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Evaluation of the Air Bubbles Present in Polyurethane Shoe Outsoles as Applicable in Footwear Impression Comparisons

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ABSTRACT: Polyurethane, an increasingly popular material in the manufacture of shoe outsoles, contains air bubbles which are visible on the surface of the outsole and which may become part of a footwear impression. How to weigh the significance of each air bubble when conducting an examination of these footwear impressions is discussed. The most common methods of manufacture of polyurethane outsoles and how each of these methods affect the resulting air bubble pattern are explained. A summary of the chemical, mechanical, and physical variables influencing the position and contour of these trapped air bubbles is given. These characteristics, alone or in conjunction with the traditional wear patterns and accidental characteristics acquired during the use of the shoe, can help the examiner form a stronger opinion toward the identification of the footwear.

KEYWORDS: criminalistics, footwear, impressions, polyurethane

Polyurethanes are elastomeric polymers used in a wide variety of resins, flexible foams, and rigid foams. First produced in Europe, they have been used in footwear manufacture for over a quarter of a century.

Polyurethane footwear was originally introduced in the United States in 1972, but only for the production of athletic shoes. In the late 1970s and early 1980s the polyurethane market expanded to include men's and women's dress and work shoes. Currently, polyurethane outsoles and midsoles can be found in athletic shoes, boots, and casual and dress shoes. Present trends suggest a further increase in its usage and popularity throughout the footwear industry [*1*]. This increase is due to polyurethane's combined qualities of being lightweight, very durable, versatile, and economically feasible.

Polyurethane soling systems now represent 9% of all domestically produced footwear. In 1986, 21 million pounds (9.45 million kg) of polyurethane was used in soling in the United States, as compared to 100 million pounds (4.5 million kg) worldwide.

When polyurethane (PU) is used as an outsole material, most of the soles wind up with air bubbles on the surface of the outsole (Fig. 1). Some show only a few bubbles, while others have many. Some of the bubbles are totally random, while others have a tendency to repeat in the same areas. The occurrence, frequency, and reason for the air bubbles are related to the specific manufacturing processes and to several variables encountered within each pro-

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FIG. 1—*Polyurethane outsole showing air bubbles on surface.*

cess. While footwear impression examiners can compare any air bubble on a shoe outsole with corresponding "void" areas which may be present in a questioned footwear impression, the critical part of the examination lies in assessing the significance of the bubbles. To make an identification, it is necessary to determine that the void areas which are visible in the questioned impression specifically correspond with air bubbles in the PU outsoles and that the combined occurrence and characteristics of those specific air bubbles are unique and would not occur again in the manufacturing process.

The purpose of this paper is to provide an in-depth understanding of the manufacturing of PU outsoled shoes with emphasis on the cause and occurrence of the air bubbles. It is intended that this will provide the footwear examiner with the additional information needed to conduct an examination of PU outsole impression evidence.

Outsole Manufacturing Methods Utilizing Polyurethane

Polyurethane soling materials can be used in both "injection molding" as well as "open and closed pour molding." To explain some of the variables influencing the PU air bubbles, a general description of each manufacturing method must first be made.

Injection Molding "Direct-Attach" Method

In the "direct attach" method, the mold assembly (siderings and soleplate) is closed tightly around the previously constructed shoe upper (Fig. 2). When the soling material is injected into the mold, it produces an outsole (or midsole or both) which forms around and directly attaches to the shoe upper [*2*]. Direct attach injection mold systems vary considerably. They can use one, two, or three components, each of which may be different in color and substance.

One-component "direct attach" systems inject PU into the mold assembly, and the entire one component sole is molded and affixed to the shoe upper (Figs. 3 and 4.) When the polyurethane is injected into the mold, it fills only a portion of the mold cavity nearest the point of injection. As the chemical reaction takes place, the polyurethane expands to fill the entire cavity, and excess material is forced back out the injection port (referred to as "sprue") and between the seams where the mold parts meet (referred to as "flash").

