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Research on the Knittability of Metallic Yarns in the Warp-knitted Mesh of a Deployable Antenna

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Abstract
Metallic yarns are difficult to be knitted. To resolve the problem, the paper used the knitted yarn strength utilization factor to quantitatively characterize knittability, which was the ratio of yarn strength after being knitted to that of the original yarns. Furthermore, the relationship between the yarns' basic mechanical properties and the knitted yarn strength utilization factor was investigated by testing the yarns' basic mechanical properties. The results showed that it was feasible to quantitatively characterize the yarns' knittability using the knitted yarn strength utilization factor. And also the breaking strength of yarn was not correlated with the knittability. The elongation at break of the yarn was positively correlated with knittability. The bending stiffness of the yarn was negatively correlated with the knittability. Finally, a multiple linear regression model of the knittability and the mechanical properties of the yarn was developed. The model showed that there was a significant linear relationship between knittability and the elongation of yarns at break and the bending rigidity of yarns, with the bending stiffness of yarns being more significant.

Keywords
Metallic yarn, knittability, knitted yarn strength utilization factor, tensile properties, bending stiffness.

1. Introduction

The extensile mesh reflector of an antenna consists of fine wires with a low thermal expansion coefficient and high resistance to UV. A functional coating with good electrical properties, with a base of gold, silver, rhodium or organic materials like polyurethane, is added to these fine wires [1]. Nickel-plated stainless steel wire is normally used for low-frequency (LF) antennas, and gold-plated molybdenum for high-frequency (HF) ones [2]. Therefore, compared with conventional fabric, warp-knitted mesh-like antennas show significantly different performances, because of the high-performance metallic yarns used as raw material.

As one of the high-performance fibers, the metallic yarn knitting process is quite different from that of conventional yarns. Firstly, high strength of the yarn only appear in the axial direction, even if it has a high-performance fibers composition [3]. These fibers' low surface strain, high tensile set and low out-of-plane properties bring difficulties to the knitting process [4]. Secondly, high-performance fibers cannot not be knitted smoothly due to the high-tension peaks resulting from low elongation. While garment fibers with elastic elongation can be processed easily [5-6]. Thirdly, part of these fibers is easily broken under extremely lower loads than that that which leads to elongation breakage, because yarns are subjected to pressure from bending, and sometimes even from both bending and stretching in the knitting process [7-9]. Generally, the performance of yarn in the knitting process, i.e. whether the yarn can be knitted smoothly, is called knittability [10]. The knittability of yarns is hard to characterise and measure directly [11]. Therefore, methods for the quantitative characterization of knittability should be investigated.

The current study mainly concentrated on fiber damage, simulation testing and fiber performance measurement for knittability characterization. However, these methods were still not clear or accurate. The yarn strength loss in knitted fabric can be quantitatively characterized for yarn knittability, but only for disassembled fabric [11]. In this study, the ratio of predicted tensile properties of single yarn inside warp-knitted fabrics to that of the original one, called the knitted yarn strength utilization factor, was used for characterizing knittability. Furthermore, the method extremely easy to carry out for yarns' basic performance [10]. In this study, the basic performances were tested for further research of their relationships to the knitted yarn strength utilization factor.

2. Materials and Experiments

2.1. Materials

Specimen specifications of metallic yarns used in warp-knitting meshes are shown in ***Table 1***.

2.2. Experiments and results

2.2.1. Tensile properties

According to GB/T 3916-1997, tensile properties of metallic yarns were tested on a YG061-1500 yarn strength tensile instrument. The drawing gauge was 250mm, and the drawing speed was 20mm/min. Each sample was tested five times. The average value is shown in ***Table 2***.

