Improving shoe performance and increasing automation in footwear production with new TPU foam

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In recent years, extreme volatility in Asian-Pacific labor markets, coupled with price instability and increasing consumer demand for higher performance products has put tremendous pressure on footwear designers to incorporate more automation into their manufacturing processes. However, with the vast majority of athletic shoes today made from materials that require labor-intensive preparation (e. g., ethylene vinyl acetate (EVA), rubber), this has been difficult achieve. In 2014, Lubrizol set out to change that by combining a unique thermoplastic polyurethane (TPU) chemistry with MuCell injection molding technology to form BounCell-X (BCX) – a low density, recyclable TPU foam that not only offers performance advantages when compared to EVA and rubber, but also helps footwear manufacturers reduce waste, improve quality, and increase the efficiency of their production operations.

1 Introduction

Thermoplastic polyurethanes (TPU) are linear, multi-phase block copolymers that consist of three main components: a polyol, a short-chain diol, and a diisocyanate. Together in series, these components form alternating soft and hard segments. The hard (crystalline) segments, which are made up of the short-chain diol and an isocyanate, give the TPU its rigidness; while the soft (amorphous) segments made up of the polyol, give it elasticity.

In addition to offering extreme toughness and durability, TPUs exhibit outstanding resistance to abrasion, wear, chemicals, microbes, cold temperatures, and ultraviolet (UV) radiation – making them ideal for use in a wide range of commercial, industrial, and recreational applications. Since their commercialization in the 1960s, they've had a particularly significant impact on the manufacturing industry, allowing automotive, textile, and wire and cable makers to build lighter, stronger, and safer components.

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TPUs have also made their way into the athletic footwear industry, where their elastomeric characteristics and extreme toughness have made them an attractive alternative to ethylene vinyl acetate (EVA). Although EVA has been the material of choice for shoe manufacturers over the past few decades, its crosslinked molecular structure makes it unrecyclable and poses problems for footwear companies that are looking to increase the sustainability and environmental friendliness of their operations.

The inefficiencies associated with the EVA footwear manufacturing process have also become a cause for concern – often consisting of many labor-intensive steps, the application of hazardous chemicals, and producing a great deal of waste. With rising manufacturing costs and instability in Asian-Pacific labor markets over the past few years, these inefficiencies have presented shoemakers with a number of difficult challenges. As a result, footwear companies today are being forced to find new and innovative ways to more efficiently and cost-effectively produce high-quality footwear using process automation.

In 2014, Lubrizol introduced a solution to help address these challenges, combining Estane TPU chemistry with Trexel's MuCell physical foam injection molding technology to create BounCell-X (BCX) – a low density, plasticizer-free, recyclable, thermoplastic foam that outperforms EVA in terms of cushioning, compression, and durability, and helps athletic footwear manufacturers significantly improve overall production efficiency.

2 MuCell microcellular foam injection

MuCell technology is a foam injection molding process for thermoplastic materials that involves the highly controlled use of gas in its supercritical fluid (SCF) state to create millions of micron-sized voids in thin wall molded parts. Unlike conventional processes that use chemical foaming agents, MuCell uses N_2 or CO_2 as the physical blowing agent. As a result, it has no temperature limitation, nor does it leave any chemical residue in the polymer. This allows the product to be recycled within the original polymer classification and enables re-grind material to be re-entered into the process flow.

Furthermore, because N_2 and CO_2 are inert gases, MuCell Technology is more environmentally friendly than processes that utilize conventional blowing agents such as chlorofluorocarbons (CFCs) and hydrofluorochlorocarbons (HFCFs). Inert gases are also much safer to use than flammable blowing agents like butane and pentane.

MuCell offers significant improvement in a number of key quality measures of molded products, including flatness, roundness, warpage, and elimination of sinkmarks. These improvements can largely be attributed to the relatively uniform stress patterns that are created in the molded component, which is in contrast to the non-uniform stress characteristics created by solid molding.

