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Ice-Water Quenching Technique for Polypropylene[1]

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The use of polypropylene as a material in orthotics and prosthetics has gained widespread acceptance over the last several years. However, our basic knowledge of this material has not kept pace with its use in the design of orthoses and prostheses. This report is an attempt to make the practitioner aware of possible variations in the properties of polypropylene as a function of processing conditions. Specifically, the processing variable investigated in this report has been a rapid rate of cooling for polypropylene devices during fabrication. A description of the fabrication procedure is preceded by a brief summary of some principles of polymer science relevant to polypropylene processing.

Polypropylene belongs to a class of polymeric materials known as the semicrystalline thermoplastics. The classification of polypropylene as a material of this type implies a rather complex microscopic structure as well as extreme sensitivity of physical properties to processing conditions (1). Processing conditions involve primarily the thermal history, pressure, and the extent to which the molten material is mechanically deformed prior to its solidification. Thermal history is especially significant. At temperatures above the melting point (170 deg C for polypropylene), the long polymer molecules entangle randomly to form a network lacking structural order (amorphous network). Upon cooling, however, a certain portion of the material solidifies in the form of ordered molecular arrays known as crystallites[5], while the remaining portion retains the structure characteristic of the amorphous network. In this context, the significance of thermal history to physical properties of polypropylene lies in the possibility of controlling through temperature the relative amounts of crystalline and amorphous material present in the final product. This control is crucial in processing of semicrystalline thermoplastics since the mechanical properties of crystalline and amorphous material differ substantially. For example, crystalline material is generally stronger, yet less flexible than amorphous material (2). One possible way of controlling crystalline vs. amorphous content in the final

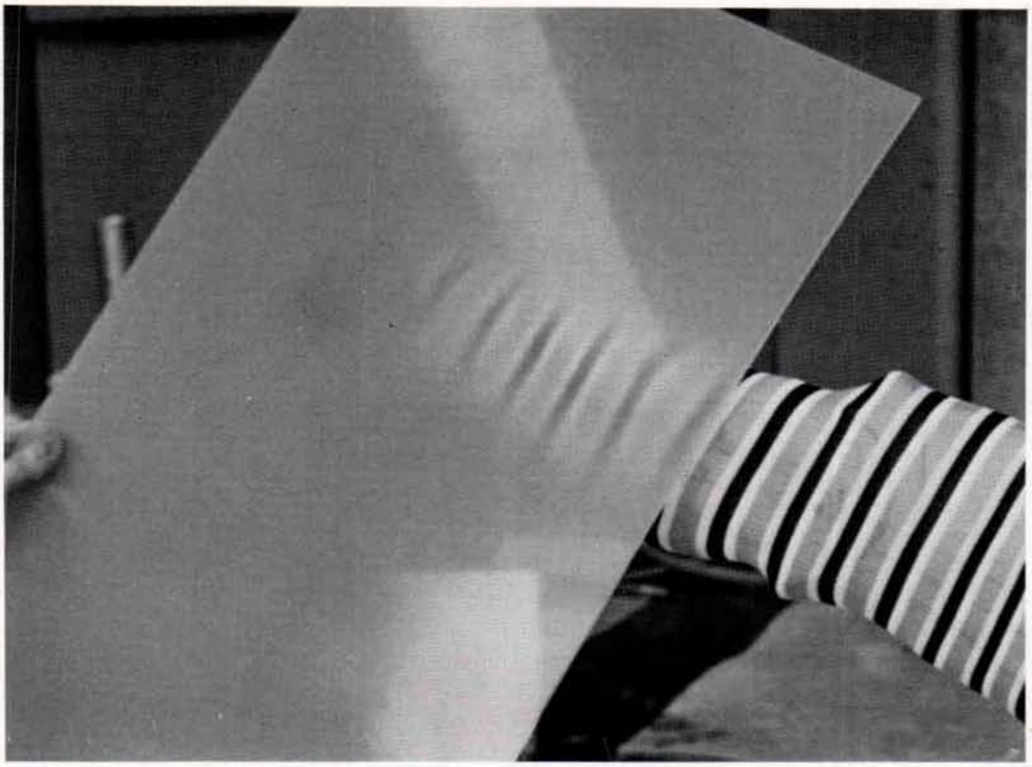
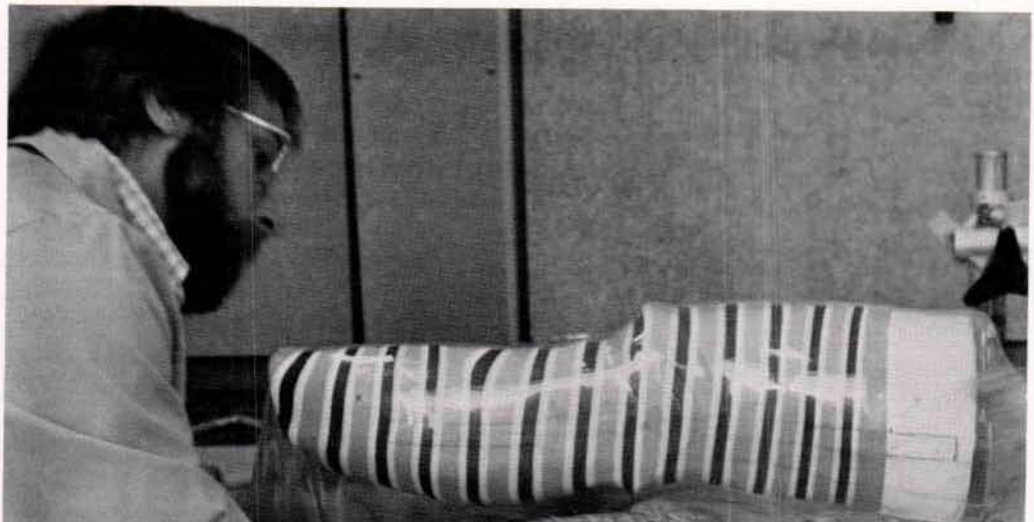


