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Physical Properties of Para-Aramid/Nylon Hybrid Air Textured Yarns for Protective Clothing

Hyun Ah Kim and Seung Jin Kim[1]*

Korea Research Institute for Fashion Industry, Daegu 701-170, Korea
[1]*Department of Textile Engineering and Technology, Yeungnam University, Gyeongsan 712-749, Korea*
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Abstract: The physical properties of a para-aramid/nylon hybrid filament, such as the denier, tensile properties and thermal shrinkage, were examined according to the processing conditions of air-textured yarn (ATY), such as the yarn speed, air pressure, heater temperature, and overfeed ratio. The instability for identifying loop formation on the yarn surface was also measured and discussed. The yarn linear density increased with increasing overfeed of the core and effect and air pressure. The tenacity decreased with increasing core overfeed and air pressure, whereas the breaking strain increased. The initial modulus of the hybrid filament decreased with increasing core overfeed, air pressure and heat-set temperature of the heater. The instability of the hybrid ATY yarns increased with increasing heater temperature. The dry thermal shrinkage increased with increasing core overfeed, and the wet thermal shrinkage decreased with increasing effect overfeed. The core overfeed was found to be a key factor affecting the physical properties of the para-aramid/nylon hybrid ATY, whereas the air pressure was found to influence only the yarn mechanical properties. In addition, the heating temperature affected the instability of the para-aramid/nylon hybrid ATY. These results show that a low core overfeed and high effect overfeed are needed for good thermal dimensional stability to wet and dry heat during thermal treatment processes.

Keywords: Air textured yarn, Para-aramid/nylon hybrid, Air pressure, Overfeed, Instability, Thermal shrinkage

Introduction

Air-jet texturing is a mechanical yarn bulking process using compressed air to improve the textile properties and adhesion through the loop fiber and crimp on the yarn surface. Considerable deterioration of the tenacity and modulus of yarns is observed after texturing. On the other hand, air-jet texturing enhances the ability to interact with the imbedded resin through mechanical locking by the loop fiber and crimp on the yarn surface, which increases the interlaminar shear strength and provides additional resistance to crack propagation on fiber-reinforced composites. Many studies have examined the physical properties of yarn according to the ATY processing conditions [1-8] but there are still differences in their findings. Jang *et al.* [1,2] examined the effects of the processing parameters of the air-jet textured yarns of diacetate and polyester filaments. They focused on the properties of diacetate/polyester air-jet textured yarns produced under different overfeeds. They also reported the effects of the air pressure, texturing speed, winding under-feed ratio, and wetting on the physical properties of diacetate/polyester air-jet textured yarn [1]. Bilgin *et al.* [3] evaluated the effects of the geometric parameters on the texturing performance of the air-jet texturing nozzle. They also reviewed the roles of air flow, wetting and spin finish on the air-jet texturing process. Sengupta *et al.* [4] examined the influence of the initial modulus and filament linear density on the air-jet textured yarn properties of POY polyester, keeping the other parameters constant. Rengasamy *et al*. [5] reported the effects of different texturing process parameters and the feed yarn properties of a fully drawn polyester filament on the resulting textured yarn properties. Abromavicius *et al.* [7] studied the dependence of the polypropylene yarn properties and air pressure in an air texturing jet. They obtained slightly different results compared to the PET and nylon air jet textured yarns. The air-jet textured polypropylene yarns are used mostly in carpets, upholstery fabrics, and fabrics in the automotive industry because of their specific properties, such as strength, elasticity, high wearing resistance, and hydrophobicity. Chuah [8] also surveyed the bulk development of air-textured poly(trimethylene terephthalate) (PTT) bulky continuous filaments by varying two texturing parameters, such as yarn pre-heating and texturing hot air temperature. According to these studies, the tensile and dimensional properties of air-jet textured yarns are generally affected by the air pressure, texturing speed and different overfeed levels of the core and effect components. On the other hand, the variations in the physical properties of ATY according to the processing conditions of air jet texturing differed slightly according to the fiber materials, such as polyester, nylon, polypropylene, and their blends. Nevertheless, there is no consensus among researchers. PPTA (aramid) is used in protective clothing and coated technical textiles, such as thermoset composites, but aramid filaments are slick, which causes a poor hand and poor dimensional stability in woven fabrics. Air texturing is an elegant solution for improving the hand and dimensional stability of aramid fabrics. On the other hand, the adhesion between aramid and the epoxy matrix is poor, which causes failure of the composites due to delamination. Accordingly,

*Corresponding author: sjkim@ynu.ac.kr

the surface loops by air texturing might improve the mechanical interlocking and delay the onset of delamination. Chaithanya [9] examined the effects of the key processing parameters on the mechanical properties of poly(p-phenylene terephthalamide) air-jet textured yarns. Langston [10] measured the mechanical properties of air-textured aramid yarns and compared them to those of regular aramid yarn to better understand how the yarn structure affects the behavior of the composites. Dani [11] examined the tensile properties of air textured yarns using polyester tire cord yarn, dyneema and Kevlar by changing the overfeed and air pressure of the air jet processing parameters. Despite these studies, there are no reports on the physical properties of para-aramid/nylon hybrid filaments according to the processing parameters of air-jet textured yarn.

