Development of a process chain for the production of high-performance 100% metal spun yarns based on planed metal staple fibres

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Abstract

The high potential of metal fibres for various technical applications including filtration, electrical, heat and cut resistance or composite applications is still not fully exploited due to their high production costs. This paper presents the development of a new process chain for spinning 100% metal spun yarns from planed metal staple fibres as an alternative to conventional metal fibres. The developed spinning process chain begins with a stretch breaking process to create metal staple fibre sliver with a narrow fibre length distribution and defined mean fibre length. Next, a drafting process on a draw frame is performed in order to produce highly uniform metal staple fibre sliver. This is the basis for the development of a flyer spinning process to realise high-performance metal spun yarn. Finally, the fundamental relationships between fibre properties, processing characteristics, semi-finished product properties and the performance of the resulting metal spun yarns are described in detail.

Keywords Metal fibres · Fibre properties · Metal yarn · Mechanical properties · Spinning · Process development

1 Introduction

The use of metal fibres for technical applications offers an enormous variety of possibilities for the targeted development of semi-finished products and components because of their special properties, such as high stiffness, strength and ductility, high temperature resistance, high thermal and electrical conductivity, good formability and permeability, corrosion resistance as well as recyclability [1–3]. For these reasons, metal fibres are used in plant construction, the chemical and automotive industry as well as in environmental, process and industrial engineering [4–9]. Other areas of application for metal fibres include seals, cut and vandalism protection, filters, exhaust systems, sound insulation, components for heat exchangers, friction linings for clutches, tire cord reinforcements and heating elements in home and clothing textiles [10–16]. Furthermore, they

are applied in composite materials, especially to improve impact properties. It has been shown that metal fibre-reinforced composites exhibit high stiffness and high elongation at break [17]. The addition of metal fibres into high-performance fibre-reinforced plastics inhibits their brittle behaviour. This improves both their damage tolerance and impact resistance [18]. Furthermore, metal fibres of finite length (hereinafter referred to as ‘metal staple fibres’) are spun together with various natural and man-made fibres (e.g. cotton, polyester, polyamide) with a low percentage into functional yarns in order to transfer specific properties of the metal fibres to the product. Such metal-enriched yarns are used, for example, as shielding in environments exposed to heat, explosions, or electromagnetic radiation [19–21].

For the production of metal staple fibres, the melt extraction process is widely used [22]. With this process,

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Fig. 1 Metal staple fibre reels: 1.4113 (a), AlMg5 (b) and Cu99 (c)

metal fibres are produced directly from the melt in a single process step. A water-cooled, rotating multi-edged roll is immersed in a molten metal bath and wetted. Metal melt is extracted from the bath by the roll movement and solidifies into fibres. Centrifugal force separates these fibres from the roll. The transverse notching in the roll fitting determines the fibre length. The rapid solidification process permits the processing of a large number of metal alloys. Fibres with diameters from 25 to 250 μm can be produced, and diameters are heavily varying as a result of the process [23].

Continuous metal fibres are produced by the metal foil and bundle drawing process. In the metal foil process, a cutting tool is pressed against the end face of a rotating metal foil reel. Thus, continuous metal fibres with a diameter of 2 up to 100 μm are cut from the front face [24]. In bundle drawing, continuous metal fibres are generated by multi-stage drawing of thick metal wires. In some cases, more than 30 stretching zones connected in series are used. A heat input (stress-relief annealing) takes place between these zones. This process can be used to produce very fine continuous metal fibres with a minimum diameter of 2 μm [25]. More detail on the manufacturing of metal fibres can be found in [26]. All these processes for the production of continuous metal fibres and metal fibres with finite length have in common that they involve a large number of complex process steps and are characterised by low productivity. For this reason, today's prices for metal fibres are in the three-digit €-range. Therefore, it has not yet been possible to establish metal fibres in broad industry. Hence, their use is limited to expensive niche products despite their enormous potential.

Opposing this, there are very low-cost metal staple fibres (known as 'metal wool') available having prices in the one-digit €-range. They are produced by planing, i.e. cutting from commercially available, comparatively thick

and thus inexpensive metal wire (Fig. 2). This technology is highly productive and easily scalable to respond to a potential increase in demand. However, the textile properties of metal staple fibres differ from those of traditional fibres that are processed using conventional spinning technologies particularly with regard to their high brittleness, high bending and torsional stiffness as well as the high irregularity of their cross-section. For these reasons, there is still no established process for the spinning of high-performance 100% metal spun yarns from metal staple fibres originating from the planing process. A promising solution could be the development of a yarn-forming process chain based on stretch breaking, draw frame and spinning [3, 27]. Nevertheless, extensive technological-constructive research and development work is required for the further development of the process chain. In this paper, the results regarding this development work are presented.

2 Materials and methods

2.1 Basic material metal staple fibres

The metal staple fibres used for the investigation were supplied by the manufacturer Deutsches Metallfaserwerk Dr. Schwabbauer GmbH & Co. KG in the form of metal staple fibre strand. The three different alloys: stainless steel DIN EN 10,088-1 1.4113, aluminium AlMg5 and copper Cu99 were initially tested to assess their suitability for the development of the spinning process chain (Fig. 1). The nominal diameter of the fibres was 60 μm . Based on the first evaluation, one type of metal staple fibre was selected, taking into account the following aspects:

Fig. 2 Planing process for the production of metal staple fibres

1. Maximum tensile strength of the fibres to ensure high-performance metal spun yarns;
2. Minimum friction of the fibres to fibre guide elements, such as false twister and traveller, to ensure a trouble-free process;
3. Minimum brittleness of the fibres to ensure minimum fibre damage, especially during the drafting of the sliver.

