Melt spinning of guitar strings made of Nylon 6 and measurement of their material properties

Ortega, Jeanette Karen; Zhao, Jasmin; Storm, Annegret; Schüll, Elena; Gries, Thomas

Jeanette.ortega@ita.rwth-aachen.de

Affiliation:
Institut für Textiltechnik, RWTH Aachen University, Otto-Blumenthal-Strasse 1, 52074 Aachen, Germany

Abstract
Monofilaments made of the polymer polyamide 6 (PA6) are produced using a laboratory sized melt tester and a drawing machine in a subsequent process. The influence of the production parameters spinneret hole diameter, draw down ratio and drawing temperature are investigated using a factorial design plan. To evaluate the melt spinning process, the spun filaments are compared to commercial nylon guitar strings. Mechanical and thermal properties such as filament titer, tensile strength, relaxation behavior, degree of crystallinity, melt temperature and melt enthalpy are measured to evaluate the quality of the production process. Four of the eight spun filament types are able to withhold the tension needed to tune the string to the correct pitch. Thus, these monofilaments could be used as guitar strings. The production parameter with the highest impact on monofilament quality is the draw down ratio, followed by drawing temperature. No effect was found for spinneret hole diameter.

Introduction
Synthetic fibers have become increasingly important in recent years [1]. One reason for this is that they are versatile and can fulfill different requirements and functionalities. Among other things, their functionality spectrum is influenced by the manufacturing process, for example melt spinning. One everyday application example for synthetic fibers is guitar strings.

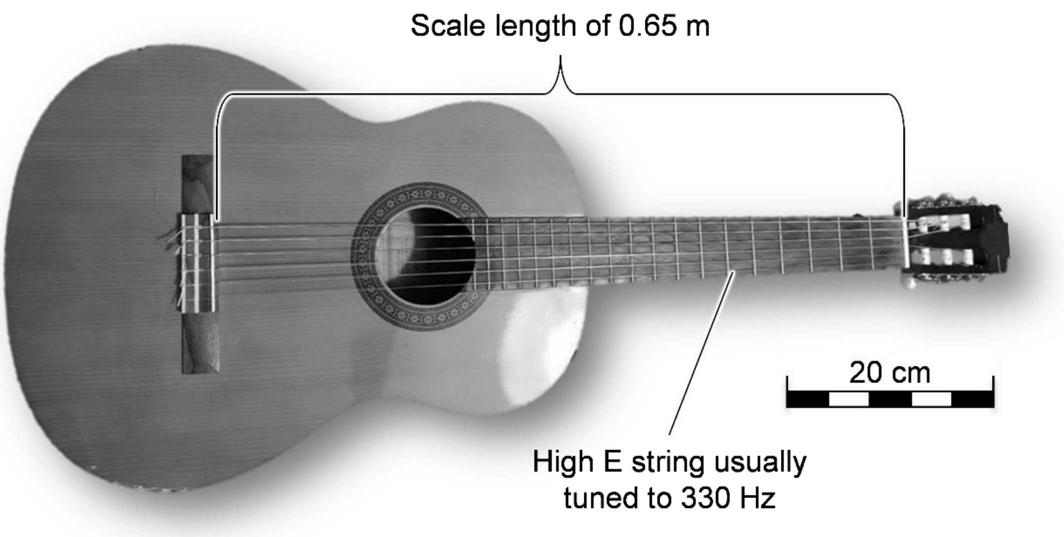

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Figure 1: Components of a guitar

Classical guitar strings are monofilaments made of nylon, which is the trade name of polyamide. They are usually designed to be used with guitars which have a scale length of 0.65 m. Of the six typical guitar string, the first and highest string is the high E string. It is usually tuned to a pitch of 330 Hz and has a diameter around 0.7 mm. [2] Many acoustical properties of guitar strings can be linked to mechanical properties of the string, which are measured in this work.

The aim of this paper is to evaluate the melt spinning process of monofilaments of polyamide 6 and to compare them to commercial monofilaments. Therefore, the influence of different production parameters on the quality of monofilaments will be investigated. The considered production parameters are spinneret hole diameter, drawing temperature and draw down ratio (Ddr). Different kinds of mechanical and thermal properties, for example tensile strength, relaxation behavior, degree of crystallinity and melt temperature, are measured and compared for different filament types.