In the present study, the physical properties of air textured nylon/aramid hybrid yarns were examined systematically according to the ATY process parameters, and an experimental study was performed to determine the key process parameters affecting the physical properties of nylon/aramid hybrid ATY yarn.

Experimental

Specimen Preparation

Heracron®, as a para-aramid (840 d/655 f) and nylon (420 d/48 f) filament, was used as the core and effect component, respectively, to prepare the specimens on an AIKI air jet texturing machine with a Heberlein Hemajet T351 nozzle. Figure 1 shows a schematic diagram of the AIKI air jet texturing machine. The core yarn (1c) was wetted using a wetting device (4) with 1.0 L/h water consumption before entering the jet nozzle (2). The effect yarn (1e) was fed directly into jet nozzle (2). The air jet textured yarns combined with the core and effect yarns in the Hemajet nozzle were impacted with a baffle ball (5) and passed through the yarn guide (3). The core overfeed was adjusted by the ratio of the surface velocity of the 1st feed roller (F/R 1.1) to that of the 2nd feed roller (F/R 2). The effect overfeed was adjusted by the ratio of the surface velocity of the 1st feed roller (F/R 1.2) to that of the 2nd feed roller (F/R 2). Table 1 lists the specimens according to the ATY process conditions. Specimens 1, 2 and 3 were prepared using three different yarn speeds with the following conditions fixed: core overfeed (8.7 %), effect overfeed (16.7 %), and air pressure (10 kg/cm^2). Specimens 4 to 8 were prepared with 5 different core overfeeds, and specimens 9 to 13 were texturized with 5 different effect overfeeds. Specimens 14 to 18 were prepared at different air pressures, and specimens 19 to 23 were also prepared using 5 different heater temperatures with the following conditions fixed: speed (220 m/min), core overfeed (8.7 %), effect overfeed (16.7 %), and air pressure (10 kg/cm^2).

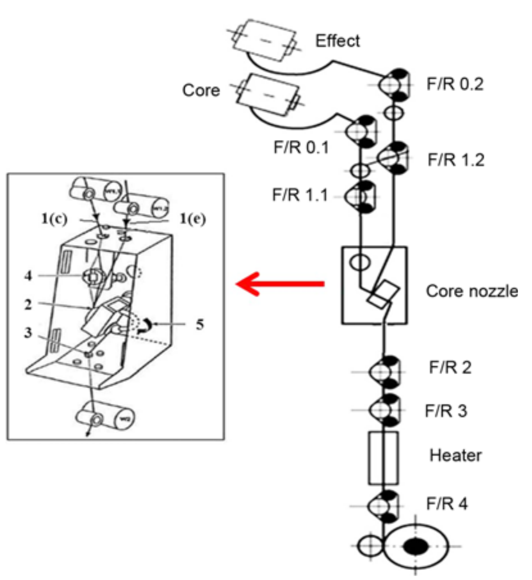


Figure 1. Schematic diagram of the air texturing machine.

Table 1. Process conditions for the hybrid ATY specimens

Specimen		Process condition		Fixed condition
ATY: 1260 d Core: PA (840 d) Effect: Ny (420 d)	1	Yarn speed (m/min)	200	Core: 8.7 %, no heater Effect: 16.7 % Air pressure: 10 kg/cm^2
	2		220	
	3		250	
	4	Core overfeed (%)	4.2	Speed: 220 m/min Effect: 16.7 % Air pressure: 10 kg/cm^2 No heater
	5		6.4	
	6		8.7	
	7		11.1	
	8		13.6	
	9	Effect overfeed (%)	12	Speed: 220 m/min Core: 8.7 % Air pressure: 10 kg/cm^2 No heater
	10		14.3	
	11		16.7	
	12		19.7	
	13		21.7	
	14	Air pressure (kg/cm^2)	7.5	Speed: 220 m/min Core: 8.7 % Effect: 16.7 % No heater
	15		9	
	16		10	
	17		11	
	18		12	
	19	Heater temperature (^{o}C)	150	Speed: 220 m/min Core: 8.7 % Effect: 16.7 % Air pressure: 10 kg/cm^2
	20		170	
	21		190	
	22		210	
	23		230	

Measurement of the Yarn Physical Properties

The physical properties of the specimens were examined (Table 2). The yarn linear density was measured by weighing 90 m of textured yarn wound on a wrap reel, and the tenacity, breaking strain and modulus, as the tensile properties of

Table 2. Measurement method of the yarn properties

Measuring item	Measuring equipment	Detail method	Remark
Yarn linear density	Wrap reel	Sample length: 90 m	KSK 0416
Yarn tensile property	Testometric MICRO 350	Sample length: 100 mm Test speed: 100 mm/min.	KSK 0520
Thermal shrinkage	Dry-(heat chamber) Wet-(water bath)	180 °C, 30 min. 100 °C, 30 min.	KSK 0215
Instability	Scale and weight		Heberlein method
Microscope	SV-55, SOMETECH	×40	Video type