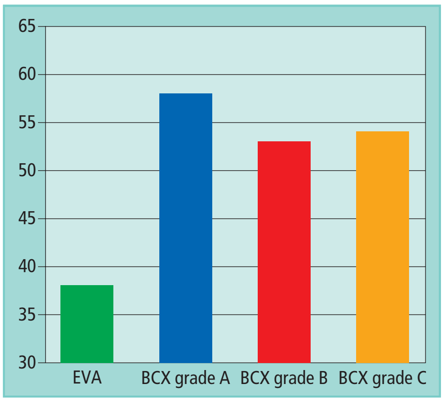
Although, since its commercialization, MuCell Technology has most widely been applied to the automotive industry, where manufacturers have used it to reduce weight and improve the dimensional stability of interior components, the many advantages it provides with regards to production efficiency, quality, and recyclability make it an ideal fit for TPUs. Recognizing this, Lubrizol set out to develop a unique TPU blend that could be combined with MuCell to form a highly elastic, lightweight, microcellular product that offered both superior compression and long-term durability. The result was BounCell-X TPU foam.

3 BounCell-X vs. EVA

Athletic shoes are made up of three main components: an upper section, which is typically made of fabric or leather and secures the shoe to the foot; a soft midsole; and an outsole that contacts the ground during use.

The midsole is arguably the most important part of the shoe as it is responsible for cushioning and stability. The overwhelming majority of athletic footwear today features midsoles made from EVAs. In addition to being lightweight, EVAs offer softness, flexibility, and number of other desirable characteristics such as resistance to water and stress-cracking. However, they do not perform as well with regards to long-term durability and compression. Over time, as EVA midsoles lose some of their elastomeric properties, their ability to absorb impact from the ground decreases. And when this occurs, the energy from the impact of the stride is transferred into the foot, ankle, and leg of the runner.

Fig. 1: Vertical resiliency in % (ASTM D2632)



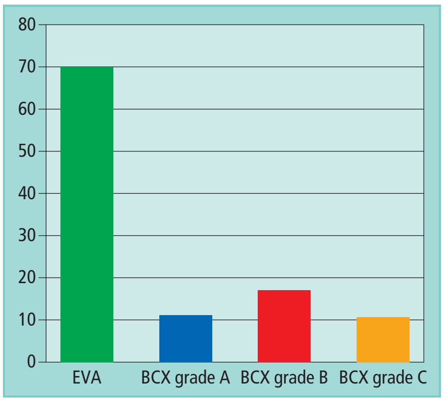
Although TPUs do offer advantages in terms of long-term durability, cushioning, and compression when compared to EVAs, their commercial application has largely been limited by their weight. BounCell-X foam aims to solve that problem, using MuCell Technology to generate a highly uniform cell structure that provides more than an 80 % reduction in density when compared to conventional TPU molds. BounCell-X foam also retains all of the properties that are desirable in a high-performance TPU, including resiliency, toughness, low-temperature flexibility, and chemical, microbial, and UV resistance.

3.1 Vertical resiliency

The American Society of Testing and Materials (ASTM) defines resilience as a function of both dynamic modulus and internal friction of a material. ASTM D2632 is used to test materials by vertical rebound. It provides an indication of how much energy is returned from initial impact, which in the case of a midsole occurs when the shoe impacts the ground.

As can be seen in **figure 1**, all three BounCell-X grades outperformed EVA in the vertical resiliency test. The test itself is an indicator of a material's instantaneous energy return. Or in simple terms, how the midsole will react when the shoe impacts the ground during a stride.

Fig. 2: Static compression set @ 50 °C in % (ASTM D395)



3.2 Static compression

The static compression set test (ASTM D395) is intended to measure the ability of a material to retain elastic properties after a prolonged period of sustained compressive stress. It measures how well the material can maintain its original shape after being exposed to a certain amount of deflection. In the case of footwear, the test indicates how much of the midsole cushioning will "bottom-out" after being worn and/or used for a number of hours.

As can be seen in **figure 2,** all three BounCell-X grades performed better than EVA in the static compression set. This indicates that a midsole made from BounCell-X foam rebounds back to its original shape extremely well after being deflected, which is critical to both the shock absorption and energy return properties of a shoe.

