Chapter 2
Natural Recycled Super–Fibers: An Overview of a New Innovation to Recycle Cotton

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Abstract In their report 'A New Textiles Economy: Redesigning Fashion's Future' (Ellen MacArthur 2017a), the Ellen MacArthur Foundation describes the need for the global textile industry to mobilize 'moonshot' innovations. Natural Fiber Welding (NFW) is a disruptive technology and materials company that is answering this call. In particular, NFW is developing technologies which enable abundant natural materials to be utilized in applications that are presently dominated by resource intensive plastics. In so doing, NFW is connecting production of textiles and other materials to regenerative agriculture. This has the potential of greatly reducing plastic pollution, significantly reducing the carbon footprint of the industry, and offers new cost-effective options for circularity—all while providing material performance and tunability that was not possible before.

Keywords Natural composites · Ionic liquids · Textile recycling · Plastic pollution · Startup

2.1 Introduction

In their report 'A New Textiles Economy: Redesigning Fashion's Future' (Ellen MacArthur 2017a), the Ellen MacArthur Foundation describes the need for the global textile industry to:

> Mobilize large-scale, targeted 'moonshot' innovations. In areas where existing innovation is sparse but a significant impact could be expected, innovation 'moonshots' should be mobilized. Stakeholders from across the industry would gather and spark innovation. One area for such innovations could be the search for a 'super-fiber' with similar properties to mainstream ones, but suitable for a circular system, with no negative externalities.

A practitioner's perspective

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The Ellen MacArthur Foundation report goes on to identify four key areas of innovation that must be addressed in order to realize sustainability on a global scale. These areas are to:

- Phase out of substances of concern and microfiber release
- Increase clothing utilization
- Radically improve recycling
- Make effective use of resources and move toward renewable inputs.

In this report, Natural Fiber Welding, Inc. (NFW) will share data that demonstrates our team's revolutionary answers to calls for global circularity. In short, the NFW fabrication platform uses renewable natural inputs—including recycled cotton—to produce great feeling, durable textiles that outperform petroleum-based plastic incumbents. Importantly, NFW's patented closed-loop manufacturing solutions are both atom and energy efficient and thus positioned with favorable unit economics to enable penetration into global markets. NFW is focused on enabling a new circular economy that (re)uses natural, sustainably sourced inputs at a regional level. Using the cardboard recycling industry as a model, NFW is scaling a new type of textile mill Peoria, IL which is in close proximity to Chicago, IL (which is a significant source of waste textiles). NFW is pleased to be working with partners such as Fashion for Good (FFG) (Fashion for Good 2018, 2019) and within the FFG network of partners. NFW is not just demonstrating that circularity and regional textile recycling is possible, it is the most economically favorable way forward.

2.2 Scalable Sustainable Technology

NFW technologies combine new ionic liquid-based chemistries with automated hardware that executes patented closed-loop processes. In short, NFW technologies utilize very small, controlled amounts of eco-friendly ionic liquids to controllably fuse fibers within spun yarns. Fusion happens when intermolecular hydrogen bonding networks are controllably extended to bridge neighboring fibers. This is accomplished even while preserving microstructure of natural fibers and with complete recovery and recycling of ionic liquid-based chemistries. This has the effect of making short fibers (e.g., 'waste' and recycled cotton) behave as though they are long fibers and creates finer, stronger, more abrasion resistant yarns and fabrics. This is a major advance, one that positively impacts every key summary point outlined in the Ellen MacArthur Foundation report to realize greater sustainability.

The NFW platform offers revolutionary opportunities to engineer high-performance composites using renewable inputs from sustainable agriculture as well as reusing fibers already grown. NFW, located in Peoria, IL USA, is positioned to be the exclusive provider of this scalable fabrication platform (Haverhals et al. 2010; Haverhals et al. 2012a, b, c, d). NFW's proprietary technologies are contextually linked with profound discoveries that ionic liquid chemistries are extraordinarily tunable and cost effective for biopolymer manipulation (Swatloski et al. 2002, Phillips et al. 2004). NFW leverages the existing capacity of nature which already produces gigatons of biopolymers (e.g., cellulose) and thousands of billions of pounds of high-performance fibers annually (Cox et al. 2000; Griffith et al. 2008). Instead of denaturing natural materials or utilizing expensive biotechnologies (Edlund et al. 2018) that must produce commodity materials starting from scratch, NFW solves major manufacturing problems while finding proprietary new ways to retain complex order and hierarchies exhibited by natural fibers such as cotton, flax, silk, and industrial hemp (Haverhals and Sulpizio et al. 2012a, b, c, d, Haverhals and Nevin et al. 2012a, b, c, d, Haverhals and Foley et al. 2012b). This approach not only enables new performance applications with virgin fibers, it also enables recycled natural fibers to outperform their (conventional) virgin counterparts (Table 2.1).