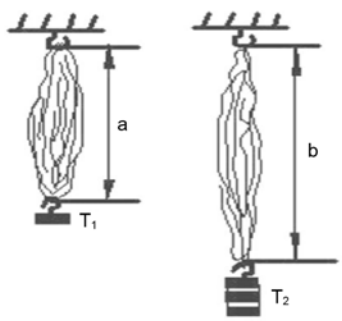


Figure 2. Schematic diagram of the instability tester [2].

yarn, were measured using a Testometric MICRO350, at a constant rate of the extension tensile tester, a gauge length of 100 mm and a crosshead speed of 100 mm/min. Twenty readings were taken for each specimen. The thermal shrinkage under wet and dry conditions was measured to control the dimensional stability in the thermal treatment process using a KSK 0215. Hanks were prepared by winding ten turns of the yarn on a wrap reel at a tension of 0.01 g/d. The length of the skein l_0 was measured at a tension of 0.2 g/d. The hanks were then placed into a bath of boiling water at a tension of 0.01 g/d for 30 minutes, and dried for 24 hours. The length of the skeins l_f was measured again under the same tension of 0.2 g/d, and the wet thermal shrinkage (%) was estimated using the following equation:

$$\text{Wet thermal shrinkage (\%)} = (l_0 - l_f) / l_0 \times 100.$$

The level of dry thermal shrinkage was also measured using the same procedure; only a dry thermal treatment was performed in a heat chamber at 180 °C. The yarn instability was measured using the Heberlein method, as illustrated in Figure 2. The hank was first tensioned for 1 minute with a load of approximately 0.009 g/d, and the length, *a*, was measured. A 0.45 g/d load was then substituted for the light load and applied for 1 minute. The length, *b*, was measured, and the instability *I* (%) was estimated using the following equation:

$$\text{Instability } I\text{ (\%)} = (b-a) / a \times 100.$$

The yarn surface profile was determined using a video microscope (SV-55, SOMETECH).

Results and Discussion

Mechanical Properties of ATY

Figure 3 shows the yarn linear density according to the ATY process parameters. The yarn linear densities increased between 30 d and 40 d with increasing overfeed of the core and effect, and increasing air pressure. This was attributed to an increase in the mass per unit length because of the relatively large number of loops of nylon effect filaments formed on the yarn surface. It was shown that the yarn linear density at core overfeed of 11.1 % critically decreased. According to an earlier study [11,12], as the overfeed is as low as around 10 %, the excess length of nylon filaments available to form loops is small, which makes low yarn linear density. This behavior is correlated with low dry heat shrinkage at core overfeed of 11.1 % as shown in the next Figure 5.

The hybrid yarn linear density was relatively unaffected by the heater temperature and yarn speed. The linear densities of the yarns (specimen no.19-23) heat treated on the ATY machine were 80 d lower than those of the untreated yarns (specimen no.11), which was attributed to the flat of the nylon filament loops on the effect component by the heat setting.

Figure 4 shows the yarn tensile properties according to the ATY process parameters. As shown in Figure 4(a), the tenacity of the hybrid ATY yarns was distributed from 6 g/d to 10 g/d. The yarn tenacity decreased significantly from 10 g/d to 6.5 g/d with increasing core overfeed, which was attributed to the smaller number of straight filaments to bear the load caused by the increasing entanglements among the para-aramid core filaments in the yarn. For the core and effect ATY yarns, the overfeed ratio of the core component was generally lower than that of the effect component [1]. This gives the core filaments a higher orientation with the textured yarn axis, and the tenacity is determined mostly by the core component [2]. This study revealed the effects of the yarn tenacity of the core overfeed but not of the effect overfeed. The yarn tenacity of the hybrid ATY yarn decreased from 8 g/d to 6 g/d with increasing air pressure due to the increased influence of the disorientation among the nylon filaments on the effect component at higher air pressures. According to previous studies [12], the non-uniform velocity