For the production of metal staple fibres, metal wire was planed as illustrated in Fig. 2. The metal wire coming from a storage (I.) was wound multiple times side by side to form a flat metal wire package (II.). This package was then guided over serrated blades under a defined pressure, which was adjusted by a blades positioning mechanism. These serrated blades cut into the wire package, whereby the metal staple fibres are planed (III.). Multiple fibres are combined together to build a metal staple fibre strand (IV.) which was finally wound onto a reel (V.). The residual metal wire was coiled up and could be used for further processes (VI.). The metal wire had a diameter of several millimetres.

2.2 Development of the spinning process chain

2.2.1 Development of the stretch breaking process

Since the mean fibre length of the basic material was several 100 mm, such overlong fibres led to irregularities during their drafting. This in turn complicated the reproducible production of high-quality metal spun yarns. Therefore, the aim of the stretch breaking process was to achieve a mean fibre length of 80 mm so that they could be processed on conventional spinning machines. Furthermore, a narrow fibre length distribution of the metal staple fibre sliver was a target parameter in order to ensure trouble-free processing.

Interestingly, the process used for the stretch breaking of synthetic filament yarns that exhibit high elasticity and thermal adaptability is usually comprised of a main breaking, several pre- and post-breaking as well as thermal units. Since metal fibres have low elasticity and minimum thermal adaptability, the additional units mentioned above were not necessary. For the purpose of stretch breaking, a single-stage stretch breaking unit was

Fig. 3 Micro-structured and hard chrome-plated bottom rollers of the stretch breaking unit

Fig. 4 Metal fibre semi-finished products and metal spun yarn

developed based on a modified drafting unit of a draw frame Rieter RSB-D 40. In this process, the fibres are broken between two driven bottom rollers, which were loaded by two passively driven top rollers each. Thus, stretch broken sliver was formed (Fig. 4, I.). The surfaces of the rollers were designed to resist high abrasion to improve durability and friction, thus minimising fibre slippage. Therefore, the bottom rollers were equipped with a specifically adapted micro-structuring and hard chrome-plating by Topocrom GmbH, Germany [28]. The applied surface coating exhibited a semi-open hemispherical structure with a roughness of 20–25 μm (Fig. 3). The influence of process parameters such as the distance between bottom rollers was analysed and the corresponding mathematical relationship determined.

2.2.2 Development of the drafting process on a draw frame

The rough surface of the metal fibres led to great cohesiveness in the sliver. This complicated their drafting and increased slip in the clamping area of the roller pairs. In order to minimise drafting irregularities and maximise the uniformity of the draw frame sliver (Fig. 4, II.), one aim was to reduce slip. At the same time, fibre damage should be minimised to improve the mechanical performance of the resulting yarn. For this purpose, the effects of three bottom roller types exhibiting different surfaces on sliver uniformity and fibre damage were analysed with a draw frame Rieter RSB-D 40 (Rieter Holding AG, Switzerland). The surfaces were the following: a conventional diagonally fluted, a smooth, and a

Topocrom-coated surface analogous to the bottom rollers of the stretch breaking unit (Fig. 3). In order to better understand the drafting process of metal staple fibres, a high-speed video analysis was performed with the high-speed camera HXC20c (Baumer Optronic GmbH, Germany). Image acquisition took place predominantly in the main draft zone, as this was where the fibres were accelerated most strongly. The computer-aided image analysis was conducted with the Image Processing Toolbox software package of Matlab (TheMathWorks, Inc., USA).

2.2.3 Development of the spinning processes

The roving frame F 15 (Rieter Holding AG, Switzerland) was used to investigate the spinnability of metal fibres. Due to their high tendency towards plastic deformation and their high bending and torsional stiffness, the spinning of yarns from roving using ring spinning technology was not effective in terms of mechanical performance. Since the fibres in the roving were twisted, they could no longer be drafted in a stable process. Thus, yarns (Fig. 4, III.) were spun directly from the draw frame sliver on the roving frame.

The drafting units of the spinning machine were adapted according to the results of drafting process developments on a draw frame. Due to the high tendency of the metal staple fibres to damage surfaces, fibre guide elements, especially the false twister, were developed. In order to generate a uniform high-performance yarn and increase the lifetime of fibre guide elements, they were constructed with a smooth yet hard surface. Four different false twistors were analysed (Fig. 5).

False twistors made of rubber (Fig. 5, I.) and extra hard plastic (Fig. 5, II.) used for conventional fibres were analysed initially. However, the lifetime of rubber and extra hard plastic-based false twistors was insufficient for economic production since the surface structure was completely removed after a few hundred meters. In order to prevent excessive wear and tear, a false twister made of stainless steel (Fig. 5, III.) was developed and additionally coated with ceramic (Fig. 5, IV.). Various investigations were carried out on the influence of the type of false twister on yarn irregularity and on the influence of yarn count and twist density on the mechanical properties (samples 1–5) of the metal-spun yarns (Table 1). The following parameters have been set for this purpose: delivery speed and total draft were set in the range of 4.44–6.67 m/min and 2.41–3.80, respectively. The break draft, break draft distance, main draft distance and rotational speed were set to 1.20, 84 mm, 82 mm and 800 min^{-1} , respectively.

