1 Introduction to Elastic Yarns and Textiles

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Historical Review of Elastic Yarns and Textiles

Elastic textiles, which are able to adjust their shape reversibly to a sufficient degree in response to external influences or technical conditions, are essential for meeting numerous customer needs and requirements. Since the first appearance of textiles, recoverable elongations of up to several dozen percent have been made possible by selecting suitable textile structures. For example, comparably high levels of elongation and recovery are generally provided by knitted fabrics with respect to those by woven fabrics. This elasticity can be additionally supported and increased by using specially textured yarns. However, the achievable dimensional stability as well as the recoverability are nowadays insufficient for numerous applications, especially in the medical and technical sectors. In addition, these textiles tend to lose their shape quickly, which occurs in the form of bulges and improper fit [1, 2].

In the 19th century, a material was specifically incorporated into textiles to increase and adjust elasticity for the first time: threads made from cut and vulcanized rubber sheets. However, the rapid aging tendency of these rubber threads in combination with a low resistance to UV radiation, oils, greases, alkalis as well as organic solvents quickly led to a limitation of the application of elastic textiles once again. It was not until the development of the first elastomeric polyurethanes (PURs) based on the diisocyanate polyaddition process by O. Bayer et al. that the material basis for the world of elastic textiles to this day has been shaped. Since the middle of the 20th century, PURs have been processed into elastic filament yarns, so-called "*elastanes*", by means of solution spinning. Elastanes have been used in increasing quantities in more and more applications over the past years and decades. The particular reasons are significantly higher elongation values and almost complete recoverability. In addition, elastanes have a higher resistance to aging than rubber threads. In Table 1.1, characteristic shares of elastane depending on the textile type, from D. Veit [2], are listed [1, 2].

Table 1.1 Characteristic Shares of Elastanes Depending on the Textile Type, from [2]

Textile type	Share of elastane [%]
Underwear	2–5
Woven fabrics	2–8
Fine stockings	2–12
Lingerie	10–45
Bath and sports goods	12–20
Medical stockings	35–50

In Figure 1.1, the force versus elongation curves of elastane, flat polyamide yarn, textured yarn, and rubber thread are compared to each other, based on D. Veit [2]. The curve that belongs to the elastane is located between the one of a rubber thread and the one of a textured yarn [2].

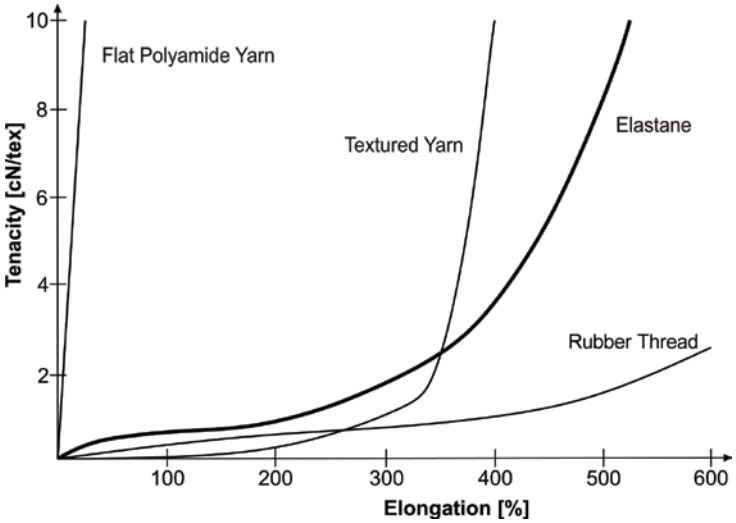

Figure 1.1 Force/elongation curve of elastane compared to other yarns, based on [2]

Elastanes, like rubber threads, have to be combined with yarns made from other materials, such as natural fibers (like cotton) or man-made fibers/yarns (e. g., made from polyester or polyamide), because of their adhesive and unpleasant touch. In addition to the conventional elastanes made from elastomeric polyurethanes, elastic yarns made from thermoplastic materials such as thermoplastic elastomers (TPEs), specific polyamides, or elastolefins are currently in development or already commercially

available for smaller market segments. In Table 1.2, important milestones achieved in elastic yarn and specifically in elastane development are displayed [1, 2].