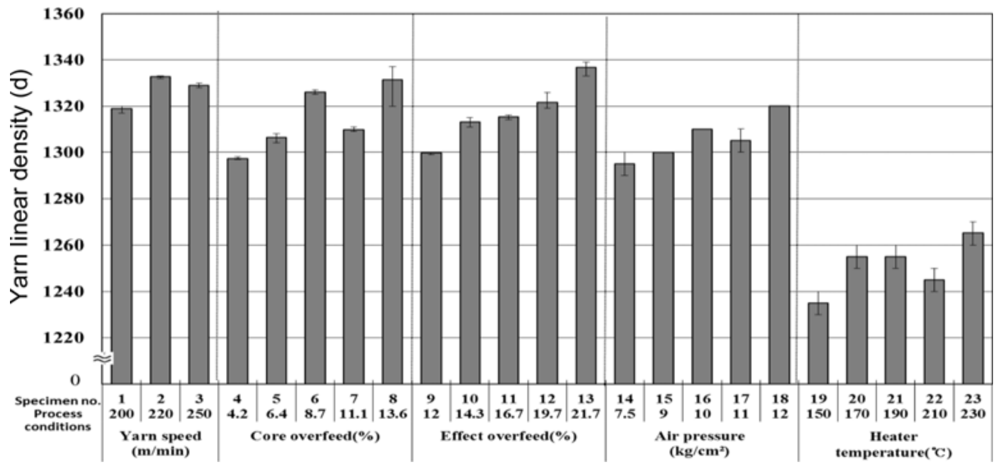
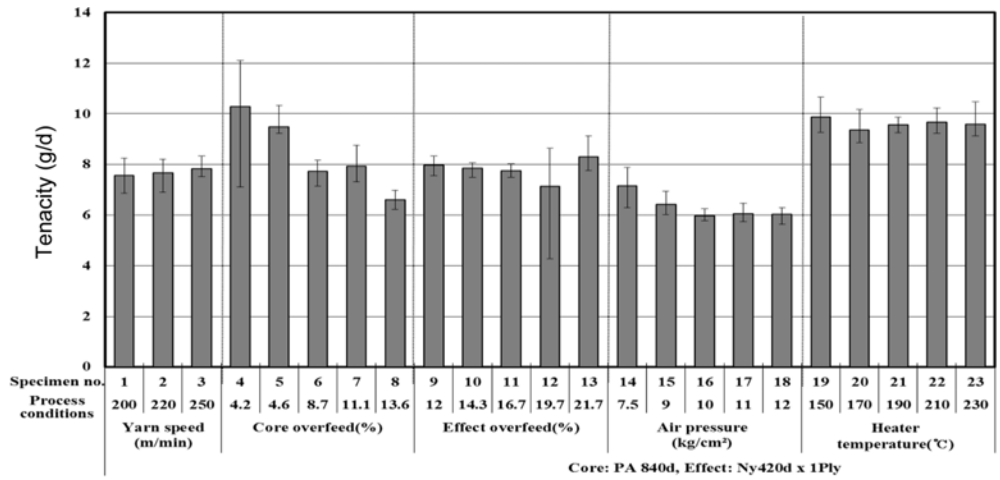


Figure 3. Yarn linear density according to the process parameters.

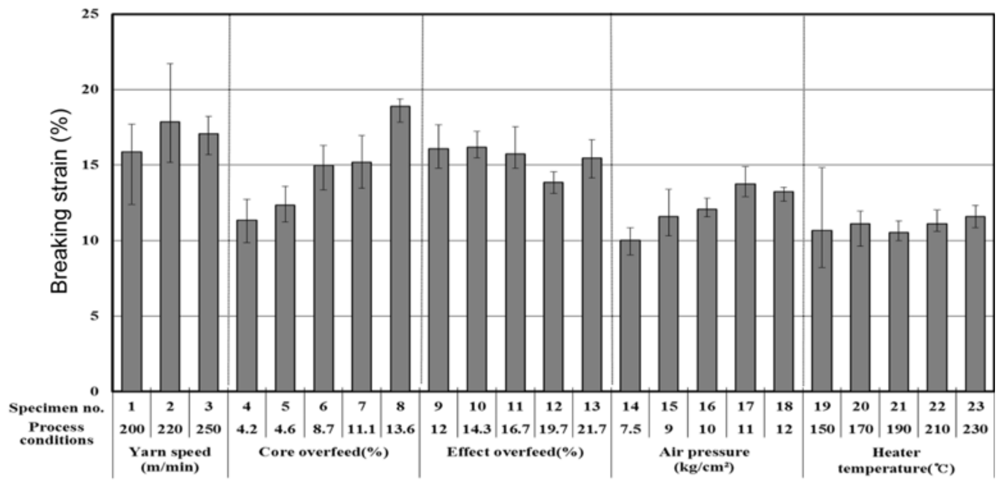
distribution and turbulence at the nozzle inside increases with increasing air pressure. On the one hand, Zhang *et al.* [1] explained that increasing air pressure makes the longitudinal displacement of nylon filaments on the effect component and become more effective, which makes the filaments to change their positions. This results in a smaller number of straight filaments to bear the load, which reduces the tenacity. On the other hand, the para-aramid filaments on the core component begin to bend with increasing air pressure, and both the entanglement and interlocking between the para-aramid core filaments increase, which leads to more compact yarn in the core component [1]. No changes in the hybrid yarn tenacity according to the feed speed, effect overfeed and heater temperature were noted but the tenacities of the yarns treated with the heat-set were 2 or 4 g/d higher than those of the untreated yarns due to a decrease in the yarn linear density by the heat-set treatment. According to earlier study [9], aramid ATY yarn tenacity increased with increasing yarn speed (from 100 m/min to 300 m/min.) and overfeed (from 30 % to 50 %). In this study, yarn speed was changed from 200 m/min to 250 m/min. and effect overfeed was changed from 12 % to 21.7 %, which was relatively small range comparing to earlier study, This results in the insignificant changes of ATY tenacity according to the feed speed and the effect overfeed. Insignificant change of ATY tenacity according to the heater temperature appears to be due to high thermal resistance of aramid filaments in the core component in the hybrid ATY.

