is placed in an empty tub to catch water. The opening of the toe must be the highest point so water comes in contact with all of the inner surface. A hose is attached to a faucet at one end and a Watts Regulator Co. (North Andover, MA) pressure regulator at the other. The pressure regulator has a range of 3 to 50 psi. The pressure gauge on the regulator has a range of 0 to 30 psi, with accuracy of 3–2–3 percent accuracy. The phrase "0 to 30 psi with 3–2–3% accuracy" means the pressure reducer's reading is accurate to within 3% of the actual pressure from 0 to 10 psi, an accuracy of 2% from 10 to 20 psi and an accuracy of 3% from 20 to 30 psi. The pressure regulator is then connected to the pipe holding the orthosis and mold. The initial water pressure is 5 psi ± 3 percent until water is viewed exiting the toe. It is then the water pressure is increased to 15 psi ± 2 percent. The water is allowed to flow between the ankle-foot orthosis (AFO) and polyurethane mold until an exiting water temperature of less than 80°F is reached.

THEORY

Conduction occurs when there is a temperature gradient across a stationary medium. Fourier's law calculates the rate of energy change per unit area. [1]

$q'' = -k(T_2 - T_1)/\text{Length}$

k is the conduction coefficient of the material and $T_2 - T_1$ is the change in temperature across the material. Because the outer surface of the AFO is cooling by free convection and the inner surface is insulated, the outer surface is cooling at a faster rate than is the inside surface. It is this imbalanced cooling that causes warp in the plastic. Our goal is to balance the cooling to eliminate distortion.

Convection is the transfer of heat from a surface to a fluid moving over the surface. Free convection is a result of buoyancy forces in a fluid caused by a difference in density (temperature) in the fluid. [1] The hotter air at the outer surface of the AFO is less dense than the ambient air and thus rises from the surface. Free convection is not as efficient as forced convection when the forced convection medium is much more dense and traveling at a faster velocity than the free convection medium. Convection caused by the internal flow of water in the AFO is not easily calculated. First, the AFO wrapped around a polyurethane mold is not a uniform shape. Second, water is not flowing in a hollow pipe. It is flowing between two surfaces that are less than 0.1 mm apart. Finally, water mass flow is not uniform from test subject to test subject because of minor leaks between the copolymer and the pipe. Considering Fourier's law is phenomenological (it is developed from observed phenomena, rather than being derived from principles), [1] our conclusions based on observations go hand in hand with the subject matter. Tap water was chosen as the convective fluid because convective heat transfer is directly related to mass flow, and the mass of water is approximately 800 times the mass of air, which is cooling the outer surface.

RESULTS

Through trial and error and use of the data collected, the exit water temperature for stopping water flow was determined to be 80°F, with an inlet water temperature of 60°F (tap water). Figure 1 demonstrates the external cooling process of an AFO if it is allowed to cool without any assistance. The lines are not "smooth" because of fluctuations in the recorded temperature. However, the graph lines do portray a trend in the cooling process, and a best-fit polynomial is an accurate formula for predicting temperatures. Figure 2 demonstrates how quickly the water is cooling the inner surface of the AFO. The graph does not indicate that steam exits the toe just before water approximately 4 minutes 30 seconds after the plastic is taken from the oven. This indicates the inner surface is in excess of 212°F. (Note: Legs 1 to 4 in Figure 1 are separate experiments than Legs 1 to 4 in Figure 2 .)

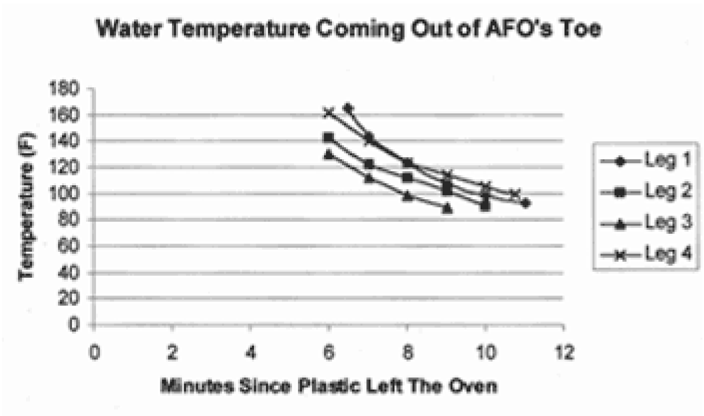

Figure 2. Temperature of water coming out of the AFO's toe.