2.2.2. Bending stiffness of yarns

A KES-FB2 bending tester was used for the bending stiffness test. Cardboard was cut into 11 mm pieces, with 60 yarns arranged in parallel (***Figure 1***) [12]. During the test, both ends of the rectangle cardboard were removed and fixed between two chucks. Six samples

No.	LF-1 yarn	LF-2 yarn	HF-1 yarn	HF-2 yarn
Material	**Nickel-plated stainless steel wire**	**Gold-plated molybdenum wire**	**Gold-plated molybdenum wire**	**Molybdenum wire**
Diameter of monofilament (μm)	30	27	17	16
Number of monofilaments	3	3	4	4
Yarn linear density (tex)	19.8	16.7	10.5	8.2
Twist Coefficient α_t	3.7	3.4	2.7	2.4

Table 1. Specification of metallic yarns

No.	LF-1 yarn	LF-2 yarn	HF-1 yarn	HF-2 yarn
Breaking strength (cN)	167.1	389.4	216.6	185.8
Elongation at break (%)	23.8	1.8	2.0	1.9

Table 2. Tensile properties of metallic yarns

No.	LF-1 yarn	LF-2 yarn	HF-1 yarn	HF-2 yarn
Bending stiffness B_y (cN·cm^2)	0.0121	0.0152	0.0039	0.0037

Table 3. Bending stiffness of metallic yarns

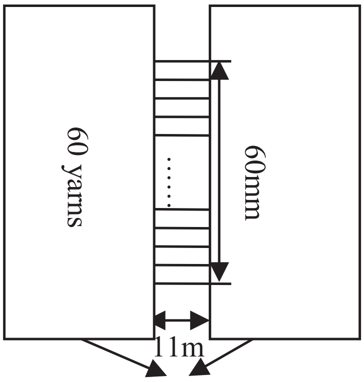


Fig. 1. Schematic diagram of specimen for bending test of yarns

were tested and calculated, shown in ***Table 3***.

2.2.3. Warp-knitted mesh knitting

LF-1 and LF-2 yarns were warp-knitted on an E16 warp-knitting machine with an open atlas tricot structure. In the process, two guide bars were adopted one in one out in a 4-line atlas lap, and closed loops were used in laying-in diversion. LF antennas were prepared with specific process parameters, shown in ***Table 4***. HF-1 and HF-2 yarns were warp-knitted on an E24 machine with a reverse locknit structure. HF antennas were prepared with specific process parameters, shown in ***Table 5***. Mesh reflectors with good external appearance are shown in ***Figure 2*** and ***Figure 3***.

2.2.4. Unidirectional tensile properties of warp- knitted meshes

The test was conducted on a WDW-20 universal testing machine. The specimen length was 100 mm, and the width was 40 coils columns. The width of HF specimens was 20 columns of coils. Each specimen was tested 5 times along the longitudinal and transverse directions, respectively. The results are shown in ***Table 6***.

3. Discussion

3.1. Knittability quantification of metallic yarn

The knittability of warp-knitted fabrics was able to be characterised by the damage degree of yarns after knitting. But warp-knitted fabrics could not be dislodged to obtain intact yarns against the knitting direction or with the knitting direction. Having been replaced, each knitted yarn's strength utilization factor was calculated from single yarn's tensile strength, which was obtained from the fabric's tensile performance. The knitted yarn strength utilization factor could be used for knittability characterization. The higher the knitted yarn strength utilization factor, the better the knittability.

The number of yarns bearing loads during the tensile process was related to the stretching direction of the fabric. Mainly two yarns were loaded in longitudinal stretching, while only one in transverse stretching. Therefore, the fabric breakage strength was able to be calculated down to single yarn strength for a known number of stretched yarns [13].

In the longitudinal direction, 40 columns of LF-1and LF-2 specimens, which were actually 80 yarns, were stretched. 40 horizontal rows of LF-1 and LF-2, which were 40 yarns, were stretched along the transverse direction. While there were two overlapping loops in the HF-1 and HF-2 meshes, which amounted to 20 columns, with 80 yarns being stretched in the longitudinal direction, in the transverse direction, 20 horizontal rows including 40 yarns were stretched in HF-1 and HF-2 meshes.

From ***Table 7***, the knitted yarn strength utilization factor of LF-1 yarn was higher than that of LF-2 yarn. While in HF antennas, the knitted yarn strength utilization factor of HF-1 was close to that of HF-2, that of HF-1 and HF-2 yarns was higher than that of both LF-1 and LF-2 yarns, even if their different structure and processing parameters were used. In general, the higher the gauge of the knitting machine used, the more difficult it was for fabrics to be knitted. Therefore, HF-1 and HF-2 yarns could be judged to have better knittability.