It is well understood that petroleum-based synthetics have changed the world in complex ways (Ellen MacArthur Foundation 2017b). During the past 50 years, innovations that leverage fossil resource-based synthetics (e.g., polyester) have displaced natural material inputs because synthetic polymers can be 'formatted' into geometries (e.g., filaments) that make strong, abrasion resistant, moisture wicking fabrics. While plastics are significantly more energy intensive to produce than natural materials (Table 2.1), the performance associated with filament-type geometries has led to large-scale adoption. In 2019, the textile industry will utilize about 100 billion pounds of polyester for filaments and staple fibers (Plastic Insight 2019). If the data in Table 2.1 were not enough of a call to action, it can be noted that the empirical formula of polyester is approximated as C_2H_2O (varies slightly depending on specific formulations) and means that roughly 57% of the mass of a metric ton of polyester, roughly 570 kg, is carbon which is derived from fossil sources. Plants, in contrast, remove carbon from the atmosphere as they grow. Of course, the empirical formula of cellulose is ~$C_6H_{10}O_5$ and means roughly 440 kg of carbon are sequestered in a metric ton of cotton. Moreover, agriculture can be accomplished in regenerative ways that also sinks carbon on longer timescales within healthy soils. Importantly, Table 2.1 also does not communicate important context about plastic microfiber pollution. In particular, polyester microfiber released from over one billion washing machines worldwide means that synthetic textiles—including recycled plastic textiles—are a major source of pollution into the world's watersheds and oceans (Browne et al. 2011). (Even if synthetics could 'safely' biodegrade, it is apparent that a major new problem would emerge as fossil carbon from synthetic materials would become a substantial new greenhouse gas emission source.) Synthetics are known to absorb and concentrate toxins such as microcystins (Kohoutek et al. 2008). Scientists around the world are now reporting that overdependence on nonbiodegradable plastics comes at great cost and risk to virtually every ecosystem (Cole et al. 2013; McCormick et al. 2014; Rochman et al. 2017; Jeong et al. 2016). Pollutants have been documented in seafood (Smith et al. 2018), sea salt (Yang et al. 2019), and tap water (Tyree and Morris 2019) samples from around the world.

Of course, some in the industry have raised alarm about some natural materials as well. While apologists for polyester often downplay the larger context and statistics of land use associated with petroleum extraction, distribution, and processing versus agriculture (US Department of Agriculture 2018a, b) and the potential for crops like cotton to produce food (Wedegaertner and Rathore 2015; Charles 2018), they do correctly point out the (over) use of pesticides in industrial production of cotton as well as the intensive use of water in many of the dye processes that color cotton. Fortunately, regenerative forms of agriculture that use less water and eliminate the need for pesticides are on the rise and many scalable solutions are being explored. In contrast, the large carbon footprint of synthetics and including the resource footprint for recycled plastics is stubbornly not tractable and cannot be ignored. At the same time as regenerative agriculture is on the rise, NFW is solving relevant water use problems at their root by enabling efficient recycling of cotton and even while simultaneously enabling new zero-waste dye processes. With the NFW platform, it can be argued that the 'super-fiber' the world is looking for has actually been in plain sight all along, or perhaps just hidden away in the back of our closets—it is the natural fiber that can be reused multiple times before being regrown by nature. NFW is pioneering a circular system, whereby fabrics can be mechanically broken down and then (re)manufactured into fabrics that can even outperform conventional fabrics made from virgin fibers. As will be shown, NFW is demonstrating 'super-natural' performance from materials that are today destined either for landfill or incineration.