Fig. 5 False twisters for the spinning of metal spun yarns with flyer spinning technology

Table 1 Experimental investigation on the influence of false twister, yarn count and twist density on yarn irregularity and mechanical properties of metal spun yarn

Sample	False twister	Nominal Tt [tex]	Nominal twist density [T/m]
–	Rubber	1774	180
–	Extra-hard plastic	1774	180
–	Stainless steel	1774	180
–	Stainless steel with ceramic coating	1774	180
1	Stainless steel with ceramic coating	1634	150
2	Stainless steel with ceramic coating	2009	120
3	Stainless steel with ceramic coating	2009	150
4	Stainless steel with ceramic coating	2009	180
5	Stainless steel with ceramic coating	2578	150

2.3 Characterisation of textile-physical properties

The characterisation of the textile-physical properties of metal staple fibres included testing the fibre count, tensile

strength, elongation at break, elongation at maximum tensile stress, fibre cross section, fibre surface and fibre geometry according to the methods listed in Table 2. Due to the expected material-specific necking of the metal fibres under

Table 2 Testing methods of the textile-physical analyses of metal staple fibres, metal slivers and metal spun yarns

Sample type	Tested parameter	Testing method	n
Metal staple fibre	Fibre count	DIN EN ISO 1973:1995	50
	Fibre diameter	Derived from fibre count	50
	Fibre aspect ratio	Derived from fibre count	50
	Specific flexural rigidity	Derived from tensile test	50
	Tensile strength		30
	Elongation at maximum tensile stress	DIN EN ISO 5079: 1995 with FAVIMAT+, (Textechno Herbert Stein GmbH & Co. KG, Germany)	30
	Elongation at break	Derived from tensile test	30
	Young's modulus	Derived from tensile test	30
	Coefficient of friction of fibre to solid material	In accordance with ASTM D3108, see below	10
	Crimp elongation	In accordance with the Puchegger method [34]	50
	Fibre cross section	Optical: AXIO Imager.M1m (Carl Zeiss AG, Germany)	20
	Fibre surface and	Tactile: Tosca 400 (Anton Paar GmbH, Germany)	10
	Geometry	ESEM: Quanta FEG 250 (Thermo Fisher Scientific Inc, USA)	10
Metal staple fibre sliver	Sliver count	In accordance with DIN EN ISO 2060:1995	20
	Sliver irregularity	In accordance with DIN EN ISO 2060:1995	20
	Fibre length distribution	DIN 53,808-1: 2003	50
	Fibre damage	Derived from fibre length distribution	–
Metal spun yarn	Yarn count	DIN 53,830-3: 1981	50
	Yarn irregularity	DIN 53,830-3: 1981	50
	Twist density	DIN EN ISO 2061:2010	20
	Tensile strength	DIN EN ISO 2062:2009	20
	Elongation at maximum tensile stress	DIN EN ISO 2062:2009	20
	Elongation at break	Derived from tensile test	20
	Max. tensile elongation	In accordance with DIN EN ISO 2062:2009	1
	Elongation at break	Derived from tensile test	–

tensile load, the elongation at break was defined as the elongation that occurs at 70% reduction in tensile strength after reaching tensile strength. Furthermore, Young's moduli E_s were derived from tensile tests as the slope of the curve of the stress–strain diagram was between 0.0 and 0.2% elongation in accordance with DIN EN ISO 6892–1:2016 and Eq. 1.

$$E_s = \frac{\sigma_{0.2\%} - \sigma_{0.0\%}}{0.2\%} \quad (1)$$

In addition, the fibre diameter d , the fibre aspect ratio s and the specific flexural rigidity R_f were derived from the fibre count T_t [tex] according to Eqs. 2, 3 and 4, respectively. For the calculations, the fibre cross section was assumed to be ideally circular. This resulted in the shape factor $\eta = 1$ [29]. Furthermore, the densities of $\rho = 7.85 \text{ g/cm}^3$ for 1.4113 [30], 2.64 g/cm^3 for AlMg5 [31] and 8.93 g/cm^3 for Cu99 [32] were considered.

$$d = \sqrt{\frac{4}{\pi} \cdot \frac{T_t}{\rho}} \quad (2)$$

$$s = \frac{\text{length}_{\text{fibre}}}{d_{\text{fibre}}} \quad (3)$$

$$R_f = \frac{1}{4\pi} \cdot \frac{\eta E_s T_t}{\rho} \quad (4)$$

In order to obtain information regarding stick–slip-motions, the coefficient of friction of fibre to solid material was tested by Textechno Herbert Stein GmbH & Co. KG, Germany, in accordance with ASTM D3108. In this friction test, a head equipped with three stainless steel friction cylinders was moved from top to bottom with a preload of 10 cN along the fibre during which the tensile force acting on the upper end of the fibre was measured. The coefficients of friction were determined based on measured tensile forces and the wrap angle of the fibre around the friction head. Furthermore, the crimp elongation of the metal staple fibres was tested in accordance with the Puchegger method [34]. For this purpose, 100 mm of metal sliver was taken from the reel (i.e. crimped fibre length). Single metal staple fibres extending from one end of the sliver to the

Table 3 Properties of basic material

Fibre type		1.4113	AlMg5	Cu99
Mass density	[g/cm ³]	7.85 [30]	2.64 [31]	8.93 [32]
Fibre count	[tex]	20.12 ± 7.45	8.51 ± 4.61	13.71 ± 4.57
Fibre diameter	[μm]	56.27 ± 9.84	61.96 ± 16.25	43.59 ± 7.41
Fibre aspect ratio s*	[-]	1462.41 ± 237.32	1377.47 ± 340.56	1891.93 ± 338.20
Spec. flexural rigidity	[mN mm ² /tex ²]	0.0866 ± 0.0315	0.1555 ± 0.0694	0.0330 ± 0.0083
Shear modulus [35]	[GPa]	78	26	43
Mean fibre length	[mm]	360.16 ± 199.64	271.98 ± 131.05	605.04 ± 289.69
Crimp elongation	[-]	0.881 ± 0.319	–	–
Tensile strength	[cN/tex]	12.21 ± 1.38	9.08 ± 6.07	3.46 ± 1.99
	[MPa]	958.35 ± 108.24	256.26 ± 171.29	197.05 ± 113.11
Elongation at maximum tensile stress	[%]	2.07 ± 0.47	1.11 ± 0.25	0.57 ± 0.28
Elongation at break	[%]	2.17 ± 0.48	1.15 ± 0.25	0.60 ± 0.27
Young's modulus	[GPa]	67.03 ± 24.39	13.59 ± 6.08	33.09 ± 8.30
Coefficient of friction of fibre to solid material	[-]	0.236 ± 0.043	0.303 ± 0.064	0.236 ± 0.040
Nominal sliver count	[ktex]	25	6	32