No. of mesh reflector	LF-1 mesh		LF-2 mesh	
Materials	**LF-1 yarn**		**LF-2 yarn**	
Knitted structure	Open atlas tricot structure		Open atlas tricot structure	
Chain notation	Guide Bar 1	Guide Bar 2	Guide Bar 1	Guide Bar 2
	1-0/1-2/2-3/2-1//	2-3/2-1/1-0/1-2//	1-0/1-2/2-3/2-1//	2-3/2-1/1-0/1-2//
Threading ways	1*1*	1*1*	1*1*	1*1*
Let-off amount (mm/rack)	2330	2370	2875	2870
Machine speed (mm/min)	150-300		150-300	

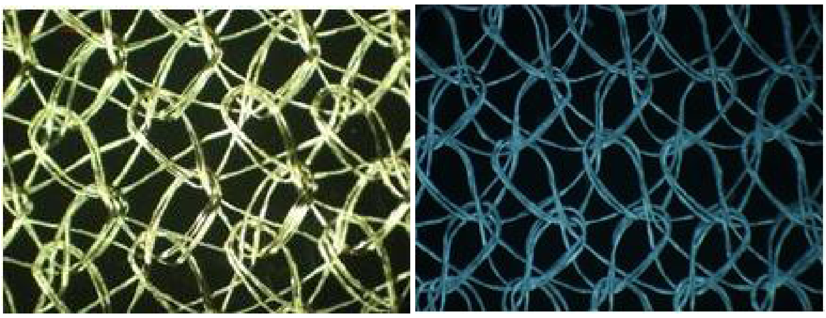
Table 4. Knitting process parameters for LF antennas

No. of mesh reflector materials	HF-1 Mesh HF-1 yarn		HF-2 Mesh HF-2 yarn	
Knitted structure	reverse locknit structure		reverse locknit structure	
Chain notation	Guide Bar 1	Guide Bar 2	Guide Bar 1	Guide Bar 2
	1-0/1-2//	2-3/1-0//	1-0/1-2//	2-3/1-0//
Threading ways	Full	Full	Full	Full
Let-off amount (mm/rack)	2220	2370	2220	2690
Machine speed (mm/min)	150-300		150-300	

Table 5. Knitting process parameters for HF antennas

(a) LF-1 mesh *(b) LF-2 mesh*

Fig. 2. Warp-knitted mesh for LF antennas



(a) HF-1 mesh *(b) HF-2 mesh*

Fig. 3. Warp-knitted mesh for HF antennas

3.2. Effect of tensile properties on metallic yarns' knittability

From ***Table 2*** and ***Table 7***, the relationship between the strength of metallic yarn and knittability is uncorrelated, but that of the elongation at break is positively correlated. The elongation at break of yarns in LF-1 and LF-2 samples is 23.8% and 1.8%, respectively (***Table 2***). From ***Table 7***, the knitted yarn strength utilization factor of LF-1 yarn is 1.8 times that of LF-2 in both the longitudinal and transverse directions; that is, the knittability of LF-1 yarn is better than that of LF-2 yarn. The yarn elongation at break of HF-1 is close to that of HF-2, as seen from ***Table 2***. And also, no significant difference was found in the knitted yarn strength utilization factor, which means the HF-1 and HF-2 meshes are very similar. Most high-performance yarns are of the long filament type, whose elongation at break is related to twist. To improve the knittability, the elongation at break of yarns should be increased by reducing the twist coefficient [14,15].