Materials

PA6 chips, supplied by BASF SE (Ludwigshafen, Germany), are used for the melt spinning of monofilaments. The material is Ultramid B24 N 03, which, according to the producer, has a density between 1.12 and 1.15 g cm^{-3} and a melt temperature of 220 °C [3]. The self-spun monofilaments are compared to commercial monofilaments of different price categories. For this purpose, commercial guitar strings by two different manufacturers are considered. The prices of the guitar strings are 0.90 € for guitar string GS1 and 2.55 € for guitar string GS2 in 2020. The specific type of nylon of the guitar strings is unknown.

Manufacturing methods

Melt spinning

PA6 chips are dried at 100 °C for at least 16 hours in a vacuum oven before spinning. This is to prevent hydrolysis of the polymer, which may occur for moist polymer during extrusion. The polymer will then decompose and will no longer be useable for melt spinning. According to preliminary experiments, a temperature of 100 °C and a time of 16 hours is sufficient to dry PA6 chips.

Monofilaments are then spun using the high temperature spin tester, which is available at the Institut für Textiltechnik of the RWTH Aachen University in Aachen, Germany. This spin tester is suitable for application-oriented testing of polymer melt in laboratory scale. It consists of a single screw extruder with a diameter of 22 mm and a L/D ratio of 25. The extruder pressure during spinning is 35 bar. There are a total of five heating zones located in the extruder, the extruder flange, the spinning pump, and the spinning head, which can be set individually. The temperature settings of the spinning process are listed in Table 1. The spinning pump is an external gear pump with a conveying volume of 2.4 cm^3/rotation. Two different spin packs are employed in this work. One spin pack consists of a filter with a mesh size of 45 µm and a spinneret hole with a diameter of 2 mm and a L/D ratio of 4. The second spin pack has a mesh size of 20 µm and a spinneret hole with a diameter of 3 mm and a L/D ratio of 4. As the monofilaments have a large diameter, water is used to quench the fibers, cooling them quicker than in air. A separate winder is used to collect the as-spun filament.

Table 1: Temperature setting for melt spinning of PA 6

Heating zone	Temperature [°C]
Zone 1	250
Zone 2	260
Zone 3	265
Flange	265
Spin pump	265

Drawing

In a next step, the as-spun monofilaments are drawn using the drawing machine Micro Fiber Line by Xplore Instruments BV (Sittard, Netherlands). The monofilaments in this experiment are all heated using the heating shoe. The drawing temperature and the Ddr are described in the next subchapter. The take-up speed after drawing was 3 m min^{-1}.

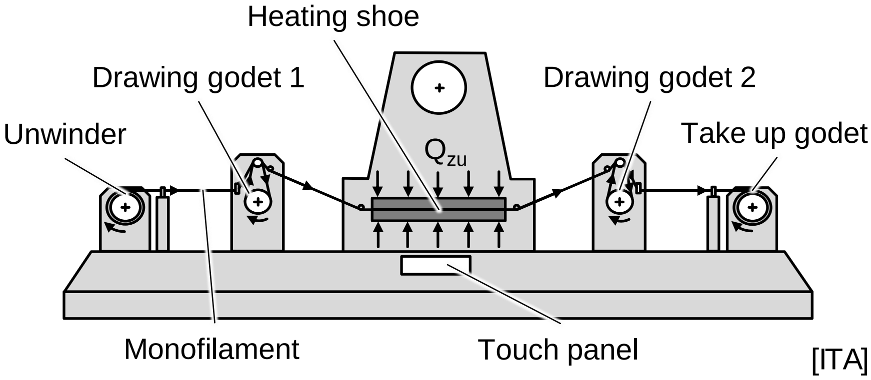

Figure 2: Schematic representation of the drawing machine

Factorial design plan

One of the goals is to determine how a change in manufacturing parameters affects the quality of the monofilaments. To evaluate this, a 2³ factorial design plan is used. The considered parameters are spinneret hole diameter, Ddr, and drawing temperature. The types of filaments and their parameters are listed in Table 2.

Table 2: Parameter setting for different types of filaments

Type of filament	Spinneret hole diameter [mm]	Ddr [-]	Drawing temperature [°C]
SM1	2	1.5	120
SM2	2	1.5	200
SM3	2	4	120
SM4	2	4	200
SM5	3	1.5	120
SM6	3	1.5	200
SM7	3	4	120
SM8	3	4	200

The average guitar string has a diameter of about 0.7 mm, but there are thinner strings available starting from 0.5 mm. The melt spinning tester is not suitable for diameters above

0.8 mm, with a spinneret hole diameter of 2 or 3 mm. Therefore, the targeted final diameter for all self-spun monofilaments is 0.5 mm.