*Calculated for its condition in yarn with a mean fibre length of 80 mm

other were aligned until they were completely stretched out. Their length, i.e. the stretched fibre length, was then measured. Finally, the crimp elongation was calculated according to Eq. 5.

$$\text{Crimp elongation} = \frac{\text{Stretched fibre length}}{\text{Crimped fibre length}} - 1 \quad (5)$$

In order to characterise fibre surface and geometry, the height parameters root mean square height of the scale-limited surface (S_q , Eq. 6) and kurtosis of the scale-limited surface (S_{ku} , Eq. 7) were measured according to ISO 25,178-2:2012 with tactile analysis using device Tosca 400 (Anton Paar GmbH, Germany). In order to generate comparable results, the curvature of the fibre was subtracted.

$$S_q = \sqrt{\frac{1}{A} \iint_A z^2(x, y) dx dy} \quad (6)$$

$$S_{ku} = \frac{1}{S_q^4} \left(\frac{1}{A} \iint_A z^4(x, y) dx dy \right) \quad (7)$$

In order to characterise the textile-physical properties of metal staple fibre slivers, the testing of sliver count, sliver irregularity and fibre length distribution according to the mentioned methods was conducted (Table 2). Additionally, the fibre damage was determined using Eq. 8. The characterisation of the textile-physical properties of the metal spun yarns included the testing of yarn

count, yarn irregularity, twist density, tensile strength and maximum tensile elongation according to the mentioned methods (Table 2). According to the expected behaviour of the metal fibres mentioned above, the elongation at break of yarn was defined as the elongation that occurs at 70% reduction in tensile strength. By applying two-tailed Student's *t* tests, it was assessed whether the mechanical properties of yarn samples 1–5 (Table 1) differ significantly from each other. Therefore, the significance level was set to 5%. Considering a sample size of $n = 20$, the critical *t*-value was 2.086. All samples were preadjusted and tested at standard climate according to DIN EN ISO 139:2011.

$$\text{Fibre damage} = \left(\frac{\text{Mean fibre length before processing}}{\text{Mean fibre length after processing}} - 1 \right) \cdot 100\% \quad (8)$$

3 Results and discussion

3.1 Properties of basic material

Properties of basic metal staple fibres are presented in Table 3 as provided by the supplier. It could be seen that all properties are highly variable. For process chain development, this had the consequence that large tolerances and safety requirements must be taken into account. As metal staple fibres 1.4113 had the highest tensile strength, a low coefficient of friction of fibre to solid material and the highest elongation at break (i.e. least brittleness), they were superior in comparison with AlMg5 as well as Cu99

Fig. 6 Stress–strain master curves of 1.4113, AlMg5 and Cu99

(see Table 3). Thus, the development of the spinning process chain was conducted using them. The nominal count of delivered sliver was 25 ktex.

The fibres were cold-deformed during production. This hardening of the material increased its strength, but reduced its ability to deform both elastically and plastically. This was confirmed by the comparison of tensile strength and elongation at break of the metal fibre 1.4113 with parameters from the literature. It could be seen that the average tensile strength of the fibre (958.35 MPa, Table 3) was at least 45% higher than the maximum tensile strength mentioned in the literature (max. 660 MPa) [30]. By contrast, elongation at break of the fibre (2.17%, Table 3) was at least 88% lower than the minimum elongation at break mentioned in the literature (min. 18%). In order to analyse the specific behaviour of the metal fibre 1.4113 during tensile load, the fibre shape parameter β was calculated according to the results of Chou [36], taking into account Eq. 9. For the metal fibre, 1.4113 it was 10.63 and at a similar level to glass fibre. Thus, the tensile behaviour of the fibre was between brittle ($\beta = 2 \dots 4$) and ductile ($\beta = 20$).

In order to compare the stress–strain behaviour of different types of metal fibres (Fig. 6), stress–strain master curves were generated. Therefore, for each sample, the stress–strain data were normalised with respect to both mean elongation parameters and mean stress parameters. It could be seen that stresses increase degressively. In addition, no change from elastic to plastic deformation was visible. Furthermore, the derived mean Young's moduli of 67.03 GPa for 1.4113, 13.59 GPa for AlMg5 as well as 33.09 GPa for Cu99 were far lower than the material constants of 220 GPa for 1.4113 [30], 70 GPa for AlMg5 [31] as well as 110 GPa for Cu99 [32] found in the literature. Hence, it could be concluded that the elastic deformation of the fibres was so low that they deform plastically almost

Table 4 Correlation analyses of tensile properties of 1.4113

Parameter 1	Parameter 2	r	Correlation effect [37]
$\varepsilon(\sigma_{\max})$	$\sigma_{\max}$	.3162	Medium
Tt	$\sigma_{\max}$	.2006	Small
Tt	$\varepsilon(\sigma_{\max})$	.4293	Medium

r, Correlation coefficient; $\varepsilon(\sigma_{\max})$, elongation at maximum tensile stress; $\sigma_{\max}$, tensile strength; Tt, fibre count

immediately under tensile load. The most significant reason for this was the geometry of the fibres, since their span length at tensile test (span length = 20 mm) was approx. 330 times higher than their diameter (approx. 60 μm , Table 3). A probable explanation for the failure of a metal fibre subjected to tensile stress is necking, which leads to isolated plastic deformation. Its rough surface intensified the aspect of the isolated occurrence of this phenomenon. The plastic deformation took place along and transverse to the fibre direction. Since the plastic deformation occurred almost uniformly in every spatial direction, a relatively strong reduction transverse to the fibre direction led to a relatively small reduction along the fibre direction. Thus, failure occurred at low elongation along the fibre direction, resulting in low elongation at break (Table 3).