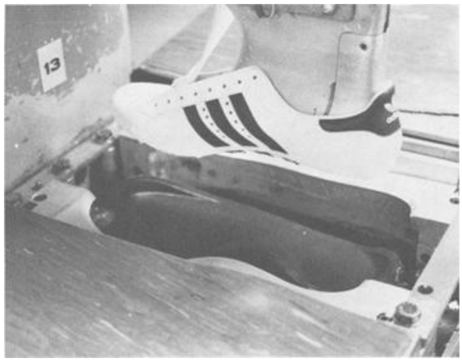

FIG. 2—*In direct attach method, the lasted shoe upper is lowered into the mold assembly, which then closes tightly around it, allowing injection of outsole material directly onto shoe upper.*

Many "direct attach" injection mold systems use two or more components. These components can be different colors or different materials or both. In a two-component process, the outsole is injected first using a smooth "dummy" last in place of the shoe upper (Fig. 5*a*). After the outsole has been formed, the dummy last is rotated out of position and the shoe upper is lowered into the mold assembly (Fig. 5*b*). The midsole is then injected through a second injection port and directly attaches the previously injected outsole to the shoe upper (Fig. 5*c*). The finished footwear (Fig. 5*d*) will bear evidence where the two halves of the mold came together and where the point of injection was (Fig. 5*e*). Some manufacturers, however, may attempt to cover or grind these areas to obscure these features.

Injection Molded Unit Soles

Injection molded "unit soles" are those which are injected into a closed mold, but are not directly attached to the shoe upper. Instead, the molded unit soles are later glued or stitched to the shoe upper. Unit soles can be made on direct attach machinery with the use of the "dummy last" or they can be manufactured on separate unit sole injection machines.

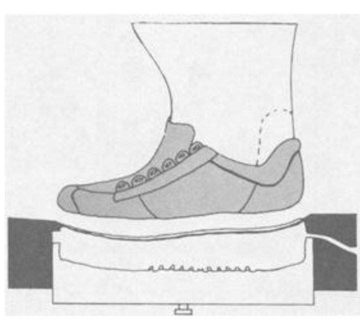

FIG. 3—*Shoe upper, on a last, being lowered into mold assembly in a one-step direct attach operation.*

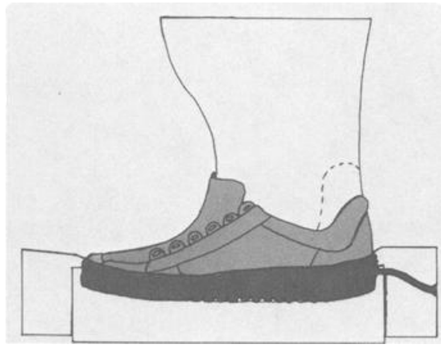

FIG. 4—*Outsole material is injected through heel area, forming the outsole in one-step direct attach operation.*

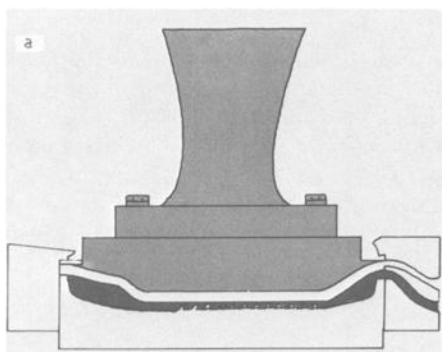

FIG. 5a—*Dummy last lowered into mold assembly over the soleplate, allowing outsole portion to be injected. This is the first step of a two-step direct attach operation.*

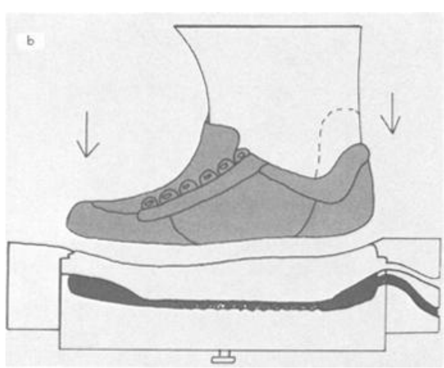

FIG. 5b—*Dummy last has been removed, and lasted shoe upper is lowered onto the already injected outsole.*

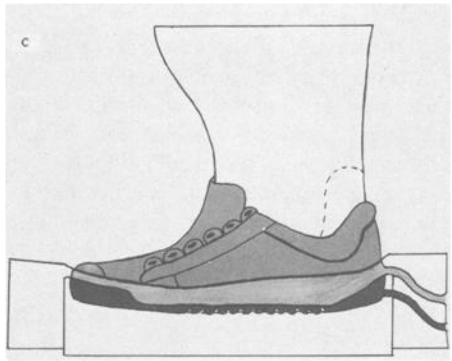

FIG. 5c—*Mold assembly closes and the midsole is injected to bond the outsole to the lasted shoe upper. This is the second step of the two-step direct attach operation.*