2.2.1 Fiber Welding Technology

A core 'pillar' of the circular NFW platform is detailed in Fig. 2.1. NFW technologies 'reformat' natural materials into composites that exhibit superior performance. It has long been known that the quality of a spun yarn is largely determined by the length and quality of the fiber utilized. The industry pays a premium for extra-long staple fibers that lend to strong, even yarns. It is a well-known problem that short fibers reduce the performance of yarns both during manufacturing (e.g., weak yarns that shed during knitting) and subsequently during use (e.g., consumers do not want fabrics that pill). In fact, sometimes as much as 20% of short virgin fiber is combed out of sliver prior to spinning. This short virgin fiber is often sold at a loss to, for example, manufactures of Q-tips and rags. Given that there were over 55 billion pounds of cotton produced globally in 2018, these losses account for many billions of pounds of 'waste' fiber that does not even get used once as a garment. Of course, short fiber is also the reason why mechanical recycling of cotton is not wide spread today. Processes that break down post-industrial and post-consumer waste fabrics tend to shorten fibers. Aggressive combing can enable some recycled content to be used, but greatly limits economic relevance. Short fibers are particularly problematic for finer (lighter weight) yarns. As such, mechanical recycling has had a difficult time expanding into fashion markets.

One of NFW's game-changing capabilities is to promote greater circularity as a 'drop-in' solution that enables large-scale mechanical recycling of cotton. 'Welding' processes tunably fuse neighboring fibers within a yarn. This creates adhesive forces that are more robust than simple friction that comes from mechanically spinning (twisting) fibers together. Because only the outermost portions of fibers need to be

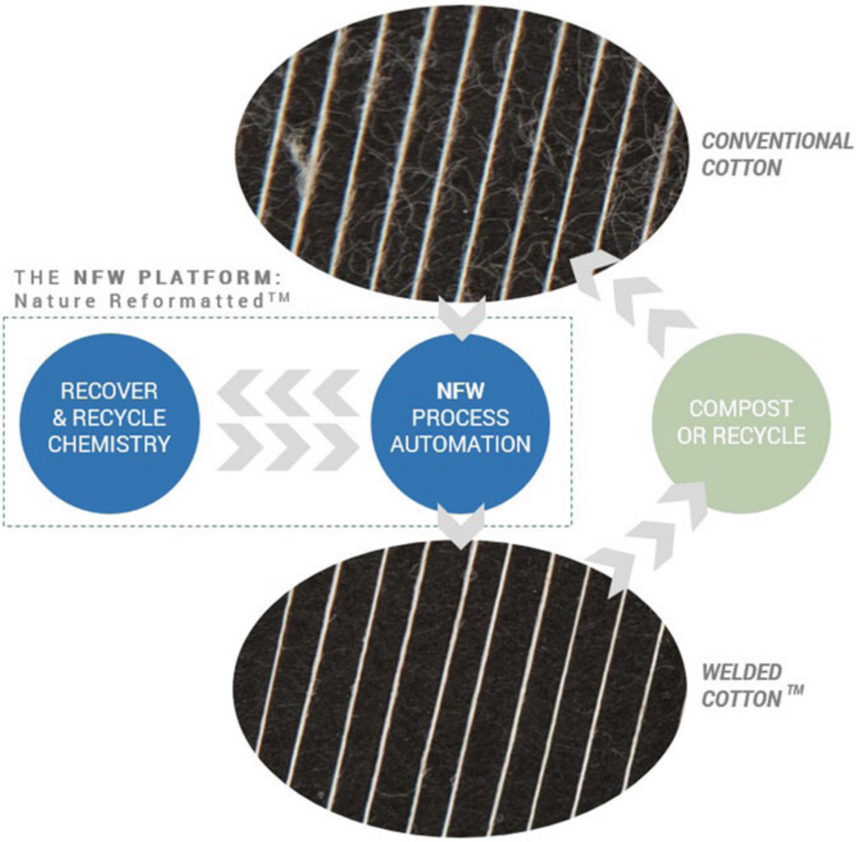

Fig. 2.1 Natural fiber substrates such as the conventional ring spun cotton yarn (top) are tunably converted to Welded Cotton™ composite yarn (bottom) using closed-loop manufacturing. NFW has developed automated processes that continuously recover and recycle the chemistries that impart a physical change to the natural fiber-containing substrates. In the meantime, natural fibers retain key structures and hierarchies even as they are 'reformatted' into new composite geometries. This yields, for example, Welded Cotton™ composite yarns that exhibit superior wet strength and abrasion resistance. (own source)

fused, fibers do not need to be dissolved. This saves time, money, and preserves the nano- and micro-sized structures that give natural fibers many of their advantageous properties. Moreover, the fusion of fibers produces a stronger, finer, more even yarn structure even when using short cotton fibers. Welded Cotton™ composite yarns thus exhibit the best of all possible worlds: all of the comfort of cotton, but with never before possible morphologies that mimic what is today only available using synthetic polymers.