$$\beta = \frac{1.2}{\text{coefficient of variation of tensile strength}} \quad [36] \quad (9)$$

To conduct Pearson correlation analyses on the tensile properties (X, Y) of single fibres of 1.4113, such as elongation at maximum tensile stress, tensile strength and fibre count, the correlation coefficients $r(X, Y)$ given in Table 4 were calculated according to Eq. 10.

$$r(X, Y) = \frac{\sum_{i=1}^n (x_i - \bar{X})(y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{X})^2 \cdot \sum_{i=1}^n (y_i - \bar{Y})^2}} \quad (10)$$

As defined by Cohen [37], small, medium, and large correlation effects take place when $0.1 \leq |r| < 0.3$, $0.3 \leq |r| < 0.5$ and $0.5 \leq |r| \leq 1$, respectively. This resulted in a medium correlation effect between elongation at maximum tensile stress and tensile strength. Due to the small amount elongation occurring after reaching the maximum tensile stress (Fig. 6), it could be seen that the stress increased in the largest part of the elongation. Thus, the tensile strength also increased with increasing elongation at maximum tensile stress. Despite this obvious relationship, the according r -value was at such a low level. This was due to the high irregularity of the Young's moduli of the

Fig. 7 Cross-sectional view of metal staple fibres; 1.4113 (a), AlMg5 (b) and Cu99 (c)

metal fibres (e.g. CV (Young's modulus) = 36% for 1.4113). The relationship between the fibre count and elongation at maximum tensile stress had a medium effect. The type of failure described above due to necking under tensile load resulted in a more pronounced plastic deformation with increasing fibre count and thus increasing diameter until complete failure. This resulted in higher elongation at maximum tensile stress. Despite the mechanisms mentioned above, only a small effect could be observed for the correlation between fibre count and tensile strength. Due to the high irregularity of metal fibre geometries and the corresponding mechanical properties, the variance conceals material scientific effects.

Figures 7, 8 and 9 show cross-sectional views in addition to AFM and SEM analyses of the metal fibres; 1.4113, AlMg5, and Cu99. It could be seen that the fibres exhibit sharp edges (Fig. 7) and notches parallel and transverse to the fibre direction (Fig. 9), induced during planing.

Two general types of fibre surface areas were identified. During production, the serrated blades cut into the wire from one side and from the upper fibre side (Fig. 7a). Thus, only one side was formed directly, while the other side was formed more randomly and the cross-sectional area and geometry varied greatly from fibre to fibre, leading to a high variance of the fibre count ($CV_{10cm} = 37\%$, Table 3). Since the metal fibres were drawn perpendicularly to the metal wire from the

cutting edge, the upper side in particular was intensively deformed. Comparing the Young's moduli with the S_q values of the metal fibres (Table 3, Fig. 8), it can be seen that the stiffer the material, the higher the resistance to this deformation. This increases the applied deformation load, resulting in stronger micro-level deformation marks that correlate directly with the specific S_q value. Accordingly, the metal fibre 1.4113 was the stiffest fibre (Young's modulus = 67.03 GPa), thus exhibiting the highest S_q value of 0.489. The softest metal fibre was AlMg5 (Young's modulus = 13.59 GPa), which possessed the lowest S_q value of 0.247.

The upper side of the fibre (Fig. 7a) surface tended to be rough and exhibited notches, mainly transverse to the fibre direction (Fig. 9, AlMg5_2). This was additionally confirmed by the frequency distribution of the height values of this fibre side, which was similar to a normal distribution with a single main peak (Fig. 8). Thus, the kurtosis of the scale-limited surface, S_{ku} , was higher than with the lower fibre side. There it could be seen that the frequency distribution of the height values of this fibre side was not normally distributed, but exhibited several peaks, which yielded lower S_{ku} values. Importantly, the upstream blades and coil surface mainly affected the lower side. For this reason, no valid evaluation of S_q values could be carried out. This type of fibre surface area tended to be smooth, with notches

Fig. 8 AFM analysis of metal staple fibres 1.4113 (a), AlMg5 (b) and Cu99 (c)

occurring mainly in the fibre direction. Its geometry tended to be flat (Fig. 9, Cu99).

Comparing the specific flexural rigidity of metal (Table 3), nylon (0.14 mN mm²/tex² [29], viscose (0.19 mN mm²/tex² [29], and wool (0.20 mN mm²/tex² [29], as indicators of bending stiffness, it could be seen that metal fibres exhibited parameters of the same level. However, due to the higher fineness of the metal fibres, their bending stiffness was also higher than that of conventional fibres. Furthermore, comparing the shear module of metal fibres [approx. 50 GPa (Table 3)], cotton fibres (1.80–2.62 GPa [38], and polyester fibres (0.65–0.86 GPa [39] as an indicator of torsional stiffness, it was revealed that metal fibres exhibited a torsional stiffness which was at least 25 times higher than conventional fibres such as cotton and polyester fibres. Overall, it could be stated that the fibres exhibited strong tendencies towards plastic deformation and stick–slip motions as well as high bending and torsional stiffness (Table 3). These properties fundamentally distinguished them from conventional fibres, which was taken into account in the development of the process chain.

3.2 Analysis of process parameters for the development of the spinning process chain

3.2.1 Stretch breaking process

The required total draft of the stretch breaking unit was determined according to the following analysis. Since the crimp elongation of the metal staple fibres 1.4113 had an average value of 0.88 (Table 3) but ranged from 0.26 up to 1.62, a total draft of at least 2.62 must be set to ensure that each fibre is aligned in the strand. In addition, the elongation at break of approximately 2% must be exceeded to ensure that even extremely long fibres are broken. This resulted in a minimum total draft of 2.64. A safety margin of 15% was considered to counteract possible slippage. Thus, a total draft of 3.03 was implemented. Afterwards, the gauge length between the roller pairs was designed. The relationships between process and material parameters (elongation at break, roller gauge, total draft) and mean fibre length described in the literature (Eq. 11, [40] were the starting point for setting the roller gauge. According to Eq. 5, which applies

Fig. 9 SEM analysis: end faces of metal staple fibres 1.4113, AlMg5(– 1 & – 2) and Cu99

to filament yarns, a roller gauge of 151 mm had to be set for a mean fibre length of 80 mm. The experimentally determined mean fibre length for this configuration was about 150 mm, which was far above the predicted value. One reason for this may be slippage or breakage of the fibres before they are fully aligned.