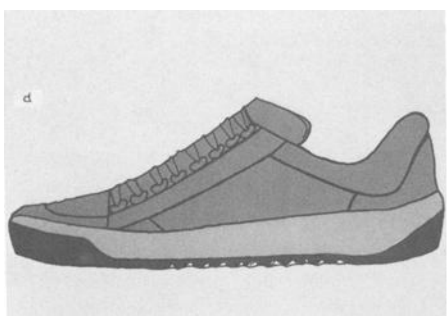

FIG. 5d—*Finished shoe.*

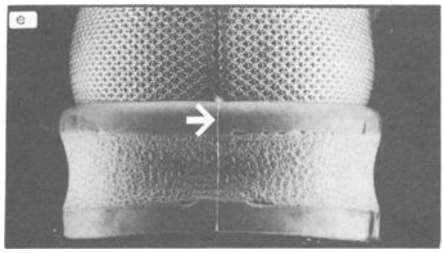

FIG. 5e—*Heel area of a two-step direct attach operation showing the seam which results in the area where the mold halves closed together.*

Open Pour Molding

Another method of polyurethane outsole manufacture is called "open pour" molding. The primary application of this process is the molding of unit soles; however, it has also been adapted for direct attach soling. The process of open pour molding is much as its name describes (Fig. 6). Polyurethane is poured from an overhead nozzle into the mold cavity. The lid (unit soling) or last (direct attach) is then immediately closed, and the chemical reaction takes place. As the PU expands, any excess material (flash) escapes at the uppermost surface of the outsole where the lid meets the mold. Closed pour molding is a combination of the injection and open pour processes. The PU is poured into a closed mold through an overhead port in the last. Unit soles constructed by these methods can later be direct attached by a polyurethane midsole or stitched or cemented to a shoe upper. They can be used in athletic footwear and casual and dress shoes.

Variables Affecting Bubble Size, Frequency, and Distribution

There are a multitude of variables influencing the frequency, size, and distribution of trapped air bubbles in polyurethane footwear, and these are divided into three groups.

1. Chemical: those relating to the chemistry of the ingredients which form the polyurethane.
2. Mechanical: those relating to the mechanical mixing of the components and the mechanical process of injection.
3. Physical: those relating to the physical properties of the mold, such as the mold design, stippling, and the application of release agents.

Chemical

Dr. Otto Bayer first pioneered the chemical process of polyaddition in the late 1930s for the production of polyurethanes [3]. The basic reaction involves the formation of a urethane from an alcohol and an isocyanate:

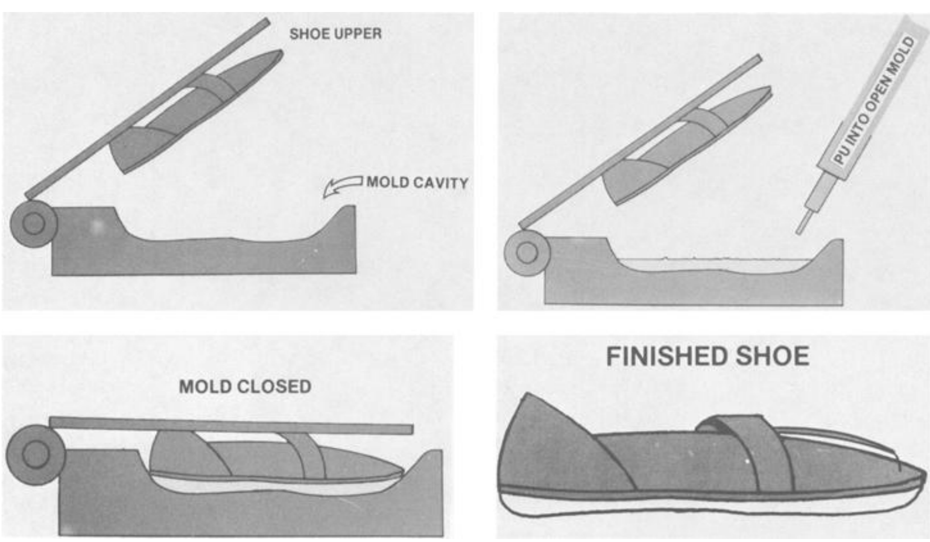

FIG. 6—*Open pour method uses an open mold to which PU is added. The mold is closed, allowing the PU to harden around the upper, resulting in a finished shoe.*

$$\underset{\text{ISOCYANATE}}{R-N=C=O} + \underset{\text{ALCOHOL}}{R-OH} \rightarrow \underset{\text{POLYURETHANE}}{R-N-C\genfrac{}{}{0pt}{}{\diagup O}{\diagdown O-R}}$$