Figure 2.2 plots data 'before' (gray bars) and 'after' (blue bars) fiber welding processing for three different yarn substrates. The left-most gray bar is the strength normalized by cross-sectional area for a 26/1 NE cotton yarn containing 30% recycled

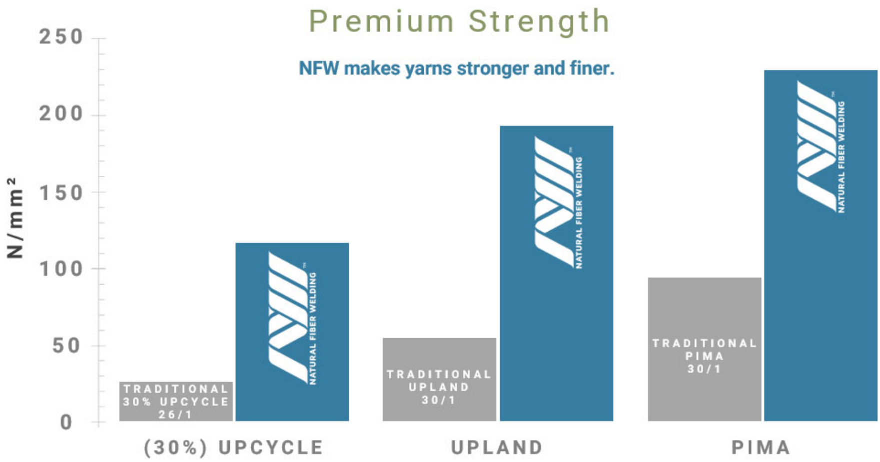

Fig. 2.2 Strength normalized by cross-sectional area is compared for Welded Cotton™ composite yarns (blue bars) versus their conventional controls (gray bars). It is observed that a Welded Cotton™ composite yarn which contains 30% post-industrial waste (left-most blue bar) outperforms a comparable conventional extra-long staple (Supima, right-most gray bar). (own source)

(post-industrial) cotton content. The middle gray bar is similar data for a 30/1 NE ‘Upland’ cotton substrate, the right-most gray bar represents a 30/1 NE ‘Supima’ (‘Pima’) yarn substrate. It is clear that the strength of a conventional yarn is directly proportional to the length of fibers therein. The Welded Cotton™ composite yarn data, in blue, show significant improvements. While the results do indicate that the quality of fiber does matter to the ultimate (maximum) performance, the Welded Cotton™ composite yarn with 30% post-industrial content exhibits a superior profile compared to conventional extra-long staple yarn. This is an outstanding achievement that is a quantum leap forward for the textile industry and that could never be attained by incremental improvements to yarn spinning frames.

Figure 2.3 shows images from Martindale Abrasion Testing. The jersey knit cotton fabrics were produced using Upland 30/1 NE Welded Cotton™ (top) and convention Upland 30/1 control. The results demonstrate the superior durability of Welded Cotton™ and are directly applicable to proving NFW produces ‘super-fibers’ that promote greater sustainability (increased clothing utilization). Several types of NFW’s brand of Clarus™ fabrics are found to have a great feeling hand and exhibited an acceptable appearance even after 30,000 cycles.