Mean fibre length = Roller gauge

$$\cdot \left(\frac{1}{2} + \ln \frac{(\text{Draft} - 1)(1 + \text{Elongation at break})}{\text{Draft} - (1 + \text{Elongation at break})} \right) \quad [40] \quad (11)$$

$$\text{Mean fibre length} = 0.98 \cdot \text{Roller gauge} + 22.5 \text{ mm} \quad (12)$$

The examination of the influence of the roller gauge on the mean fibre length was systematically conducted in the range of the roller gauge of 42–125 mm (Table 5), so that Eq. 12 resulted. Since an average fibre length of 80 mm was decisive for the successful development of the subsequent processes after stretch breaking, the roller distance was set to 58.5 mm. Figure 10 shows the fibre length distribution of unconverted and converted metal staple fibres. It could be seen that a metal staple fibre sliver with a narrow fibre length distribution and a mean fibre length of 80 mm could be realised.

3.2.2 Drafting process on a draw frame

The influence of the bottom roller surface during drafting with respect to irregularities and fibre damages of drafted slivers is shown in Table 6. It could clearly be seen that the most uniform sliver could be realised with diagonally fluted bottom rollers ($CV_{10 \text{ cm}} = 8.53\%$). Simultaneously, however, the fibre damage was at its highest. Using Topo-crom-coated bottom rollers, a significantly less damaged sliver (51.5% less fibre damage compared to diagonally fluted bottom rollers) could be realised with slightly less uniformity (4.8% less uniformity compared to diagonally

Table 5 Influence of the roller gauge of the stretch breaking unit on the mean fibre length of metal staple fibre slivers

Roller gauge [mm]	Mean fibre length [mm]
42.0	61.0
65.0	85.0
85.0	98.0
125.0	143.2

nominal delivery speed = 4 m/min, draft = 3.03, nominal incoming metal fibre strand count = 25 ktex

Fig. 10 Fibre length distribution of converted and unconverted metal staple fibres

Table 6 Sliver irregularities and fibre damage of draw frame sliver using different bottom rollers

Bottom roller surface	CV _{10 cm} [%]	Fibre damage [%]
Diagonally fluted	8.53	7.16
Smooth	19.58	0.00
Topocrom coating	8.94	3.47

Delivery speed=4.17 m/min, total draft=4.54, break draft=1.10, number of doubling=8, break draft distance=89 mm, main draft distance=87 mm, nominal incoming sliver count=8 ktex, rubber-coated top rollers with 83 Shore hardness

fluted bottom rollers). When smooth bottom rollers were used, no fibre damage was observed, but the sliver uniformity remained significantly too low. Therefore, Topocrom-coated bottom rollers were applied for further investigations. Conventional rubber-coated top rollers with 83 Shore hardness were used. This enabled good process stability at least for the research purpose underlying this publication. However, in order to scale up the process to an industrial level, developments must be made to further increase the lifetime of the top rollers.

When examining the drafting process, it was found that two main anomalies occur. First, gaps were formed at the borders of the incoming belts parallel to the production direction (Fig. 11, left). Due to the plastic deformation of the fibres, the slivers formed a compact unit. This could be partially prevented by narrowing the incoming slivers, resulting in fewer gaps. Nevertheless, this anomaly could not be completely prevented. Second, loose fibre bundles protruded at the boundaries of the sliver (Fig. 11, right). During drafting, the metal staple fibres often detached in tufts. This was due to their great cohesiveness within the sliver and ultimately to their rough surface (Fig. 7). The tufted detachment caused the neighbouring fibres to lose their grip in the

Gap parallel to the production direction

Loose fibre bundle

Fig. 11 Process anomalies during the drafting of planed metal staple fibres

production direction, which finally caused them to stand out from the sliver compound. Since compacting the fibre volume in the drafting zone increased the tufted detachment of the sliver, this impeded trouble-free and homogeneous drafting. Thus, a specific degree of narrowing was selected as a compromise between minimising gaps and tufted detachments.

3.2.3 Spinning process

The spinning limits in the form of yarn count were analysed throughout the development of the spinning process. It

Fig. 12 Yarn irregularities $CV_{10\text{ cm}}$ depending on applied false twister at the flyer spinning process

Fig. 13 Microscopic longitudinal view of flyer yarn using false twister made from stainless steel with ceramic coating

was found that the lower process limit for flyer spinning is approx. 1150 tex. Such yarns had only approx. 60 fibres in their cross section (see Table 3, fibre count 1.4113). It was not possible to further reduce the number of fibres without detrimentally decreasing the process stability. In contrast, the upper process limit for flyer spinning was approx. 3000 tex. A further increase in yarn count would have increased the yarn tension during spinning to such an extent that damage to machine components, particularly in the flyer area, would have posed a high risk.

3.2.4 Yarn properties

The spinning experiments performed with different false twisters revealed that stainless steel with a ceramic coating was superior to other types because it could be used to produce the most even yarn (Fig. 12). The microscopic longitudinal view of the flyer spun yarn produced with a false twister made from ceramic-coated stainless steel is presented in Fig. 13.