In practice, most polyurethane soling systems are made of two or more components, the resin blend and the isocyanate. Typically, the resin blend is comprised of polyol resins and auxiliary materials such as blowing agents. chain extenders. and catalysts. In outsole manufacture, polyester or polyether-type base resins may be encountered. The polyester based resins are produced by the reaction of a difunctional acid with a polyalcohol. The polyether base resins are made by reacting an alcohol with alkalene oxides. Blowing agents expand the polyurethane by either a chemical or physical reaction. The chemical process uses the reaction of water with an isocyanate to produce carbon dioxide gas. This action expands the reacting liquid and creates a "foam." The physical process is accomplished by adding low boiling hydrocarbons, such as Freon®, to the reaction mixture. The heat of reaction serves to vaporize the hydrocarbon resulting in the expansion of the foam. Chain extenders are added to increase the molecular weight of the polyurethane, and catalysts are used to accelerate the reaction time. Surfactants can be included to regulate the structure, and size of the foam cells and pigments may be used to color the polyurethane.

Before mixing, both the resin and the isocyanate, both in liquid form, must be maintained at a constant temperature and stirred [*4*] to prevent dimerization of the isocyanate and to ensure uniform dispersal of the resin components. The proper reaction ratios are established for each "batch" of PU and should be kept constant throughout production.

During the chemical reaction of the resin and isocyanate, heat is generated and pressure is created as the foam expands within the mold. This phenomenon causes the polyurethane to form an "integral skin" at the mold/outsole interface. The "skin" of the polyether base resin is much denser than the remainder of the outsole. This high-density skin accounts for the low frequency of air bubbles on the surfaces of these outsoles [5]. As a result of wear, however, the surface is eroded and the larger, coarser bubbles, beneath the skin, can be revealed. The polyester based PU has a thinner skin than the polyether variety, and as a result, is more easily ruptured by air bubbles (Fig. 7).

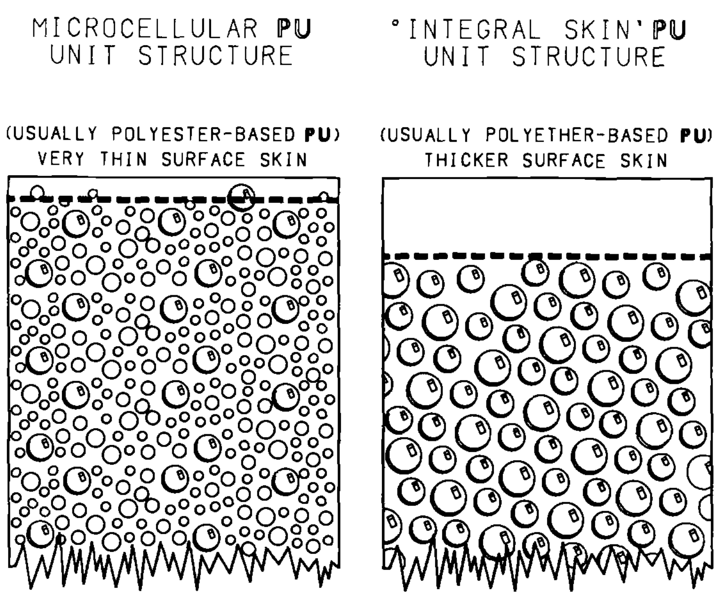

FIG. 7—*Difference between polyester based and polyether based polyurethane.*

Mechanical

It is important to mix the resin and isocyanate very rapidly and effectively since the "cream time" is so brief (usually 3 to 10 s). "Cream time" is the length of time required for the isocyanate and the resin to react and begin to expand. As cream time is decreased, generally the mixture is solidified more rapidly, the flow properties of the polyurethane are impeded, and more air bubbles are trapped. The components are mixed together by a mixing screw at speeds of 7 000 to 15 000 rpm. A considerable amount of air is entrapped in the polyurethane during this phase alone.