Figure 4(b) shows the breaking strain according to the ATY process parameters. The breaking strain increased from 11 % to 18 % with increasing core overfeed, which can be explained by the larger extension due to the increase in entanglements among the core para-aramid filaments in the yarn. This result is in contrast to those obtained using triacetate and polyester filaments [1,2]. Those studies concluded that the breaking elongation increased with increasing effect overfeed, and decreased with increasing core overfeed. In the present study, the increased core overfeed increased the disorientation for the core component, which is responsible for the high breaking strain, because of the high smoothness (slick property) of para-aramid as the core component and the high strength of nylon as the effect component. The increased effect overfeed of the nylon component does not enable an increase in the number of large loops and does not affect the binding forces between the nylon filaments because of the high strength property of the nylon filament used as the effect component. Therefore, the breaking strain of the hybrid yarn does not show any change with increasing effect overfeed.

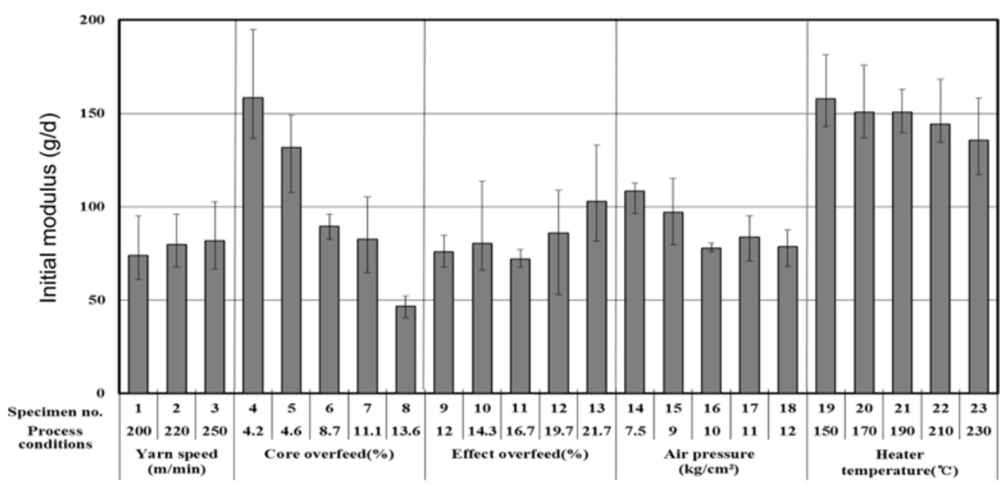
The breaking strain also increased from 10 % to 14 % with increasing air pressure due to the formation of many loops of the nylon effect filaments on the yarn surface caused by the high pressure. No change in the hybrid yarn breaking strain according to the feed speed, effect overfeed and heater temperature were found, but the breaking strains of the yarns treated with the heat-set were 2 to 8 % lower than those of the untreated yarns. Figure 4(c) shows the initial modulus as a function of the ATY process parameters. The initial modulus decreased from 158 g/d to 46 g/d with increasing core overfeed due to an increase in entanglements among the para-aramid filaments of the core component in the yarn and the size of the loop. The initial modulus of the yarns increased from 76 g/d to 102 g/d with increasing effect overfeed. This was attributed to the compact yarn structure of the hybrid ATY due to the effects of locking the core para-aramid and nylon effect filaments. The initial modulus of the hybrid yarn decreased by 30 g/d with increasing air pressure, which was attributed to the relatively large number of nylon loops in the effect component formed on the yarn surface. The initial modulus of the hybrid yarns also decreased gradually with increasing heater temperature, and the initial modulus of the yarns treated with the heat-set were much higher than those of the untreated yarns. This can be explained by an increase in the flat portion of the yarn structures caused by



(a) Tenacity



(b) Breaking strain



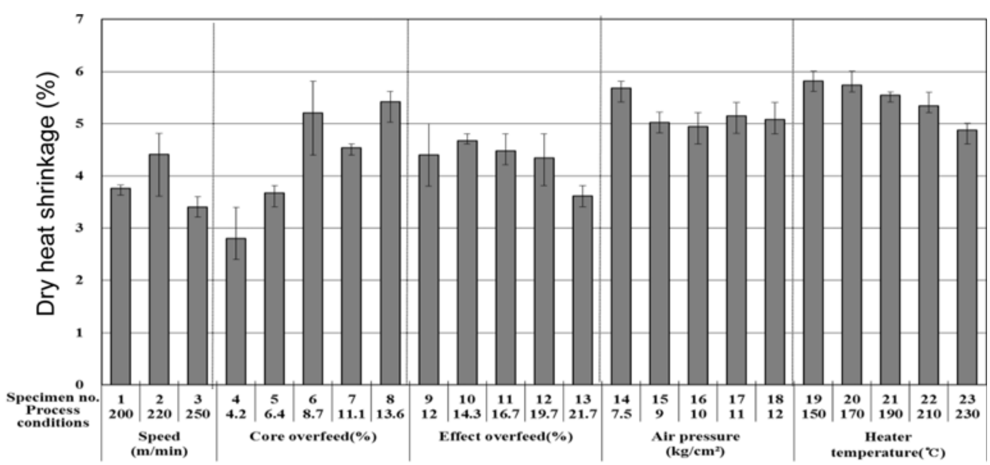
(c) Initial modulus

Figure 4. Tensile property according to the process parameters.