The influence of yarn count and twist density on the mechanical properties of the yarn is presented in Table 7 and with stress–strain diagrams of samples 1, 3 and 5 in Fig. 14, and of samples 2, 3 and 4 in Fig. 15. The associated statistical *t*-values of the Student's *t* tests are presented in Table 8. The classical theory regarding the mechanical properties of staple yarns states that yarn strength depends on twist factor [41]. Until the twist factor reaches its optimum, yarn strength increases due to the increase in cohesion. A further increase in twist factor increases the weakening of the yarn structure caused by the fibre obliquity. Due to the isotropy of the metal spun yarn material, the fibre obliquity should not weaken the fibre structure. Accordingly, for samples 2, 3 and 4, it could be seen that the twist density had no significant influence on tensile strength in the value range considered. Nevertheless, there was a decrease in yarn stiffness with increased twist density. Thus, it could be seen that with increasing twist density, the elongation at maximum tensile stress increases significantly. According to the weakest link theory [42], the load of a fibre in the yarn, if it fails, must be carried by the surrounding fibres. With increasing elongation, the probability that a single fibre will fail increases. If a critical portion of the fibres has failed, the yarn breaks. The more fibres there are in the yarn, the more single fibres can fail before the yarn fails. Accordingly, with increasing yarn count, the tensile strength and elongation at maximum tensile stress increased significantly, as could be seen from the comparison of samples 1, 3 and 5. Since the influence of the individual fibres on the yarn properties decreased with increasing yarn count, the coefficient of variation of the tensile strength decreased accordingly. This could be seen for specimens 1, 3 and 5, where the coefficient of variation of the tensile strength was 16.59%, 12.73% and 11.89%, respectively.

Table 7 Properties of samples 1–5

Sample	$\sigma_{\max}$ [MPa]	$\varepsilon(\sigma_{\max})$ [%]	T [T/m]	Tt [tex]
1	184.19 ± 30.56	0.95 ± 0.15	148.00 ± 8.88	1817.45 ± 103.16
2	195.94 ± 26.49	1.01 ± 0.15	118.95 ± 6.55	2235.76 ± 111.99
3	196.55 ± 25.02	1.37 ± 0.17	145.80 ± 8.15	2304.66 ± 72.04
4	192.41 ± 24.38	1.46 ± 0.14	167.65 ± 12.73	2228.15 ± 138.47
5	211.88 ± 25.19	1.49 ± 0.19	138.25 ± 9.61	2840.73 ± 132.12

Tt, Yarn count; $\sigma_{\max}$, tensile strength; $\varepsilon(\sigma_{\max})$, elongation at maximum stress; *T*, twist density

Fig. 14 Stress–strain master curves of yarn samples 1, 3 and 5

Fig. 15 Stress–strain master curves of yarn samples 2, 3 and 4

The experimentally determined real yarn count was higher than the nominal values. The most likely explanation for this was that slippage occurred due to the low friction between the fibres and rollers of the drafting system. Thus, the real draft was lower than the nominal draft and the yarn count was higher. Comparing Tables 1 and 7, it could be seen that the real twist density was lower than the nominal twist density. During spinning on a roving frame, a real twist as a consequence of the torque was applied to the yarn by rotating a yarn end around the yarn axis in the area between the feeding rollers of the drafting system and the flyer [41]. As the mean fibre length of the yarn was smaller than the distance between these edge points, the twist migrated from one end to another due

Table 8 Statistical *t*-values of Student's *t* tests on the influence of yarn count and twist on tensile strength as well as elongation at maximum stress of yarn samples 1–5

Compared samples	Influence of ... on ...	Tt $\sigma_{\max}$	Tt $\varepsilon(\sigma_{\max})$	T $\sigma_{\max}$	T $\varepsilon(\sigma_{\max})$
1–5		3.127*	9.936*	–	–
1–3		1.400	8.183*	–	–
3–5		1.931	2.150*	–	–
2–4		–	–	0.438	9.600*
2–3		–	–	0.075	7.006*
3–4		–	–	0.530	1.761

Tt , Yarn count; $\sigma_{\max}$, tensile strength; $\varepsilon(\sigma_{\max})$, elongation at maximum stress; T , twist density

*significant difference

to friction. Since the initial twist was applied via fibres in the outer yarn area, the inner fibres were also passively twisted. Due to friction losses, the degree of twist conduction decreased towards the centre of the yarn cross-section. This means that the applied twist was less inside than outside. When testing the twist density, the average twist density over the entire yarn cross-section was evaluated. Accordingly, real twist density reduced with increasing amount of fibres on which twist was applied passively. As the twist density increased, the torque required to apply the twist increased. This correspondingly increased torsional stress. Due to the friction-based migration of twist, the higher the torsional stress, the higher the loss of twist conduction. Hence, real twist density diminished in a more pronounced manner with both higher yarn count and higher applied twist density. Therefore, the twist difference of sample 1 (2.00 T/m) was lower than for sample 5 (11.75 T/m) with its higher yarn count. Furthermore, the twist difference of sample 2 (1.05 T/m) was lower than for sample 4 (12.35 T/m) with its higher twist density.

The conduction of the mechanical performance from the fibre to the yarn was of varying intensity. Both parameters, tensile strength and elongation at maximum tensile stress, were reduced from fibre to yarn. The elongation at maximum tensile stress was reduced by at least 28% (fibre value: 2.07%; highest yarn value: 1.49%). Taking into account the conventional mechanical behaviour of staple fibres subjected to tensile stress in the yarn, they slip against each other. Therefore, the elongation at maximum tensile stress of the yarn should be higher than that of a single fibre [43]. Since the gauge of the tensile test of the fibres (20 mm) was lower than that of the yarns (200 mm), the above-mentioned influence of necking on elongation was more pronounced for the yarn values. This led to a decreased elongation at maximum tensile stress. Following the weakest link theory, because of the high variance

of the elongation at maximum tensile stress of the fibres (variance = 23%, Table 3), the elongation at maximum tensile stress of the related yarn should be lower [42]. According to the work of Pan [42], the level of conduction of the tenacity from fibre into yarn depends on the occurrence of the fragmentation process. This process takes places when the critical level of the (l_f/l_c) ratio > 3 is exceeded. The ratio between the strength of a yarn σ_y and its constituent fibres σ_f was calculated according to Eq. 13, where β is the fibre shape parameter, η_q is the fibre orientation efficiency factor (calculated by Eq. 14), l_f is the mean fibre length, and l_c is the critical length. Due to $ns \gg 1$, $\eta_q \rightarrow 1$.