3.3 Hydrolytic stability

Hydrolytic stability is a measure of a material's ability to withstand the environmental effect of high humidity and resist the deterioration of physical properties under such conditions over time. The hydrolytic stability test allows performance properties (tensile retention) to be evaluated under the accelerated conditions of both high humidity and elevated temperature.

For athletic shoe manufacturers today, the ability of footwear to withstand and perform in harsh environmental conditions over extended periods of time has become increasingly important. **Figure 3** shows the hydrolysis resistance properties of BounCell-X vs. a traditional polyester TPU. After six weeks of being exposed to 95 % humidity and 80 °C, BounCell-X was able to retain more than 80 % of its original tensile strength, whereas the polyester TPU lost all of its tensile retention in that same amount of time.

3.4 Dynamic compression

The dynamic compression set is a procedure developed by Lubrizol to specifically test the ability of the midsole's cushioning to withstand energy impact cycles. During the test, impact pulses are applied to the sample foam at a frequency of 2 Hz for a total of 50,000 times. This gravimetric type of loading provides a more realistic simulation of running motion than other commonly used testing methods. The amount of impact energy applied during each cycle remains constant using the same mass and impact velocity.

The ability of the foam cushioning is determined by measuring the thickness change before and after the 50,000 cycles have been completed. As with the static compression test, the dynamic compression set indicates how much the midsole will lose its elastomeric characteristics over time, with a lower value indicating better performance.

Table 1 shows the results of the dynamic compression set – comparing different BounCell-X grades with EVA foam. Upon completion of the test, all three BounCell-X grades experienced less permanent deformation than the EVA sample.

3.5 Energy efficiency change

The ability of the midsole to return the energy it absorbs from impact is a characteristic that is also critical to the performance of athletic footwear. Over time, through use and natural exposure to the environment (i. e., humidity, heat), midsoles become less effective at doing this, which results in more impact energy from the stride being transferred into the foot, ankle, and leg of the runner.

In the dynamic compression test, energy efficiency of the midsole foam can be determined by taking the return energy and comparing it to the total energy generated from impact. It is calculated using the hysteresis curve of each impact cycle. For this set, initial energy efficiency values were measured at the very start of the test and once again after the 50,000 cycles were completed. A smaller percentage change indicates better performance.

Table 1 shows the energy efficiency change of BounCell-X and EVA foam after 50,000 cycles. Once again, all three BounCell-X grades performed more favorably than EVA. BounCell-X grade C had a 0 % percent change in energy efficiency after 50,000 cycles. In addition to performance, comfort, and stability, this test can be used as a determinant of the overall durability and toughness of a midsole made from BounCell-X TPU foam.

3.6 Simplified manufacturing process

In addition to actual midsole performance, the biggest advantage that BounCell-X foam can provide over conventional EVA footwear is in the manufacturing process. Extreme volatility in Asian-Pacific labor markets has largely been the biggest challenge for footwear companies in recent years with regards to production; however, product quality issues, long lead times, intellectual property theft, and price instability have also generated significant cause for concern.

Increasing automation can help overcome many of these challenges. And by reducing dependency on inexpensive manual labor, companies can decrease risk, improve quality, and even consider relocating production facilities to regions of the world that have long been considered infeasible (i. e., North America).