Table 1.2 Important Milestones Achieved in Elastic Yarn and Elastane Development, based on [2]

Year	Developer	Milestone achieved
1937	O. Bayer et al.	Development of the diisocyanate polyaddition process
1939	P. Schlack	Extension of linear polyesters with diisocyanates resulting in the production of highly extensible, elastic fibers
1941	N. N.	Usage of the diisocyanate polyaddition process for the construction of high-quality elastomers according to the *Vulkollan principle*
1942	H. A. Pohl	First investigation of reaction spinning, later used for linear and cross-linked polyurethanes
1949	E. Windemuth	Development of a process by which the high molecular weight polyurethane could first be synthesized and then spun directly
1951	W. Brenschede	First utilization of solution spinning for the production of polyurethane threads
1959	DuPont: M. D. Snyder, J. C. Shivers et al.	Further development of solution spinning for the production of polyurethane threads
1962	DuPont, USA	Launch of a large-scale production of the first elastane yarns, which were marketed under the name Lycra™
ca. 1962	US Rubber Co., USA	Launch of polyester urethane under the brand name Vyrene™
1964	Bayer AG, Germany	Launch of a similar product under the name Dorlastan™

Over the past decades, there have been several approaches by various companies to produce highly elastic yarns by melt spinning [2]. So far, none of these efforts has led to at least one melt-spun elastic yarn on the market that has the same significance in terms of production volumes as conventional elastanes have [2]. In Table 1.3, an inexhaustive list of elastic yarn suppliers is displayed [2]. In Chapter 3, “Spinning Technologies for Elastic Yarn Production”, elastane is presented as the currently most important representative of elastic yarns. Industrial elastane production is described in more detail in Chapter 4, “State-of-the-Art Elastane Production”.

Table 1.3 List of Elastic Yarn Suppliers (Inexhaustive), from [2]

Supplier	(Trade) Name or brand	Website	Country
The Lycra Company	Lycra®	*www.lycra.com*	USA
Hyosung TNC	Creora®	*www.hyosungtnc.com*	Republic of Korea
Asahi Kasei K. K.	Roica™	*www.asahi-kasei.co.jp*	Japan
Huafon Chemical Co., Ltd.	Qianxi	*www.spandex.com.cn*	China
LDZ New Aoshen Spandex Co., Ltd.	Aoshen®	*www.ldz.cn*	China
Nisshinbo Textile Inc.	Mobilon	*www.nisshinbo-textile.co.jp*	Japan
Taekwang Industrial and Daehan Synthetic Fiber	Acepora®	*www.acepora-fiber.com*	Republic of Korea
Yantai Tayho Advanced Materials Co., Ltd.	Newstar®	*www.tayho.com.cn*	China

References

[1] Gries, T.: Einleitung. In: Gries, T. (Ed.): *Elastische Textilien: Garne, Verarbeitung, Anwendung*. Frankfurt am Main: Deutscher Fachverlag, 2005, pp. 13–14.

[2] Veit, D.: *Fibers: History, Production, Properties, Market*. Cham: Springer Nature Switzerland, 2022.

2 Elasticity in the Textile Context

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2.1 General Definition of the Term "Elasticity" and Mechanical Loading Parameters

In terms of materials science, *elasticity* is the ability of a body to change its shape when subjected to a force and to return completely to its original shape as soon as this force is removed. As an interpretation by textile technology, *textile elasticity* is the provision of stretch and recovery on demand. Textile elasticity is one of the most important textile properties as it has a direct effect on the overall functionality of a textile product.

According to H. M. Westergaard, the theory of elasticity is connected to the theory of plasticity. Both theories deal with stresses and deformations in solid bodies. When loads in the form of forces are applied to solid bodies or structures and these loads are gradually increased, internal forces as well as changes of shape (referred to as "deformations" or more generally as "strains") occur. If the solid bodies or structures return to their original shape after the removal of the previously applied loads, the property of elasticity is present. If deformations remain after a previously applied load has been removed, the property of plasticity occurs [1].

In Figure 2.1, the length change Δl and the transverse contraction of a solid body of initial length l_0 caused by uniaxial tensile loading with the force F is displayed. The mechanical behavior of a material is referred to as "elastic" as long as stress and deformation are completely reversible regarding the rules of mechanics and thermodynamics. For plasticity, the relationships between stresses and strains are more complex than for elasticity. For example, the strains also depend on the elements of the previous history. In reality, solid bodies and structures have elastic and plastic components. On the basis of thermodynamics, a distinction between "*energy elasticity*" and "*entropy elasticity*" can be made [1, 2].