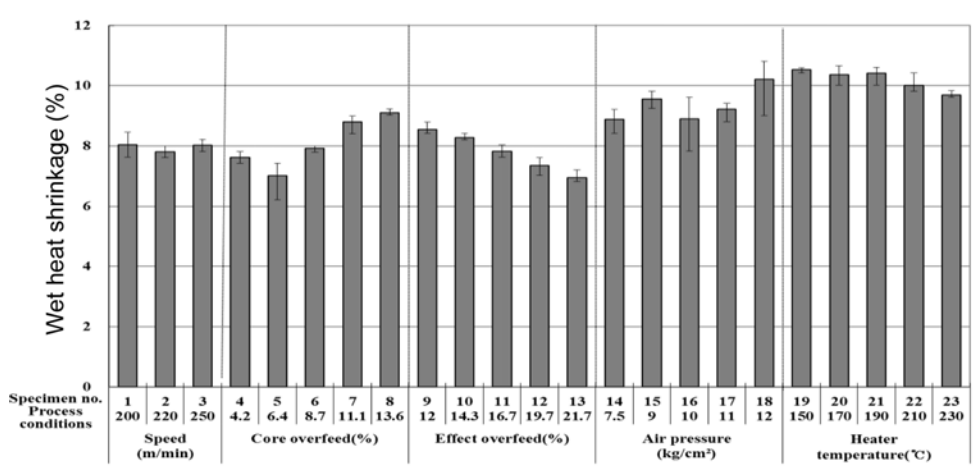
the heat-set treatment. Among the ATY processing parameters, the core overfeed had the greatest effect on the initial modulus.

Thermal Shrinkages of ATY

Figure 5 shows the thermal shrinkage according to the ATY process parameters. As shown in Figure 5(a), the dry shrinkage of the hybrid ATY yarns was distributed in the range, 3 % to 6 %, according to the processing parameters of ATY. The dry shrinkage increased from 2.8 % to 5.4 % with increasing core overfeed due to the relatively large number of entanglements of para-aramid filaments formed in the core part of the yarn. The dry shrinkage of the yarn decreased slightly from 4.7 % to 3.6 % with increasing effect overfeed. This was attributed to the compact yarn structure due to the effect of locking of the core and effect in the hybrid yarns, i.e. increasing the core overfeed makes the para-aramid of the core component more compact, which increases the dry heat shrinkage because of the bulky structure of the nylon filament of the effect component. On the other hand, increasing the effect overfeed makes the effect component of nylon locked and compact, which decreases the dry heat shrinkage because of the compact structure of the nylon filament of the effect component. The dry shrinkage of the hybrid yarn also decreased slightly with increasing heater temperature. This shows that the dry thermal shrinkage of the nylon filament in the effect component results in dry shrinkage of the para-aramid/nylon hybrid ATY. Increasing the heater temperature enables the nylon filaments to set on the surface of ATY, which decreases the dry thermal shrinkage. The dry heat shrinkage did not appear to be affected by the feed speed and air pressure in the nozzle. As shown in Figure 5(b), the wet shrinkage of the hybrid ATY yarns was distributed widely over the range, 7 % to 10 %, which is higher than dry shrinkage. The wet shrinkage increased with increasing core overfeed, and decreased from 8 % to 6 % when the effect overfeed was increased. This was attributed to the compact yarn structure, which was similar to that of



(a) Dry heat shrinkage



(b) Wet heat shrinkage

Figure 5. Thermal shrinkage according to the process parameters.

the dry shrinkage of the hybrid yarns. According to an earlier study [2], the effects of the core and effect overfeeds on thermal shrinkage showed no clear trend. They used diacetate and polyester as the effect and core components, respectively, which showed different results to the present study, because para-aramid and nylon was used as the core and effect components, respectively. No tendencies of wet shrinkage according to the feed speed and air pressure were found.

Instability of ATY

Figure 6 shows the instability of ATY according to the ATY process parameters. The instability of the hybrid ATY yarns ranged from 0.7 to 1.2. As shown in Figure 6, the instability increased with increasing feed speed, which is in contrast to the results of a previous study. Generally, at a lower texturing speed, the yarn structure becomes more closely packed because the filaments remain inside the jet for a longer time, resulting in better texturing [1]. Acar *et al.* [11,12] reported that the yarn stability was affected slightly by the increasing texturing speed. Zhang *et al.* [1], who used triacetate and polyester as the core and effect components, respectively, reported that the texturing speed affects the yarn stability significantly. In contrast to Acar *et al.* [11,12] and Zhang *et al.* [1], the present study found that an increased number of nylon loops on the effect component by the higher texturing speeds would increase the chance of being removed under an applied load, resulting in high instability. The instability of the hybrid ATY yarn decreased slightly with increasing effect overfeed, which is also in contrast to previous studies [1,2,11,12], because of the difference in the materials, such as para-aramid, nylon and polyester. In this study, the effects of the high overfeeds applied to the nylon filaments on the effect component not only led to a large number of entangled loops on the yarn surface, which enhanced the yarn compactness, but also reduced the chance of these loops from being pulled out during the test [2]. As shown in Figure 6, the instability initially decreased with increasing air pressure, and then increased. This suggests that the higher lateral forces of the nylon filaments of the effect component at the initially higher air pressure make the hybrid yarns more compact, resulting in high stability. A higher air pressure results in a larger number of loops on the nylon filaments on the effect component, resulting in an increase in yarn instability. The instability increased with increasing heater temperature due to a decrease in the elastic recovery of the yarn structure by the heat treatment.