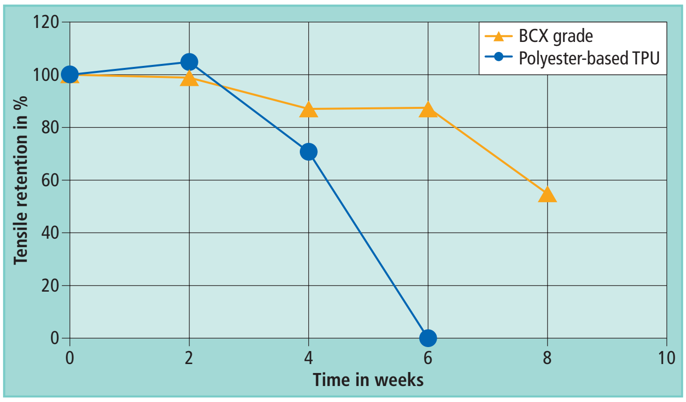


Fig. 3: Hydrolysis resistance 80 °C, hardness 95 Shore A

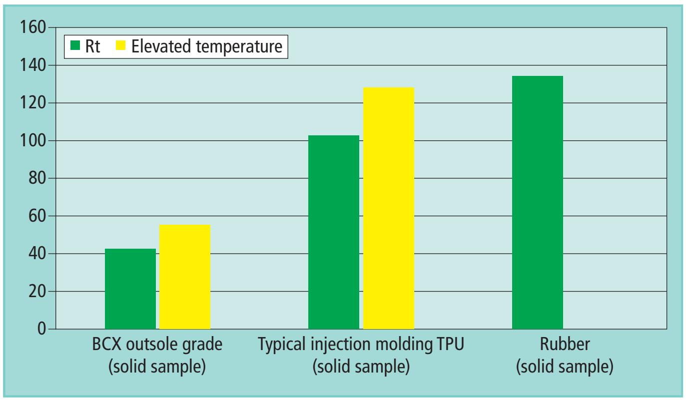


Fig. 4: Abrasion resistance (solid plaques, ISO 4649)

Tab. 1: Dynamic performance testing

	BCX grade A	BCX grade B	BCX grade C	EVA foam
Asker C	32	45	44	57
Density in g/cm³	0.27	0.30	0.26	0.20
Static property (0.27–0.30 g/cc)				
Rebound in %	58	53	54	38
Compression set at RT in %	5	7	7	8
Compression set at 50 °C in %	11	17	11	70
Dynamic property at 50 k cycle (0.27–0.30 g/cc)				
Compression set in %	4	7	2	10
Energy efficiency, initial	42	54	50	46
Energy efficiency change in %	21	5	0	25

Unlike conventional EVA midsole manufacturing today, which consists of many long, labor-intensive steps such as compounding/milling, buffing, rinsing, and trimming, BounCell-X foam midsoles can be manufactured in as little as two steps. The first is the pre-drying process, which typically takes about 2 – 4 h and can be done offline with dryers. The second is the midsole injection molding process, which takes roughly 3 – 5 min per cycle. Coloring additives can also be added during the injection molding stage, which eliminates the need for painting and allows for a wider range of design variations.

Because the unique chemistry of BounCell-X is optimized for MuCell technology, there is no need for the midsole to manually be reshaped or finished before it is sent to its next destination at the facility – resulting in a significant reduction in generated waste. BounCell-X also does not require any pre-treatment application of chemicals, which enhances environmental friendliness, safety, and quality, and greatly reduces overall production time and complexity.

3.7 Aesthetics

BounCell-X provides advantages over EVA when it comes to aesthetics as well. The MuCell injection molding process allows for a very high degree of precision and helps ensure an accurate reproduction of part design. This is in contrast to EVAs, which often have to go through a secondary compression molding procedure to correct for over expansion. As mentioned previously, additives can be added during the injection molding process to achieve specific coloration and/or appearance.

The thin solid skin that forms as a result of rapid cooling and crystallization when the BounCell-X foam is removed from the mold can be customized for texture and allows for different design variations. It also acts as a barrier – protecting the TPU from the outside environment.

4 Overmolding and outsole performance

With varying grades that offer a broad range of hardness and energy response profiles, BounCell-X foam is also suitable for outsoles. The performance of BounCell-X outsole grade compared to a typical injection molding grade TPU and rubber with regards to abrasion resistance, and kinetic coefficient of friction (COF) can be seen in **figures 4** and **5** below. The abrasion resistance test serves as a good indicator of the outsole's durability, while the COF test can be used to determine the ability of the shoe to provide traction in both wet and dry conditions.

As illustrated, the BounCell-X outsole grade demonstrated a better ability to resist abrasion than both standard rubber and the typical injection molding grade TPU. It also performed very comparably to rubber in the kinetic COF test.

Aside from these performance improvements, BounCell-X outsole grade also provides significant manufacturing advantages when compared to rubber. This is largely due to the fact that it allows for over molding with the BounCell-X midsole.