Figure 1. Polypropylene sheet (1/8 in., 0.32 cm) to be formed over a cast for a knee orthosis.

product is by manipulation of the cooling rate used to solidify the molten polymer. This possibility is based on the fact that substantial growth of crystallites requires finite periods of time at temperatures 20-100 deg lower than the melting point, depending on the material (3). As a consequence, some semicrystalline polymers, when solidified by rapid cooling of the melt to ambient temperatures or below, tend to contain a considerable volume fraction of amorhpous flexible material.

Another characteristic feature in the structure of semicrystalline themoplastics is the formation of rather large spherical aggregates upon the solidification of molten material. These aggregates can be considered as the basic 'grains' of the material and are known as spherulites. Depending partly on processing conditions, spherulites can range in size from microscopic dimensions to a few millimeters in diameter (4). These spheroidal grains consist of both crystallites and amorphous material, and their size can greatly affect both the mechanical and optical properties of the final product. For example, solidified materials consisting of small sized spherulites tend to be more transparent than those in which spherulites are of considerable dimensions (1). This difference is based on the

Figure 2. Softened polypropylene sheet being placed over the cast.



Figue 3. Sealing of softened sheet to provide vacuum contouring. This procedure is to be followed by removal of excess material.

fact that spherulites tend to scatter light when their size is comparable to visible wavelengths. Furthermore, in polypropylene and other semicrystalline thermoplastics, it is often found that small spherulites increase impact strength in the final product (5). Spherulite size is, therefore, important in determining physical properties and, again, this variable can be controlled by processing conditions such as cooling rate. Generally speaking, fast cooling rates to temperatures well below the melting point of the material lead to the formation of small spherulites in semicrystalline thermoplastics.

ICE-WATER QUENCHING PROCEDURE

The relations between microstructure and properties discussed here have provided the basic rationale for the newly developed processing technique for polypropylene devices. Orthotic and prosthetic devices quenched in ice water immediately after forming exhibit greater transparency than those exposed to slower cooling rates through the use of compressed air. Furthermore, in agreement with the discussion above, these devices have also been found to possess greater

Figure 4. Vacuum-formed cast immersed in ice-water bath.