3.3. Effect of bending stiffness on metallic yarns knittability

It can be seen from ***Tables 3*** and ***Table 7*** that the bending stiffness of metallic yarn is negatively correlated with knittability. The bending stiffness of LF-1yarn is close to that of LF-2 yarn, which is same for HF-1 and HF-2 yarns. The bending stiffness of LF-1 and LF-2 yarns is 3 times that of HF-1 and HF-2. From ***Table 7*** it can be seen the knitted yarn strength utilization factor of HF-1 and HF-2 is slightly higher than that of LF-1; that is, HF-1 and HF-2 yarns possess better knittablity. The knitted yarn strength utilization factor

Specimen specifications				Fracture strength (N)	Elongation at break (%)
LF-1mesh	Vertical	100mm×30mm	Average value	23.14	35.67
			CV%	14.68	18.87
	Horizontal	100mm×48mm	Average value	17.79	96.13
			CV%	8.24	5.9
LF-2 mesh	Vertical	100mm×45mm	Average value	29.30	52.23
			CV%	6.73	7.64
	Horizontal	100mm×40mm	Average value	23.68	72.63
			CV%	3.18	12.07
HF-1 mesh	Vertical	100mm×25mm	Average value	36.16	45.23
			CV%	7.49	2.56
	Horizontal	100mm×15mm	Average value	29.01	106.78
			CV%	7.98	2.45
HF-2 mesh	Vertical	100mm×25mm	Average value	30.4	44.40
			CV%	10.5	2.35
	Horizontal	100mm×20mm	Average value	25.93	126.10
			CV%	2.38	2.63

Table 6. Tensile properties of warp-knitted meshes

Mesh No.	Number of yarns in mesh		Strength of original yarn (N)	Strength of mesh (N)	Knitted yarn strength utilization factor (%)
LF-1	Vertical	80	1.67	23.14	17.3
	Horizontal	40		17.79	26.6
LF-2	Vertical	80	3.89	29.30	9.4
	Horizontal	40		23.68	15.2
HF-1	Vertical	80	2.16	36.16	20.9
	Horizontal	40		29.01	33.6
HF-2	Vertical	80	1.85	30.4	20.5
	Horizontal	40		25.93	35.0

Table 7.Yarn strength after conversion based on metallic warp-knitted meshes

	Fitting equations	R^2
Knitted yarn strength utilization factor in vertical direction y1	y1=24.022+0.22x1-987.742x2	0.998
Knitted yarn strength utilization factor in horizontal direction y2	y2=40.111+0.283x1-1672.848x2	0.998

Table 8. Fitting results of multiple linear regression

of HF-1 and HF-2 is twice that of LF-2, leading to a much better knittability. Therefore, a reduction in yarn bending stiffness could be achieved by reducing fiber fineness [16]. The knittability was complexly affected by both the yarns' stiffness and tensile strength. To some extent, bending stiffness may show a more significant effect.

3.4. Quantitative relationship between basic mechanical properties and knittability

It was shown that yarn elongation at break and yarn bending stiffness comprehensively affected the knittability of the yarns. To further investigate the quantitative relationship between yarn basic mechanical properties and yarn knittability, a multiple linear regression analysis was performed. The knitted yarn strength utilization factor was y1 and y2. The yarn elongation at break was x1, the yarn bending stiffness - x2, and the yarn breaking strength was x3. No reasonable fitting results were obtained. Based on the previous analysis, a reasonable fitting result should be obtained after removing the independent variable of the yarn breaking strength (x3). Results of the fitting of the knitted yarn strength utilization factor in the vertical and horizontal directions are shown in ***Table 8***.

As a result, a very strong linear relationship was found between y1(y2), x1, y1(y2) and x2. The coefficient (R2) of the prediction models was 0.998. The correlation between the elongation at break of yarn and the knitted yarn strength utilization factor was noticeable over 10% in both the vertical and horizontal directions. The correlation between bending stiffness and the knitted yarn strength utilization factor was over 5%. The yarn knittability could be quantitatively characterized by knitted yarn strength utilization factor. Therefore, the model shown in ***Table 8*** could be used to predict the yarn knittability of yarn based on the yarns' mechanical properties.

4. Conclusion

In this study, the knittability of metallic yarn was successfully quantitatively characterized by the knitted yarn strength utilization factor. The effect of yarn mechanical properties on the knittability was further studied, including tensile strength and bending stiffness. Yarn breaking strength has no relationship with yarn knittability. The elongation at break had a native correlation to knittability, while stiffness showed a more significantly positive correlation. Ultimately, metallic yarns' knittability should be improved by increasing yarn mechanical properties.

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