The required diameter after melt spinning d_{spin} can be calculated using the equation (1), if the mass and density of the polymer is assumed to be consistent. To produce filaments with the parameters in Table 2 and a final diameter d_{final} of 0.5 mm, the diameter after the spinning process needs to be 0.61 mm and 1 mm, for the Ddr 1.5 and 4, respectively. Because of the mentioned restriction of the melt spinning tester the diameter of 1 mm is reduced to 0.8 mm.

$$d_{spin} = d_{final} \times \sqrt{Ddr} \qquad (1)$$

In the spinning process the diameter can be varied by changing the mass throughput by altering the spin pump speed. The filament take-up speed must be slightly varied to maintain a stable spinning process. Table 3 shows the settings for the spin pump speed and the filament take-up speed.

Table 3: Settings for spin pump and take-up speed

Type of filament	**Spin pump speed [rotations/min]**	**Filament take-up speed [m min^{-1}]**
SM1	8.5	40
SM2	8.5	40
SM3	12.8	40
SM4	12.8	40
SM5	8.5	50
SM6	8.5	50
SM7	12.8	35
SM8	12.8	35

Analysis methods

Moisture content

In order to avoid hydrolysis of the PA6 during extrusion, the moisture content of PA6 should be below 600 ppm as stated in the material datasheet [3]. Therefore, the moisture content of dried PA6 chips is measured using the coulometric Karl Fisher titrator Coulometric KF Titrator C30 by Mettler Toledo Inc. (Columbus, US).

Temperature measurement using infrared camera

During the drawing process, monofilaments are heated, with the temperature set to either 120 °C or 200 °C. Due to the large diameter and the short exposure times of 8-10 s, the actual temperature of the filament is not certain. Therefore, the infrared camera FLIR SC640 by FLIR Systems Inc. (Wilsonville, US) is used to determine the temperature of the filament directly after exiting the heating zone.