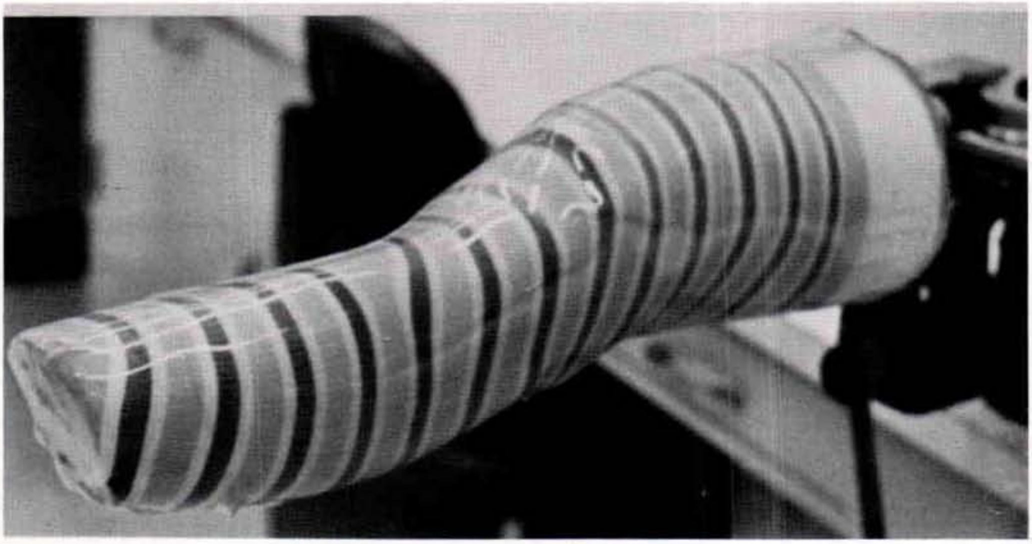


Figure 5. Vacuum-formed knee orthosis prior to removal from cast.

mechanical flexibility. The handling of the polypropylene is the same as with other vacuum forming methods with the exception that the model must be removable from the vise. Figures 1 through 5 illustrate the technique on a knee orthosis (K.O.). The cast is covered with a multicolored nylon to illustrate the transparency of the ice-water quenched orthosis. Specifically, a comparison of Figure 1 with Figure 5 illustrates the difference in transparency between the original sheet and the ice-water quenched material. One important property of ice-water-quenched polypropylene is the fact that it tends to contract upon cooling. This is evidenced by the observed overlapping of seams in devices which have been removed from the models.

RECOMMENDATIONS AND CONCLUSIONS

The use of ice-water-quenched polypropylene is recommended when increased transparency, increased impact strength, and increased flexibility are desired. Although the properties of the original material may vary according to its source, those of the processed material are expected to be similar from device to device. Increased transparency improves the acceptability of orthoses from the standpoint of appearance. It also facilitates visual examination of underlying skin in both orthoses and in sockets for artificial limbs. Increased impact strength, conversely, would be recommended for prostheses and lower-limb orthoses. It should be pointed out that even though increased flexibility is not always desired, the resulting toughtness, and thus a decreased tendency to crack or tear, are always advantageous properties. In cases where an increased flexibility in the material presents a problem, changes in geometric design can be used to overcome this disadvantage. An example of such changes is the introduction of corrugations in the device.

Some of the advantages of ice water-quenched polypropylene have been pointed out above. Currently, solidified materials obtained using various cooling rates are being quantitatively characterized in terms of both mechanical and optical properties. It is hoped that these measurements will allow optimization of properties in polypropylene orthotic and prosthetic devices through the control of processing conditions.

References

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Footnotes

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[5]Crystallites usually consist of very thin layers of material with thicknesses in the range of 10^{-6} cms.