Proposed Para-aramid/nylon Hybrid ATY Model

Figure 7 shows a video microscopy (SV-55, SOMETECT) image of the selected specimens. In summarizing the effects of the process parameters on the physical properties of the para-aramid/nylon hybrid ATY, the first key parameter is the core overfeed An increase in this parameter makes the para-aramid filament crimpy in the yarn core and produces entangling loops on the yarn surface, as shown in the No.4 and No.8 photographs in Figure 7. The high core overfeed specimen (No.8) showed a large number of entangled loops and large crimpy fibers, which resulted in an increase in linear density, breaking strain, dry and wet shrinkage, as well as decreasing tenacity and initial modulus. As the effect overfeed was increased, the loop formation was denser, which was attributed to the compact yarn structure by the effect of locking of the core and effect in the hybrid yarns. No.9 and 13 in Figure 7 show this yarn structure. These changes were found to be associated with the changes in the physical properties of the yarn, such as the increasing yarn linear density and initial modulus, and decreasing thermal shrinkage and instability. The loop formation of the yarns was tangled up when the air pressure was increased. This yarn structure is shown in No.14 and 18 in Figure 7. No.18 in Figure 7 shows a large number of loops and considerable fluff on the yarn surface due to an increase in disorientation

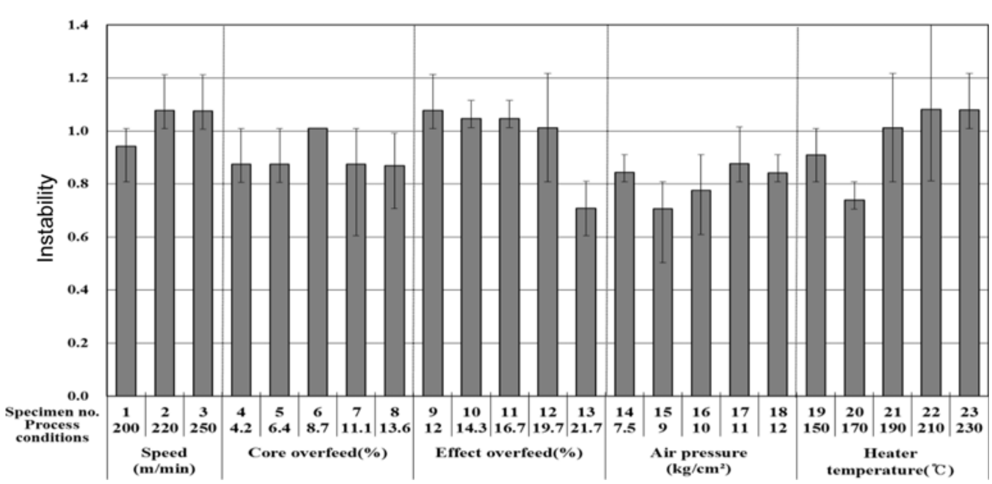


Figure 6. Instability according to the process parameters.