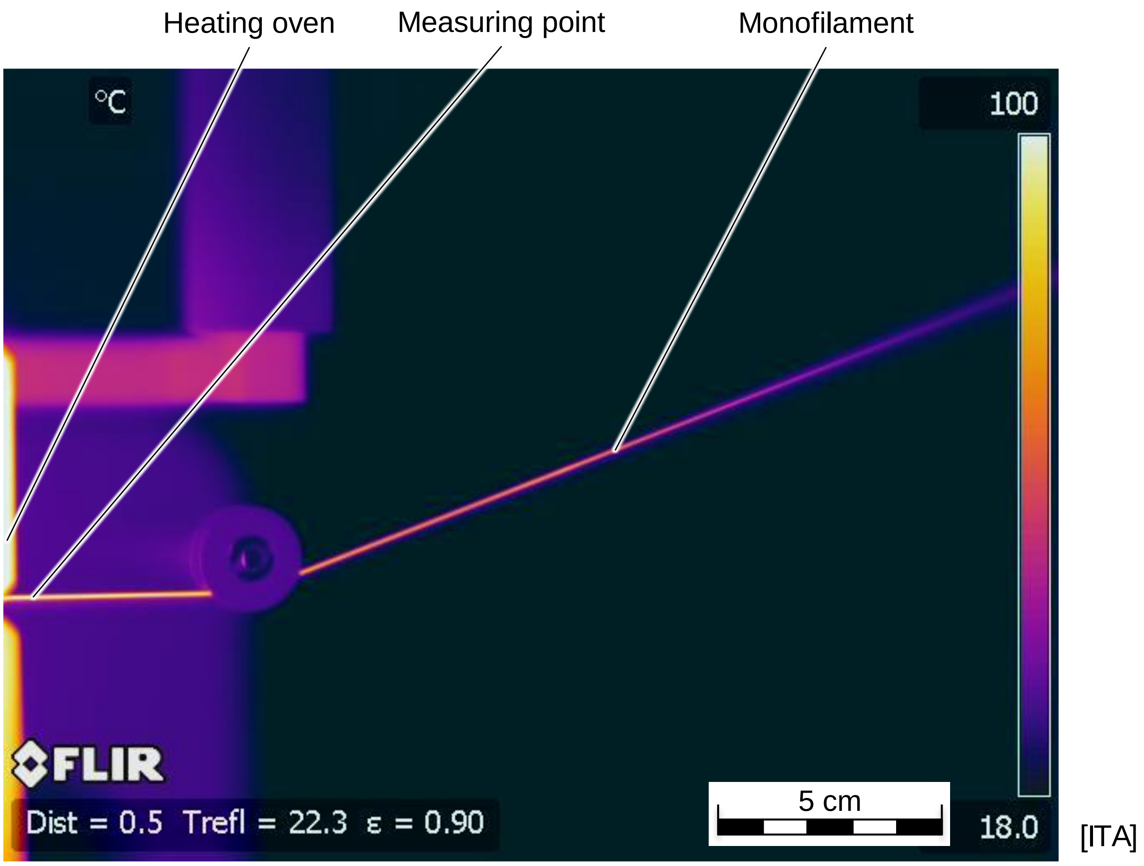

Figure 3: Thermal image of monofilament after heating oven

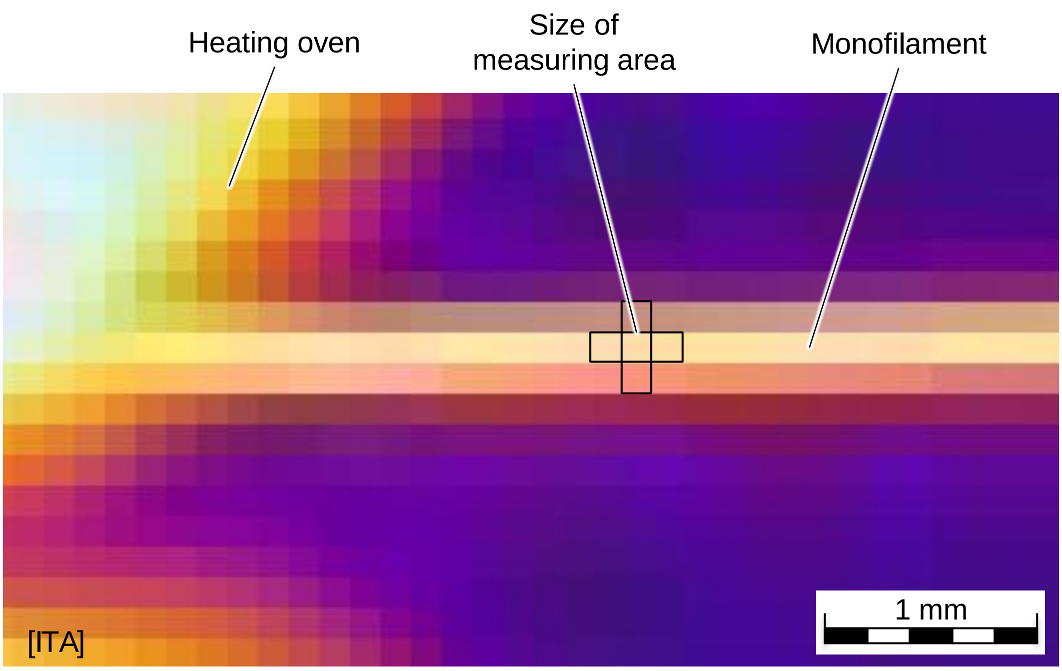

Figure 4: Strongly magnified thermal image of monofilament after heating oven

For a correct temperature measurement, the camera must be calibrated, and the object to be measured must be of a minimum dimension. At least 5 pixels in a cross formation must fit inside the measured object in the image [4]. This was possible despite the relatively thin filament with a diameter of 0.5 mm, as can be seen in Figure 4. A thick and a thin filament for each drawing temperature are measured. The position for the measurement is 1 cm after the heating zone (shown in Figure 3 ,but not in Figure 4).

Diameter and titer

The filament diameter is measured using the stereomicroscope Leica M205C by Leica Microsystems GmbH (Wetzlar, Germany). A total of 10 measurements are taken of each filament type. The standard deviation of the measurements is used as an indicator for diameter changes. The filament titer *Tt* of the self-spun filaments is calculated from the density ρ and the filament diameter d using equation (2).

$$Tt = \rho \times \frac{\pi}{4} \times d^2 \qquad (2)$$

As the densities of the commercial guitar strings are unknown, the titer must be determined using the linear density. The length l and the mass m of a guitar string is measured, and the titer *Tt* is calculated using equation (3).

$$Tt = \frac{m}{l} \qquad (3)$$

Tensile tests

The tensile strength and elongation are measured according to DIN EN 13895 [5] using the tensile tester Statimat 4U by Textechno Herbert Stein GmbH & Co. KG Textile Mess- und Prueftechnik (Moenchengladbach, Germany). The sample speed is 10 cm min^{-1}, the clamping length is 10 cm and the preload is 0.5 cN tex^{-1}. For each filament type, 10 measurements are performed.