Overmolding has become a prominent part of injection molding in recent years. It consists of joining two or more materials to form a single object without the use of adhesives. Overmolding offers a number of benefits in terms of both efficiency and product quality. The combination of the BounCell-X midsole with the outsole without any bonding adhesive improves the overall strength and durability of the shoe. It also eliminates the need for workers to manually glue the two components together. Most importantly, it allows for more design flexibility and gives manufacturers the ability to quickly and efficiently produce a large volume of high-quality parts made from multiple materials.

With footwear made from EVA midsoles and rubber outsoles, over molding is not feasible. The rubber outsole manufacturing process itself can require as many as ten different steps – many of which are labor-intensive – and takes roughly 8 – 9 h. When combined with EVA midsole production, the entire process of building the midsole-outsole section of the shoe can consist of over 30 steps.

Achieving the same result using BounCell-X requires only two steps. The first is the high-pressure injection molding for the outsole, which takes roughly 2 min, and the second is the foam injection stage using MuCell technology, which takes roughly 4 min. By effectively eliminating virtually every step that requires hands-on preparation, dependency on manual labor is greatly reduced, quality is improved, and overall production efficiency is increased.

6 Recyclability and sustainability

While the improvement in key performance metrics that BounCell-X provides over EVA can help designers develop higher performing footwear products, perhaps its most important benefit is its ability to enhance the sustainability of the entire shoe manufacturing process.

Over the past decade, this has become increasingly important, as companies in virtually every industry have strived to minimize the carbon footprint of their operations. BounCell-X helps achieve this by significantly reducing waste and eliminating

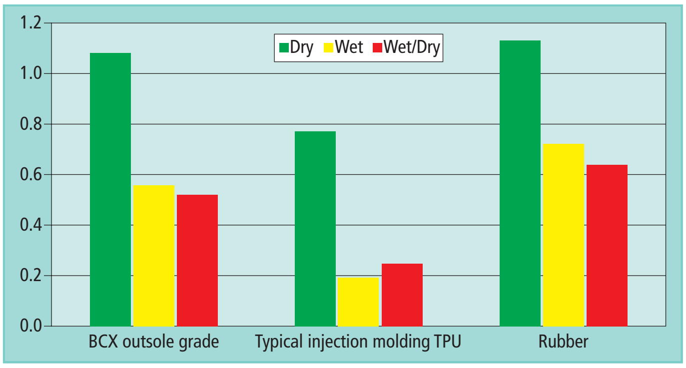


Fig. 5: Kinetic COF (solid plaques on stoneware surface)

the need for the application of hazardous chemicals. The TPU itself does not feature chemical crosslinking or chemical blowing agents in the foaming process either, which makes industrial regrind and post-consumer recycling a possibility. With crosslinked EVAs and other conventional materials like rubber, this is not feasible, and it often leads to more scrap, higher waste disposal costs, and a less environmentally friendly product.

Table 2 shows the property change in BounCell-X foam after three extrusions. The relatively modest change in the key properties and performance metrics of BounCell-X after being recycled provides footwear manufacturers with the opportunity to develop high-quality products using post-consumer material. This reduces the life-cycle cost of the shoe and increases the overall sustainability of the manufacturing process.

7 Conclusion

With increasing demands for better performance, higher production efficiency, and improved sustainability, footwear designers today are facing challenges that require innovative solutions.

In recent years, new and refined TPUs have helped shoe companies overcome those challenges and better meet the needs of consumers. Combining the unique benefits of TPU chemistry with the efficiencies of foam injection molding, BounCell-X allows shoe manufacturers to improve the quality, toughness, and environmentally friendliness of their products. As a suitable alternative to EVA and rubber, it has the potential to help the entire industry reduce its dependence on the highly volatile Asian-Pacific workforce, and opens the door to new opportunities in untraditional markets.

Tab. 2: BounCell-X foam extrusion data

	Virgin	First extra extrusion	Second extra extrusion	Third extra extrusion
Asker C	46	3.7 % (44.6)	4.4 % (44.9)	4.0 % (44.7)
Density in g/cm³	0.30	0.7 % (0.302)	2.0 % (0.306)	4.0 % (0.312)
Rebound in %	43	–10 % (39)	–12 % (38)	–11 % (38)
RT compression set in %	34		11 % (38)	
50 °C compression set in %	63		10 % (70)	