The condition of the mixing screw is continually changing during production, inasmuch as some of the PU is hardening on the screw itself, thereby reducing the area in the mixing chamber and increasing the velocity of the injected material. As the screw becomes increasingly dirty, the efficiency of the mixing chamber is reduced. Because of this, the screw in the mixing chamber must be changed at frequent intervals [*6*]. The effects of a dirty mixing screw on the resultant PU product are plainly visible (Fig. 8). Other variables of a mechanical nature would include air in the mixing port or in the mold itself. This form of air entrapment often results in larger aspherical bubbles. Some molding systems have air release vents in the mold which assist in the removal of this type of entrapped air. Other factors involving the maintenance, quality, and so forth of the equipment used to store, mix, or inject the PU are also mechanical variables.

Physical

There are many physical variables that affect air bubble size, frequency, and pattern in polyurethane soles. In injection molding, any factor that restricts the ability of the PU to flow evenly over the surfaces of the mold assembly will increase the likelihood of trapped air bubbles in the shoe sole. Sharp edges, sharp corners, deep tread, and a mixture of design elements all serve to increase turbulence, resulting in more air to be entrapped within the outsole.

The texture of the mold surface is still another variable affecting bubble size, shape, and distribution. Stippling on the mold surface increases turbulence and provides minute pockets for air entrapment (Fig. 9). The application of a mold release spray, either manual or automated, will also affect the flow of PU and the resulting air bubble pattern.

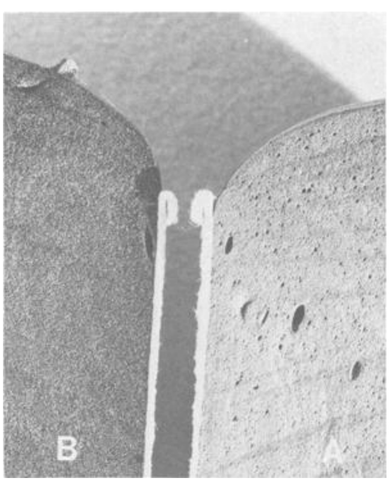

FIG. 8—*A mixing screw which is clean results in a more efficient mix and creates more turbulence and air* (a), *while a dirty mixing screw is less efficient and results in less air* (b).

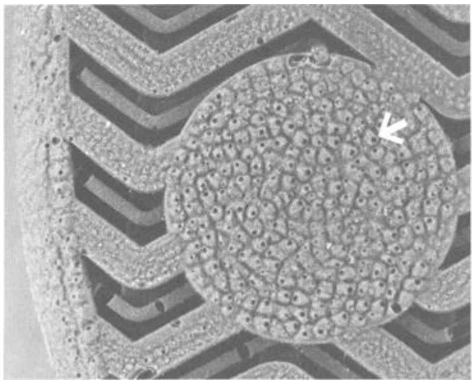

FIG. 9—*Stippled areas can also trap air in the bottom of each stipple.*

The "last" is a metal footform which supports and gives shape to the shoe upper. The texture of the last will also play a part in the final air bubble pattern. A "dummy" last has the least pronounced effect because of its smooth untextured surface. In the one-component, direct attach injection molding process, both the slip and the string lasted upper will impede the flow of urethane through the mold assembly. A slip lasted upper has a fabric or paper sole stitched to it, and its texture is rough but mostly uniform. In string lasting, the shoe upper is drawn tight against the last by a drawstring which is wound around metal pins protruding from the last. The metal pins, the webbing, the string, and the last comprise a very irregular surface which contributes to entrapping more air.

Evaluation of Polyurethane Bubbles in Casework

Some bubbles are influenced to some degree by the particular design of the mold [7] combined with the direction or point of injection of the PU or both. Using the herringbone pattern as an example, PU which is injected at the heel of the mold will leave trapped air in the "peaks" of the herringbone pattern or tops of the design features of the mold (Fig. 10).

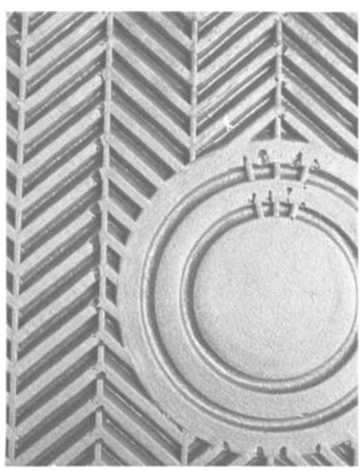

FIG. 10—*Most air bubbles favor peaks of this herringbone pattern and top of the circle pattern because direction of expansion is from heel to toe.*