Relaxation tests

The relaxation is measured using the Z2.5 TN by ZwickRoell GmbH & Co. KG (Ulm, Germany). The clamping length is 50 cm and the preload is 0.5 cN tex^{-1}. At the beginning of the measurement, the sample is brought to the loading point of 18.4 cN tex^{-1} at the sample speed of 25 cm min^{-1}. The elongation at this tensile stress is held consistent for 4 hours and the resulting tensile stress is measured. Due to time limitation, only the best self-spun filament and the commercial guitar strings are analyzed. The measurement is repeated 5 times per filament type.

Results and Discussion

Moisture content

The resulted average moisture content is 215.9 ppm (+/- 17.6 ppm). As this is below 600 ppm, the polymer is suitable for spinning.

Anomalies during manufacturing

Occasionally during the drawing process, part of the filament lifted from the drawing godets. This phenomenon may be the result of the comparatively high bending stiffness of the filaments with a larger diameter. The bending stiffness B for filaments with a round cross sectional area can be calculated from the Young's modulus E and the filament diameter d using equation (4) [6]. It can be seen, that a larger diameter leads to a larger bending stiffness.

$$B = E \times \frac{\pi \times d^4}{64} \tag{4}$$

This may result in a deviation from the expected Ddr. The actual Ddr can be taken from Figure 5, which is determined by measuring the diameters before and after drawing. It seems as though, higher Ddr and lower temperatures result in larger discrepancies.

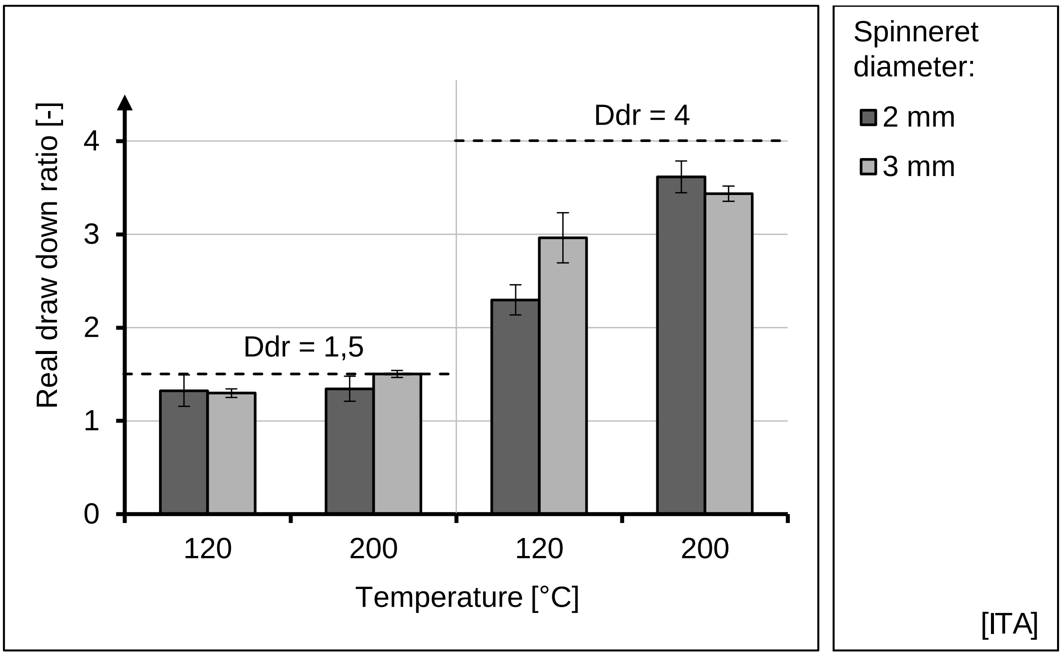

Figure 5: Comparison of real Ddr with set Ddr

The reasons for the differences between the set and the actual Ddr might be that the drawing forces are too low to draw the filament further. Since the filament does not lie flatly on the surface of the godets, it is possible that not enough friction can be applied between the godets and the filament. These two observations lead to the conclusion, that the drawing machine Micro Fiber Line by DSM Xplore might not be suitable for filaments made of PA6 with a diameter of 0.5 mm or larger. Another observation, however, is that a higher drawing temperature lead to a higher actual Ddr. Hence, the conclusions can be made, that a higher temperature causes the material to become softer, reducing the bending stiffness. This leads to more flexibility and a better contact between the filament and the drawing godets.