Fig. 2.3 Martindale abrasion testing results for Clarus™ jersey knits produced using Welded Cotton™ composite yarns and from conventional upland cotton control fabrics. Clarus™ fabrics continue to look and feel great long after traditional fabric controls have developed both pills and holes. (own source)

2.2.2 Fiber Welding Platform Breadth

The NFW platform is not limited to just producing superior yarns and woven or knitted fabrics. NFW has demonstrated both 'practical' and 'exotic' functionalization of natural fiber-containing substrates. For example, on the practical side, patented closed-loop indigo dyeing (Haverhals et al. 2018) and on the exotic side, supercapacitor energy storage (Jost et al. 2015; Durkin et al. 2014) and catalytic waste water treatment (Durkin et al. 2018, 2016) using peerless 'welded' natural substrates. The company is actively developing a range of other functional additives that utilize the proprietary platform approach. In all cases, NFW is particularly focused on delivering performance in ways that outcompete and eliminate harmful incumbent chemistries that are utilized by the textile industry today.

Figures 2.4 and 2.5 further demonstrate some of the practical aspects to the NFW platform. Figure 2.4 shows a table top made from 100% denim. The rigid and strong composite contains no glues or resins. Instead, cotton fibers in the denim were fused using welding processes that simultaneously recovered the ionic liquid solvents for reuse. The result is a beautiful visual depth (even though the composite is quite flat, as shown in the inset) that shows textiles can be functional for decades, and even centuries if desired, in building applications that are higher value than insulation or sound dampening. Of course, when composites are 100% natural, they can be composted for natural recycling at the end of their useful lifetime.

Figure 2.5 highlights a different side to the NFW platform: the production of plastic-free vegan leather-type materials. However, instead of using plastics like

Fig. 4 Welded Cotton™ composite table tops are made from 100% scrap denim without any resins or glues. The inset shows the table is flat even while it displays a visual depth that comes from the layering of the starting materials. Images courtesy of turnstone® a Steelcase brand. (own source)

polyvinyl chloride or polyurethane like other 'vegan' leather-type materials available today, NFW's Mirum™ materials are 100% made from natural materials and nutrients and are plant-based and thus biodegradable. For this material class, NFW is scaling a unique type of process automation that will enable millions of square meters of annual production of tunable, differentiated materials. NFW is developing footwear, belts, wallets, handbags, and other accessories, even automotive interiors in collaboration with global brands, OEMs and a select group of independent designers and upstarts. In every application, the NFW team is focused on solving the manufacturing limitations that have prevented 100% biodegradable materials from being adopted at scale. In most applications, the NFW team is able to recycle cotton and even food waste and other agricultural 'waste' byproducts into these truly vegan materials and makes them extremely cost competitive. Moreover, a recent agricultural law has legalized industrial hemp to be grown in the state of Illinois. NFW is well located to benefit from the large-scale production of fiber that can be produced in the USA and, in particular, the Midwest where materials can be grown regeneratively at large scale.

Fig. 2.5 Mirum™ is 100% plant-based leather-like composite. NFW is able to produce scalable materials that do not use harmful plastics like polyvinyl chloride and polyurethane. NFW believes ‘vegan’ should mean ‘plants’ not ‘petroleum’ nor ‘plastic’. (own source)

2.3 Summary

Natural Fiber Welding, Inc. is a technology and materials company that is positioned to be the exclusive driver of a circular materials revolution. Using innovative chemistry paired with efficient proprietary automation, NFW is able to leverage the abundance of nature in ways that were previously not considered. NFW is particularly focused on utilizing the large-scale availability of ‘waste’ fibers that exist and is creating systems to reuse, recycle, and regenerate high value materials at a regional level. In so doing, NFW is achieving:

- Eliminating substances of concern and microfiber release by instead using biodegradable plant-based inputs

Table 2.1 Carbon dioxide emissions in kilograms per ton of spun fiber (Oekotextiles 2011; Zamani 2011)

Filter type	Filter cultivation	Filter production	Total
Polyester	–	9.5	9.5
Arcyclic	–	12.4	12.4
Conventional cotton	4.2	1.7	5.9
Conventional hemp	1.9	2.2	4.1
Organic cotton	0.9	1.5	2.4
NFW recycled cotton	–	1.9	1.9

- Increasing clothing utilization with high-performance 'welded' fibers
- Radically improving recycling into a variety of material classes
- Making efficient use of resources and exclusively using renewables.

NFW understands that to truly solve sustainability issues at the global scale, new processes and materials must deliver performance at price points that can outcompete petroleum-based incumbents. NFW technologies are peerless in their ability to deliver and our team's mission is to create the circular system that will last for as long as the sun shines.

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