The critical length l_c , known as the minimum length into which a fibre can be broken, was calculated according to Eq. 15 where σ_b is the tension that causes the fibre segment to break,¹ r is the fibre radius, μ is the coefficient of friction between fibre and fibre,² and g is the local lateral pressure. The local lateral pressure g was calculated according to Eq. 17, where E_f is Young's modulus of the fibre, ϵ_f is the elongation at maximum tensile stress of the fibre, s is the fibre aspect ratio (Table 3), and n is the yarn cohesion factor. Since $ns \gg 1$ and $\tanh(ns) \rightarrow 1$, Eq. 17 simplified to Eq. 16. The yarn cohesion factor n was calculated according to Eq. 18, where G_{TL} is the yarn longitudinal shear modulus, which was derived from Eq. 19. There, q is the yarn surface helical angle, which was derived from Eq. 20. There, $a_q = 2.5$, ρ_f is the fibre density ($\rho_f = 7.85$ g/cm³ [30] for metal fibre 1.4113), V_f is the yarn fibre-volume fraction, and T_y is the yarn twist factor. V_f and T_y were calculated according to Eqs. 21 and 22, respectively, where TPC is the twist density in twists per centimetre and Tt is the yarn count in tex.

$$\frac{\sigma_y}{\sigma_f} = \left(\frac{l_f}{l_c}\right)^{\frac{1}{\beta}} \frac{V_f \eta_q}{\beta^{\frac{1}{\beta}} e^{\frac{1}{\beta}} \Gamma\left(1 + \frac{1}{\beta}\right)} \quad [42] \quad (13)$$

$$\eta_q = 1 - \frac{\tanh(ns)}{ns} \quad [43] \quad (14)$$

$$l_c = \frac{\sigma_b}{\pi r \mu g} \quad [44] \quad (15)$$

$$g = \frac{n}{2\mu} E_f \epsilon_f \quad [45] \quad (16)$$

Table 9 Critical length of yarn samples 1–5 and according parameters

Sample	1	2	3	4	5
$\frac{\sigma_y}{\sigma_f}$ [–]	0.569	0.699	0.727	0.749	0.742
$\frac{l_f}{l_c}$ [–]	1.92	1.48	2.39	3.03	2.65
l_c [mm]	41.67	54.07	33.46	26.38	30.19
g [MPa]	516.98	398.45	643.94	816.65	713.49
n [–]	0.176	0.136	0.219	0.278	0.243
G_{TL} [MPa]	718.45	426.80	1114.70	1792.82	1368.49
q [–]	0.646	0.592	0.697	0.758	0.722
V_f [–]	0.700	0.700	0.700	0.700	0.700
T_y [$\frac{T}{m} \sqrt{\text{tex}}$]	63.09	56.24	69.99	79.14	73.69

$$g = \frac{n}{2\mu} E_f \epsilon_f \tanh(ns) \quad [33] \quad (17)$$

$$n = \sqrt{\frac{G_{TL}}{E_f} \frac{2}{\ln 2}} \quad [43] \quad (18)$$

$$G_{TL} = \frac{E_f V_f}{\frac{\pi(1-\cos q)\sin^3}{6\left(\frac{q}{2} - \frac{1}{4}\sin 2q\right)^2} + \frac{8\sin^3 q}{3\pi(1-\cos q)(1+\cos q)^2} + \frac{\pi(4-3\cos q-\cos^3 q)}{6\left(\frac{q}{2} - \frac{1}{4}\sin 2q\right)(1+\cos q)}} \quad [33] \quad (19)$$

$$q = \arctan\left(a_q 10^{-3} T_y \left(\frac{40\pi}{\rho_f V_f}\right)\right) \quad [43] \quad (20)$$

$$V_f = 0.7(1 - 0.78e^{-0.195T_y}) \quad [43] \quad (21)$$

$$T_y = \text{TPC} \sqrt{Tt} \quad [43] \quad (22)$$

In order to derive the maximum tensile strength of yarn samples 1–5 (Table 1) as well as to check the possibility for fragmentation to take place from a theoretical point of view, the ratios σ_y/σ_f and l_f/l_c , respectively, were calculated using the parameters derived from the mentioned equations. Since the (l_f/l_c) ratio > 3 did not exceed extensively, no or little fragmentation of fibres during yarn extension occurred. The highest tensile strength was achieved with sample 5. Nevertheless, only 22.1% of the fibre strength was transferred to the yarn, while 74.2% was theoretically possible (Table 9).

¹ σ_b is approx. the tensile strength of the fibre. For metal fibre 1.4113, $\sigma_b = 958.35$ MPa.

² The coefficient of friction of metal fibre 1.4113 to solid stainless steel friction cylinder is .236 (Table 3). It was considered that this value equals approx. the coefficient of friction from fibre to fibre.

4 Conclusions and outlook

The research and development work regarding the spinning of 100% metal spun yarns based on planed metal staple fibres proved that with the highly productive process chain consisting of stretch breaking, drafting and flyer spinning, the desired yarns could be generated. Moreover, the specific development of metal spun yarns adapted to the newly emerging applications is a major field of development. These yarns already possess favourable mechanical properties, and future work should deal with the following two main aspects.

1. In order to increase the probability for the fragmentation process, the mean fibre length and thus the (l_f/l_c) ratio should be increased.
2. In order to increase local lateral pressure, the coefficient of friction from fibre to fibre should be increased. Therefore, fibre surface has to be modified.

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