Temperature measurements using infrared camera

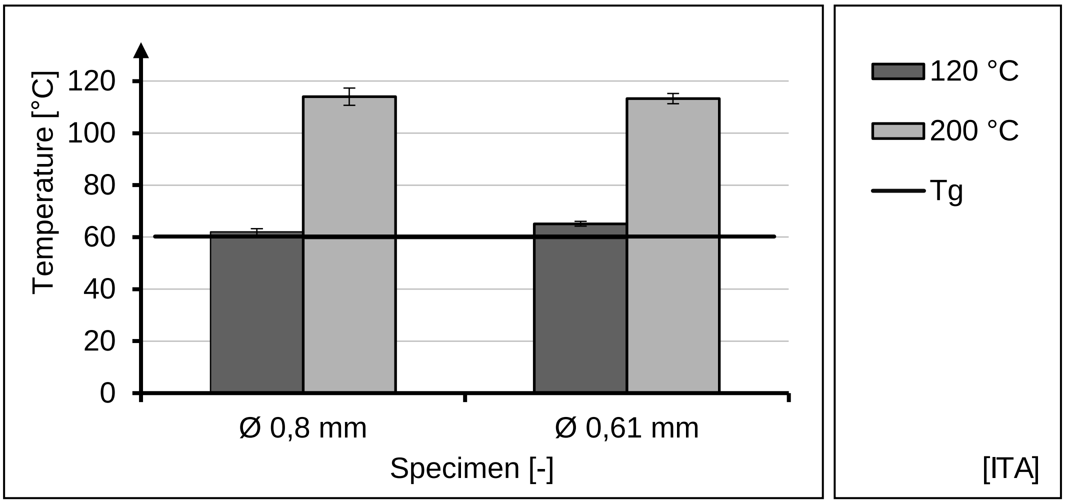

Figure 6: Temperature measurements using the infrared camera

The results of the temperature measurements can be taken from Figure 6. Although the measurement of the filament cannot be made inside the heating zone, the data can be used as a comparative study. The actual temperature of the filament inside the heating zone may be higher than the measured temperature. However, it must be noted, that the temperature in the middle of the filament might be different than on the surface. The data show that each filament reaches the glass transition temperature for dry PA6, which is at 60 °C [7]. Therefore, it can be assumed that the filaments have been oriented and post crystallization has taken place during the drawing process.

Tensile test

As the filaments have different diameters, it is not possible to compare the absolute tensile force directly. Therefore, to compare the tensile strength of the filaments, the maximum tensile force is normalized in respect with the titer. The minimal required tensile strength is the tensile strength needed, for a filament used as guitar string to be tuned to the correct pitch. It will be further described in a following subchapter.

Filaments with a lower Ddr have a larger elongation after breakage. Furthermore, the tensile test diagrams of filaments with a Ddr of 1.5 shows an uneven course. A comparison of an uneven (left) and even (right) course can be seen in Figure 7. Another observation is that the commercial guitar strings have a much lower elongation compared to the self-spun filaments. This may result from higher drawing or also different materials in the commercial strings in comparison to the self-spun filaments. On these assumptions, it can be deduced from the tensile test data that filaments to be used as guitar strings should be properly drawn to reduce elongation and increase tensile strength.