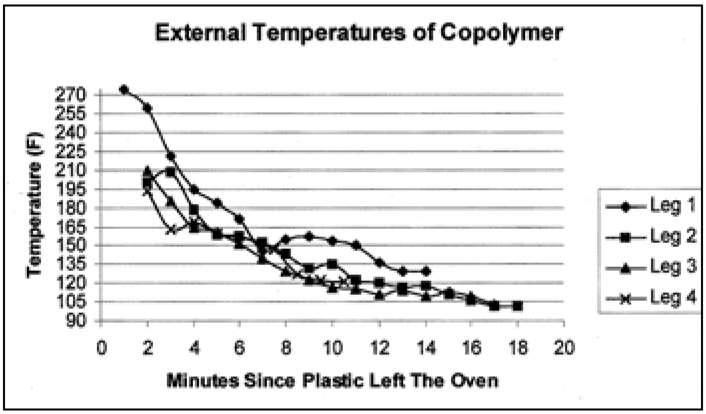

Figure 1. External temperatures of copolymer AFO.

All models were immediately cut from their molds, and initial measurements were taken across the opening at various positions and along the back vertically. The maximum distortion measured after 24 hours was 1 mm (± 0.5 mm) outward for all measurements taken. Note: If the water was stopped after the outlet water temperature reached 100°F, distortion was 1 mm (± 0.5 mm) inward.

STRENGTH TESTING OF COPOLYMER

The purpose of testing the copolymer after it had been cooled is to compare any loss of strength with the original cooling method. Our assumption before the testing was the forcecooled samples would show degradation in the strength compared with the overnight samples. A SATEC T10000 Materials Testing Machine (SATEC, Grove City, PA) was used to apply a tensile load to the plastic, and a MTS Systems Corp. LX500 Laser Extensometer (MTS Systems Corp., Eden Prairie, MN) was used to measure the elongation of the copolymer. The tensile strength testing revealed some unexpected results. The samples that were force-cooled showed a higher yield stress (sigma $_y$) and modulus of elasticity (E) than did the samples allowed to cool overnight.

(sigma) = P/A

P is the axial load and A is the cross-sectional area of the material. Strain (epsilon) is the change in length of the material resulting from an axial force divided by the original length of the material.[2]

(epsilon) = (delta)L/L

The modulus of elasticity is the stress/strain ratio.[2]

E = (sigma)/(epsilon)

After looking at the data, it appears the plastic is allowed to cool below its recrystallization point then quenched using the water and therefore strengthening the plastic (increasing its modulus of elasticity). By quenching the AFO, the inner surface is hardened, more so than if it were left to cool on its own.

The three force-cooled samples had a yield stress/modulus of elasticity of 1,844 psi/106,862 psi, 1,894 psi/113,502 psi, and 1,830 psi/95,859 psi. The samples allowed to cool overnight had a yield stress/modulus of elasticity of 1,136 psi/ 65,512 psi, 1,960 psi/88,073 psi, and 1,220 psi/58,753 psi. The overnight samples varied more than did the force-cooled samples. Although the middle sample of 1,960 psi/88,073 psi should be dropped as a "wild point" in the data, using it as the only data point would still prove little, if no, decrease in the structural integrity of the plastic using the force-cooled method.

CONCLUSION

Distortion is a result of stresses placed on the molecules in the plastic. Cooling the inner and outer surfaces more uniformly allows the stresses to offset one another. Quenching the inner surface of the AFO also contributes to eliminating stress associated with distortion. During the first 3.5 minutes after removal of the thermoplastic from the oven, the external surface temperature decreases considerably compared with the internal surface. Quenching decreases the thermal gradient to zero, then increases the gradient but with the internal surface at a lower temperature. This lowers the stresses associated with thermal gradients while hardening the inner surface. Hardening the inner surface also increases the tensile strength of the plastic. The internal cooling process using water makes cooling AFOs and removing them from a polyurethane mold in less than 15 minutes possible. This is preferred to leaving them to cure overnight while increasing the plastic's tensile strength.

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