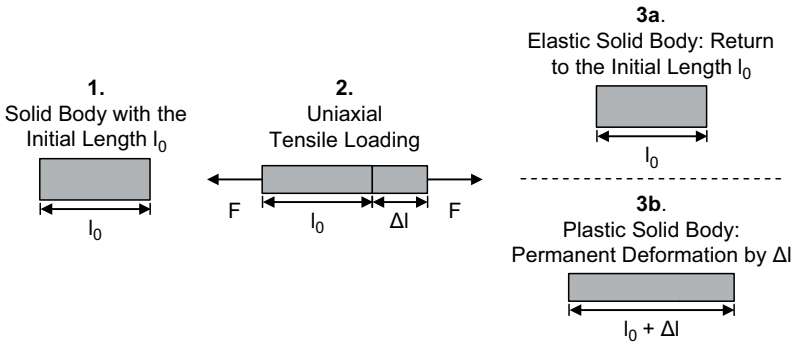

Figure 2.1 Elasticity and plasticity of a solid body under uniaxial tensile load

2.1.1 Energy Elasticity

Energy elasticity is related to the material structure and caused by changes in median interatomic distances and bond angles under the influence of mechanical loading. The required mechanical work is stored as potential energy or an increase in internal energy. According to the first law of thermodynamics, this energy is fully regained as soon as the loading is removed. Because of these structural causes, energy-elastic behavior is limited to comparably small deformations, observable in a linear relationship between stress and strain as described by Hooke's law [2].

According to Hooke's law, discovered in 1660 and formulated in 1678 by Robert Hooke, ordinarily deformations will be linear functions of forces that are applied as loads. If these forces are increased, the deformations will be found to be proportional to the load. In general, this can be formulated by the Young's modulus E, which quantifies the relationship between a stress σ and its corresponding strain ε (Equation 2.1) [1].

$$E = \frac{\sigma}{\varepsilon} \tag{2.1}$$

In general, the term *"stress"* refers to a force F per unit area A acting on a plane in a material. In terms of the mechanical behavior of elastic yarns, normal stresses are central. These normal stresses occur when the reference plane and the loading direction are parallel. The resulting stress occurs in the cross-sectional area of an elastic yarn under uniaxial loading. For simplification, the cross-sectional area of the non-deformed specimen A_0 is often used in engineering as a reference, ignoring the shrinking of the cross-sectional area during tensile loading (Equation 2.2). In order to obtain the true stress, the shrinkage must be considered and the actual cross-sectional area must be applied [2].

$$\sigma = \frac{F}{A_0} \tag{2.2}$$

In terms of yarn characterization, the determination of stress is often not relevant since the value of the cross-sectional area of the yarn is unknown or difficult to obtain. Instead, the tensile force is measured during loading trials and recorded. In general, these absolute force values are then set in relation to the fineness. In this edited work, the fineness-related or absolute forces are used over the stresses.

Relative shape changes, called “*strains*”, are induced in mechanically loaded bodies by these normal stresses. The stretching of an elastic yarn by uniaxial tensile loading is illustrated in Figure 2.2 [2].

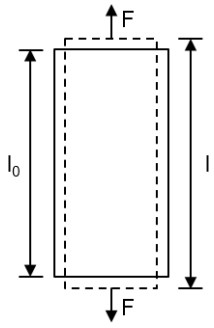

Figure 2.2 Principle sketch: deformation of an elastic yarn under normal stress loading, based on [2]

The strain ε in the normal direction is the ratio of the length change Δl (which is the difference between the current length l and the initial length l_0 of the unloaded body) to the initial length l_0 of the unloaded body (Equation 2.3) [2]. Regarding elastic yarn and textiles, strain is also referred to as “*elongation*” or “*stretch*” due to the uniaxial tensile loading, often neglecting the shrinkage of the cross-sectional area. In this edited work, the terms “elongation” and “stretch” are used over the term “strain” due to their widespread application in the textile world.

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0} \tag{2.3}$$

In reality, the true strain ε_w, also referred to as “*Hencky strain*”, is used to describe comparatively large deformations and is defined as shown in Equation 2.4, using the main strain λ . The main strain λ is defined as the quotient of the current length l of the yarn and its initial length l_0 (Equation 2.5) [2].

$$\varepsilon_w = \int_{l_0}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_0}\right) = \ln(\lambda) = \ln(1 + \varepsilon) \tag{2.4}$$

$$\lambda = \frac{l}{l_0} = 1 + \varepsilon \tag{2.5}$$