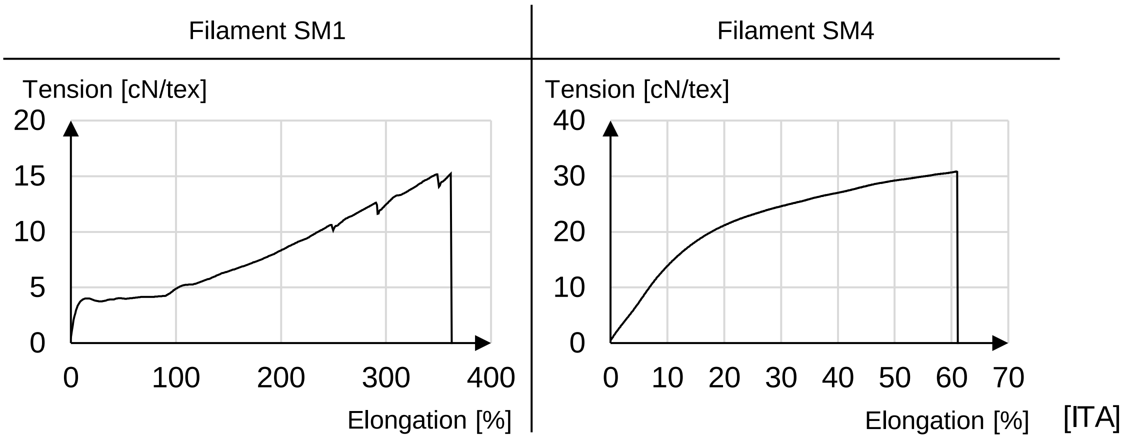

Figure 7: Comparison of Tension Elongation Diagrams

Relaxation test

As described earlier, only the best self-spun filament and the guitar strings are analyzed. Four self-spun filaments have a greater tensile strength than the minimally required tensile strength. From these filaments, SM4 has the smallest standard deviation of the diameter. Therefore, it is so far considered the best filament.

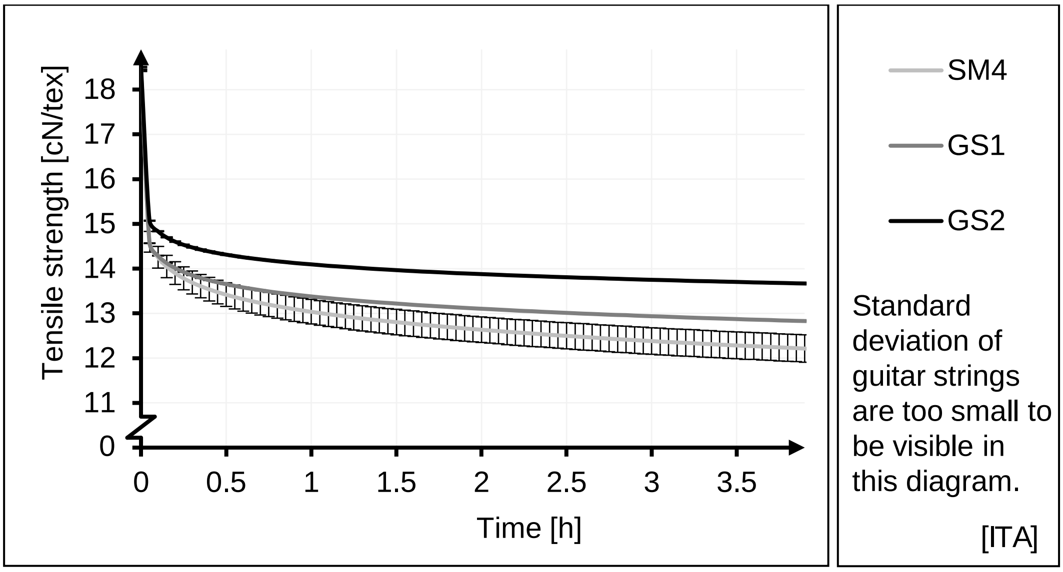

Figure 8: Results of relaxation test

During the relaxation analysis, the tensile stress decreases over time. The results can be seen in Figure 8. It can be observed, that GS2 has the least loss of tensile strength after 4 h, while SM4 has the greatest strength loss. Similar to the explanation for the variation of the tensile tests, this may result from different processing or materials, which are less susceptible to relaxation.

Impacts of filament properties on quality of guitar string

The goal of a guitar string is to produce a musical note, which is a vibration with a defined frequency. According to Woodhouse and Lynch-Aird [8], the vibration frequency *f* of a string can be calculated from the tension of the string *F*, the titer of the string *Tt* and the vibrating length of the guitar *L* using equation (5).

$$f = \sqrt{\frac{F}{Tt}} \times \frac{1}{2 \times L} \quad (5)$$

With a fixed vibrating length of 65 cm, the frequency of a high E string of 330 Hz is therefore only achievable if the guitar string is hold under a tension of 18.4 cN tex^{-1}. Filaments which break under this, or a lower tension are not suitable as guitar high E strings. Of the self-spun filaments, the filaments SM1, SM2, SM5 and SM6 have a lower tensile strength and thus cannot be used.