FIG. 11—*Most air bubbles favor valleys of this herringbone pattern and bottom of circle pattern because direction of expansion is from toe to heel.*

Likewise, PU injected at the toe of the mold would favor the "valleys" of the herringbone pattern or the bottoms of the design features of the mold (Fig. 11). In a simple tread design, some repetitively molded PU outsoles will show remarkably similar patterns of air bubbles. Looking at a portion of three sequentially molded Adidas outsoles (Fig. 12), a combination of unique and pattern bubbles can be seen. Some bubbles are so closely duplicated that, in their new condition, portions of the three outsoles could not be distinguished from one another. Yet further examination reveals that there are many different bubbles that are not present in all three outsoles, as well as others which, although present in the same location, are distinguishable in specific size and shape. In fact, as similar as the bubble pattern may appear (superficially), it is hard to find any area (of the outsoles) which has more than a few bubbles that could be mistaken as originating from the same outsole.

As the tread design becomes deeper and more complex (that is, with the combination of many design elements), there is an increased tendency for air entrapment in the mold bottoms [*8*] (finished outsole surface.) There is also a more pronounced variation of the specific positioning as well as size and shape of the air bubbles. In general, the simpler the mold design, the more easily pattern influenced bubbles will repeat. The more complex a mold design, the less likely it is that the bubble pattern will repeat.

In yet another example, two different shoe soles of the same tread design, molded by the same company in two different molds several months apart, exhibit dissimilar bubble patterns (Fig. 13). Although one of these shoes has been worn, the obvious differences can still be seen by observing the positioning and approximate size of the bubbles.

The bubbles in PU outsoles range from spherical to aspherical and tiny to large. The variations of spherical bubbles are observed in terms of their size and positioning, whereas aspherical bubbles have the additional characteristic of shape. Aspherical bubbles tend to be among the largest bubbles and because of their variable sizes and shapes are less likely to be duplicated in another outsole. As a result, they contribute more heavily toward the individuality of an outsole. Some of the tiniest bubbles are found in the stippled areas (Fig. 9) of the outsole and have little room for variation aside from their presence of absence. In addition, since these bubbles are so small and wear off of the outsole so quickly, they are seldom visible in footwear impressions.

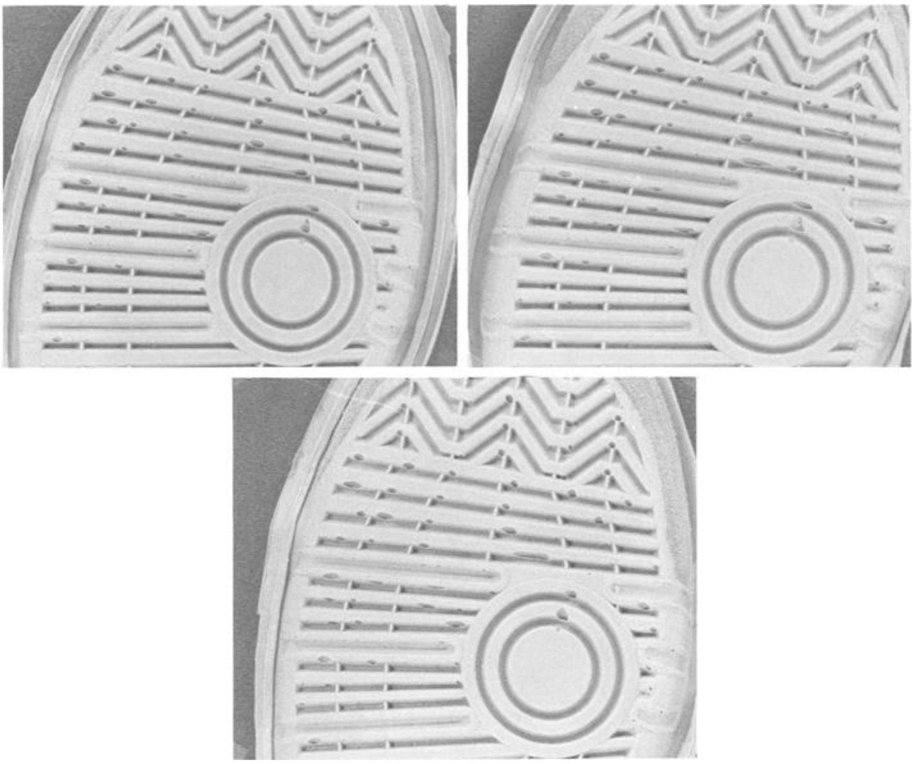

FIG. 12—*Similarities and differences of three outsoles from the same mold and injected simultaneously within minutes of one another.*

The design of many boots and casual shoes can be quite shallow or flat, thus the frequency of pattern influenced bubbles is generally reduced. These air bubbles are more likely to be spherical and smaller, but their positioning is more likely to be random. Because of the density of the PU and the shallow nature of these designs, there are usually fewer surface bubbles when the shoe is new but a greater number of totally random subsurface bubbles, which will appear as the shoe is worn.