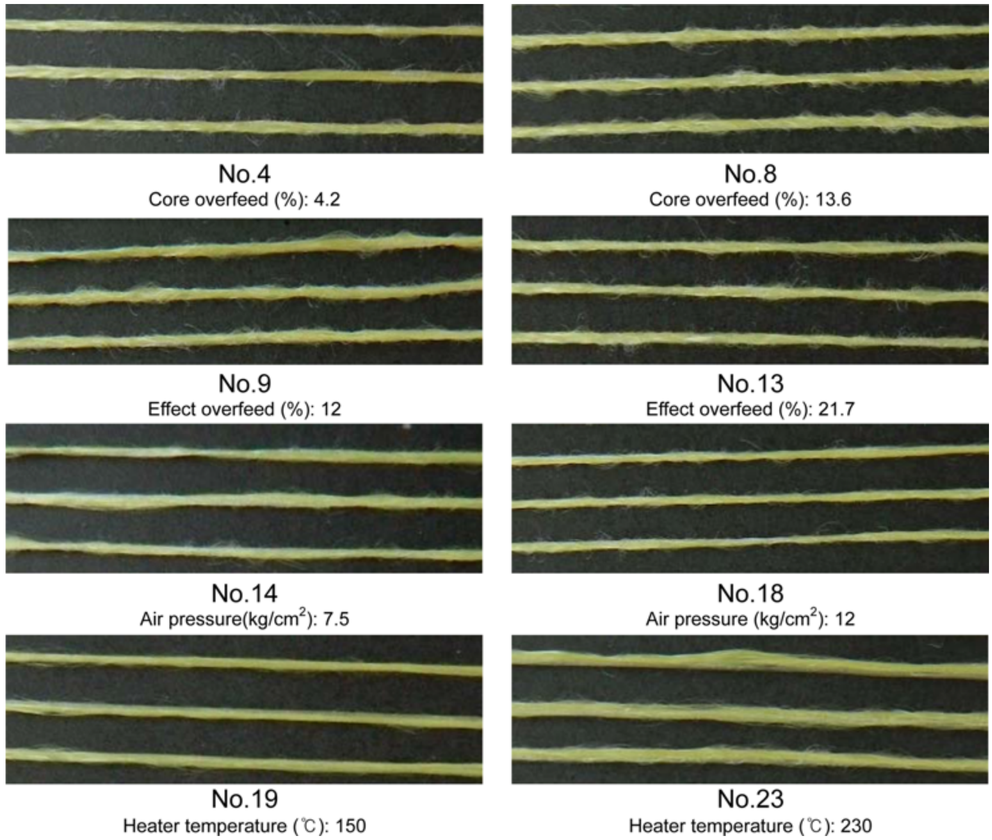


Figure 7. Microscopy images of the specimens.

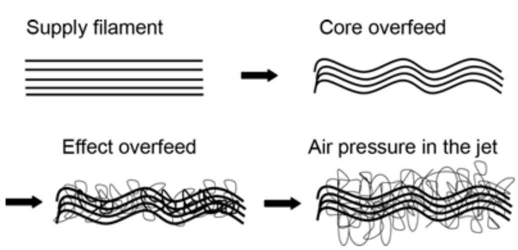


Figure 8. Proposed para-aramid/nylon hybrid ATY yarns model.

with increasing air pressure, which deteriorates the yarn physical properties, such as tenacity and initial modulus. In contrast, the linear density and breaking strain were high. The loop formation of the hybrid yarns was not affected significantly by the heater temperature. The initial modulus, wet and dry shrinkage decreased slightly, and the instability increased with increasing heat set temperature. This appears to be due to a decrease in the elastic recovery of nylon filaments treated with high temperatures. No.19 and No.23 in Figure 7 show the yarn surface profile related to the heat temperature. The para-aramid/nylon hybrid ATY yarn model was proposed (Figure 8) considering the yarn physical properties with the microscopy image. The crimp of the para-aramid in the core component was determined by the core overfeed. The effect overfeed resulted in entanglement of the nylon filaments on the effect component. The air pressure in the jet nozzle to provide more entanglement of the nylon filaments on the effect component of the hybrid ATY was estimated.

Conclusion

The heat set treatment of para-aramid/nylon ATY hybrid yarns decreases the yarn linear density. The core overfeed is a key factor affecting the physical properties of para-aramid/nylon hybrid ATY yarns, which determines the crimp in the yarn core and entangled loops on the yarn surface. The effect overfeed is related to the increase in initial modulus, decrease in thermal shrinkage and high stability of ATY with increasing overfeed, which is estimated to be a compact yarn structure caused by locking of the core and effect filaments with increasing effect overfeed. The air pressure affects only the yarn mechanical properties, such as the tenacity, breaking strain and initial modulus. This suggests that increasing the air pressure produces a large number of loops and considerable fluff on the yarn surface, as well as causing high levels of disorientation of the filaments in the yarn core. The heat setting treatment affects the instability of the hybrid ATY yarns. High temperatures increase the yarn instability due to a decrease in the elastic recovery of the para-aramid/nylon hybrid ATY yarns. In particular, both low core and high effect overfeeds are required for good dimensional stability, i.e. low thermal shrinkage. Yarn physical properties of Aramid/nylon hybrid ATY such as linear density, breaking strain and thermal shrinkage were highly correlated with each other and increased with increasing core overfeed and air pressure. The tenacity and initial modulus were also correlated and decreased with increasing core overfeed and air pressure. In particular, effect overfeed and heater temperature affected initial modulus and dry and wet thermal shrinkages, and yarn linear density was affected and increased with all kinds of processing parameters.

Acknowledgement

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References

1. J. Zhang, Z. Zhang, S. Wang, and X. Qing, *Fiber. Polym.,* **8**, 427 (2007).
2. J. Zhang, Z. Zhang, S. Wang, and X. Qing, *Fiber. Polym.,* **8**, 84 (2007).
3. S. Bilgin, H. K. Versteeg, and M. Acar, *Text. Res. J.,* **66**, 83 (1996).
4. A. K. Sengupta, V. K. Kothari, and J. K. Sensarma, *Text. Res. J.,* **66**, 452 (1996).
5. R. S. Rengasamy, V. K. Kothari, and A. Patnaik, *Text. Res. J.,* **74**, 259 (2004).
6. M. Acar, S. Bilgin, and H. K. Versteeg, *Text. Res. J.,* **76**, 116 (2006).
7. R. Abromavicius and R. Milasius, *Fibers Text. East. Eur.*, **17**, 48 (2009).
8. H. H. Chuah, *J. Appl. Polym. Sci.*, **92**, 1011 (2004).
9. C. Renduchintala, M. S. Dissertation, NCSU, North Carolina, USA, 2002.
10. B. L. Thomas, M. S. Dissertation, NCSU, North Carolina, USA, 2003.
11. A. Demir, M. Acar, and G. R. Wray, *Text. Res. J.*, **58**, 318 (1998).
12. M. Acar and G. R. Wray, *J. Text. Inst*., **77**, 377 (1986).