Furthermore, for a guitar to be perfectly in tune, not only must the open string be in tune, but the diameter deviation over the length of a string must be low as well. Otherwise, tones which are not played on the open strings may be out of tune. It may even be possible that one tone is higher while the subsequent tone is lower than it should be. Hence, a played melody might be more out of tune when using an inhomogeneous string. It is noticeable that the standard deviation of most self-spun strings is much higher than that of the commercial strings. For the self-spun filaments, it can be expected that the filaments will have a less clean tone compared to commercial guitar strings, due to larger deviations.

The thickness of a guitar string is correlated to the impedance of the sound wave, which can be taken as a reference for the sound volume. The equation describing the correlation between the wave impedance Z_0, the tensile strength of the string F and the titer of the string Tt is given in equation (6) [8].

$$Z_0 = \sqrt{F \cdot Tt} \quad (6)$$

The self-spun filaments only have a diameter around 0.5 mm. Compared to commercial guitar strings with diameters around 0.7 mm, it can be assumed, that a quieter sound will be produced with the self-spun strings.

When a guitar string is first strung on a guitar, only few minutes passes until the string goes out of tune. One factor for this phenomenon is the relaxation property of monofilaments. From the data of the relaxation tests, it can be concluded, that the self-spun filaments will need longer to settle in and need more retuning when these are first strung on a guitar. Therefore, longer time will be needed for guitar tuning, which is subtracted from the guitar playing time.

Evaluation of factorial design plan

The effects and interactions of the parameters from the factorial design plan described in Table 2 are listed in Table 4. The underlined values are values which are significant to a confidence level of 95%.

All of the parameters individually have a significant effect on the tensile strength. Additionally, there are significant interactions when combining the drawing temperature with Ddr and all parameters. The only parameter, which has a significant effect on the diameter is the drawing temperature. On the elongation, only the parameter Ddr has a significant effect. Furthermore, there is a small interaction of all parameters.

From these data, the only production parameter, which has a large effect on the overall quality of the filaments is the Ddr. This effect can also easily be observed, as only the filaments with a high Ddr are usable as guitar strings as determined through the tensile tests. The drawing temperature only has a small effect on the filament quality. Nevertheless, it is an important parameter, as an interaction between drawing temperature and Ddr exists. This enhances the filament quality further, by improving the tensile strength. The spinneret hole diameter does not have a large impact on the filament quality. Therefore, it is not of great importance with which spinneret hole diameter the filament is spun.

Table 4: Effects and interactions of production parameters with following abbreviations: a: spinneret hole diameter [mm], b: Ddr [-], c: drawing temperature [°C]; underlined values are significant

Measurements	a	b	c	ab	ac	bc	abc
Tensile strength [cN/tex]	<u>1.10</u>	<u>6.95</u>	<u>1.43</u>	0.72	0.17	<u>2.26</u>	<u>-0.81</u>
Diameter [µm]	-12.12	-13.49	<u>-24.71</u>	9.66	1.4	-16.24	8.77
Elongation [%]	-3.12	<u>-111.53</u>	-5.73	-2.23	-5.39	-0.08	<u>10.34</u>

Conclusion

It can be said, that monofilaments which are used as guitar strings can be melt spun. Four of the eight different types of self-spun monofilaments are able to withhold stresses of 18.4 cN tex^{-1}, which is needed to tune the string to the high E note. However, the produced filaments have a smaller and more inconsistent diameter of only 0.5 mm, which results in less accurate and quieter tones.

The considered production parameters are the spinneret hole diameter, the Ddr and the drawing temperature. For all measurements made within the framework of this paper, a consistent trend can be found. The Ddr is the most important parameter to produce homogenous and strong monofilaments for use as guitar strings. The higher the Ddr, the lower the elongation and the higher the tensile strength will be, which both affect the quality of the filament positively. The second most important parameter is the drawing temperature. It has a slightly smaller effect on the quality of the monofilament, but higher drawing temperatures also results in stronger monofilament. However, it should be said, that the drawing temperature should stay below the melt temperature of the material to ensure a stable process. The spinneret hole diameters tested only have a small effect, if any, on the quality of the monofilament. Drastically larger or smaller diameters may, although, effect the stability of the process, which was not investigated in this work.

Acknowledgments

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