As any shoe with a PU outsole is worn, the air bubbles that are on the surface of the outsole will undergo change. The bubbles, as they begin to wear down, can change in size,

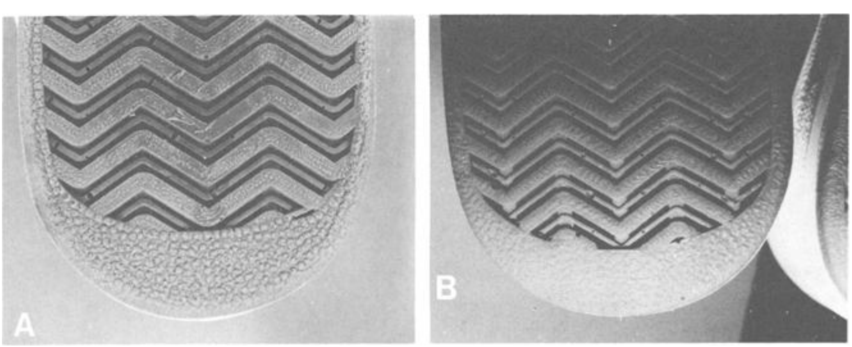

FIG. 13—*Two outsoles of the same design from the same company and PU process but from different molds and taken at different times.*

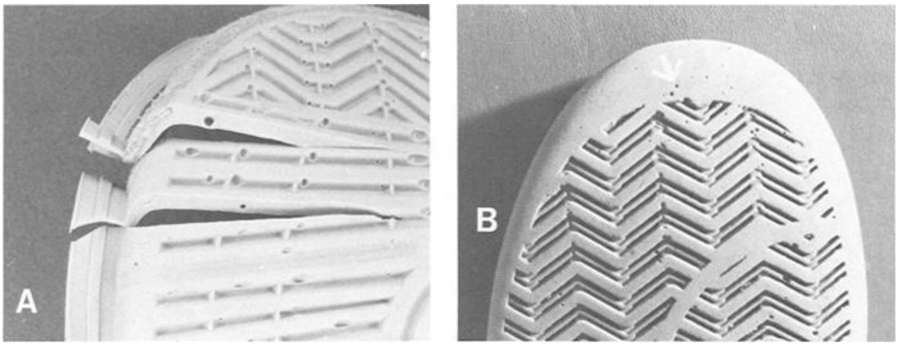

FIG. 14—(a) *A new outsole which has been cut to expose air bubbles beneath the surface.* (b) *Part of an outsole which has been worn for a year and which now has exposed many random bubbles which were not influenced by the mold pattern, but which were simply trapped in the PU at the position when it hardened.*

shape, and position. These bubbles are more likely to acquire random characteristics since they are quite fragile and their edges can be easily frayed or torn. They will also eventually wear off and disappear, and other bubbles which were trapped beneath the surface of the PU outsole will appear. Thus the specific bubble pattern will continue to change throughout the life of the shoe (Fig. 14).

By now, it can be easily seen that because there are so many factors influencing the air bubbles in PU outsoles, no bubble is the result of one factor alone, but rather is the product of many. In examination of PU outsoles encountered in casework, it is not possible to "reconstruct" the exact chemical, mechanical, and physical influences that were present when the shoe was made. In recognizing the many variables involved in outsole manufacture and understanding how the bubbles are modified as a result of wear, an examiner will be able to strengthen his or her observations during the footwear examination. In many instances, polyurethane outsoles contain a combination of bubbles which are unique to that shoe alone. The evaluation of each bubble and its likelihood to recur (or not occur at all) in the exact size, shape, and position on sequentially manufactured outsoles from the same mold must be determined by the examiner in order to reach a valid conclusion. Caution should be exercised when conducting examinations of impressions that lack sufficient clarity and detail or that reflect only a limited number of pattern influenced bubbles.

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