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Study of maximum tensile strength of fancy yarns using the design of experiments

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Abstract. This study was conducted to identify the factors and the interactions which affect the maximum load of multi-thread fancy yarns. The objectives of this research was to identify the relative contribution of each factor and interaction leading to the maximisation of the tensile strength. The fancy yarns were made on a hollow-spindle spinning machine. The experimental design of this study had seven factors – with two levels each and was repeated five times. It was found that using two single yarns, instead of a similar two-ply yarn, for the core component increased the value of maximum load. The effect component contributed positively to the load only when it was a three-ply cotton yarn rather than a three-ply bamboo yarn since the former had interactions with the core and the binder. Excessive wraps reduced the maximum load. The effect of the overfeed ratio on the maximum load was weak. The manufacturing process in general had low levels of variability. This research is important because it contributes to a broader understanding to the effect of seven factors on the structure, quality, and mechanical properties of multi-thread fancy yarn.

Keywords: Fancy yarns / tensile strength / design of experiments / hollow-spindle spinning system

1 Introduction

Fancy gimp yarn is a composite novelty yarn that can be made on conventional doubling and twisting machines in a two-stage process or in a one-stage process on hollow-spindle spinning machines. Studying the load of fancy yarns is important to predict the strength of fabrics and clothes made of those yarns. When the hollow-spindle system was used to make the fancy yarns, several researchers conducted experimental studies to understand fancy yarns and their properties and to advise on the best practice for their designs [1–6]. In a study on two types of differential-twist wrapped yarn, the first yarn was made of a multi-filament wrapping a drafted roving while the second yarn was made of a filament wrapping a yarn. These two composite yarns were processed separately by a further twisting stage. It was found that the tenacity of those two composite yarns had a positive relationship with both the twisting twist and the wrapping twist. However, the tenacity decreased when the sum of both types of twist reached 900 tpm. Moreover, the tenacity was higher for the yarn which was made from a multi-filament wrapping a drafted roving. Similarly, the evenness of the differential-twist wrapped yarns, except for the yarn produced from a filament wrapping a yarn, improved after the second twisting stage when raising both the wrapping twist and the twisting twist [6]. In another research on overfed fancy yarns, it was reported that decreasing the supply speed while increasing the delivery speed (i.e. reducing the overfeed ratio) led to an increase in the breaking tenacity [1].

Two more comprehensive studies were also conducted by Nergis and Candan who used input yarns which were different in various aspects, i.e. being single or plied, coarse or fine, standard or high bulk [7,8]. Those two studies also accounted for the influence of the wrapping direction of the binder, whether Z or S, on the bouclé yarn structure. The bouclé yarns of those studies were made in a one-stage process by a combined system of a hollow-spindle and a ring spindle. The results showed that the number of the effect profiles for the 100% overfed s-wrapped yarns was higher than those made at a 200% overfeed ratio. However, when the Z-wrapping was used, opposite results were reported. Further, following the use of coarser input yarns, a significant increase in the average number of the profiles was reported. Moreover, the average height of the effect profiles was slightly greater for the Z-wrapped yarns than

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those of the S-wrapped yarns. The previous two studies gave consistent results regardless of the type and number of the input yarns. They also showed that the structure of the resultant multi-thread bouclé yarn is more influenced by the manufacturing conditions than the type of material of the components. However, since the numerical results were not exactly the same, this suggests that the type, number, and properties of the input yarns may also be important for the structure of multi-thread bouclé yarn. This particular concept is important and can be built upon to start a new investigation.

Further, a study was conducted to study the effect of the supply speed, the delivery speed, and the rotational speed of the machine on the number of plain knot-knot fancy profiles made of various loops of the final fancy yarn [2]. This study resulted in an informative and significant statistical model for the relationship between these three input factors and the number of these fancy profiles. However, this research was not exhaustive in terms of combinations of manufacture parameters, yarn count, yarn types, and tension of the input yarns. Further, it did not implement all types of final effect profiles in the discussion and analysis. Following this study, the same author conducted a similar study, using the same methodology, but making fancy yarns from two linen effect input yarns (components). The new study resulted in another informative regression model expressing the relationship between the same three technological parameters and the number of open loop-arc effect profiles, in the unit of length, of the fancy yarn [3]. This relationship was proportional to the overfeed ratio but inversely proportional to the number of wraps. Again these three factors (the supply speed, the delivery speed, and the rotational speed) were used to design a three-level experiment to determine their influence on the height and the width of the effect profiles and the number of profiles in the unit length of the final fancy yarn [4]. In another study, the effect of these three factors and their interaction on linear density and distance between the effect profiles was measured [5].

In a recent study, the effects of false-twist on structure and tensile properties of multi-thread gimp and overfed fancy yarns were reported. Several incomplete breaks and corresponding peaks were observed in the load-extension charts which indicated that those fancy yarns had been subjected to several breaks before the whole structure failed completely [9]. The multiple-break of the structure is a unique feature for multi-thread fancy yarns that is unseen in traditional ply yarns. Further, any textile structure made from such multi-thread fancy yarns, such as fabrics and clothes, may become weak and lose their stability as soon as the core yarn breaks for the first time. However, the fancy yarns may still be able to withstand further increases in the load until it reaches a maximum value or until the fancy yarn breaks completely.

More recently, the structural properties, texture, and aesthetic qualities of multi-thread gimp yarns and overfed fancy yarns were studied in detail [10]. In this study, the influences of the overfeed ratio, the number of wraps, the component properties and the machine settings on the structure and quality parameters of the final fancy yarn were reported. This study showed that using two single yarns, instead of one two-ply yarn, in the core of the gimp yarns, gave positive benefits to the gimp yarn structure. Those benefits included reductions in the number, size, and circularity ratio of non-gimp profiles. Moreover, a thicker, 167/34, textured polyester binder also decreased the number of non-gimp profiles and made them smaller than the case of a thinner, 145/77, regular nylon binder [10].

When considering the effect of tension of the core yarn on the final bouclé yarn structure, it was found improvement of the bouclé yarn structure could be made using a low level of tension [11]. The improvements included increases to the number of bouclé profiles, reductions to the variability of the size of bouclé profiles, increases the circularity ratio of fancy profile, and obtaining regular spiral and sigmoidal sections and wavy corrugations between the fancy profiles. Following this, the influence of the overfeed ratio, the number of wraps, the component properties, and the machine settings on the linear density of fancy yarn was also studied [12]. To complete those two studies by accounting for the maximum tensile strength of the final fancy yarns, the current study was conducted. Further, this study was built upon the same fractional experimental design and materials. Combining those studies may give a comprehensive and rounded understanding of fancy yarns.

2 Methodology

Seven factors were used with two levels for each factor. Factor A was the material type, form, and thickness of the core component. Factor B was the material type, form, and thickness of the binder. Factor C was the material type, form, and thickness of the effect component. Factor D was the supply speed of the effect component. Factor E was the rotational speed of the hollow-spindle. Factor F was the delivery speed of the final gimp yarn. Factor G represented the use the false-twist hook at the bottom outlet-hole of the hollow spindle. Due to the high number of factors and levels, and because of the possibility of interactions between some factors, the technique of design of experiments (DOE) was used. Further, a fractional experimental design was used instead of the full factorial design in order to reduce the high number of trials which would be necessary to conduct the experiment in the case of a full factorial design, i.e. $2^7 = 128$ trial. This fractional factorial design was the same orthogonal array that was used previously [10,12] and as given in Table 1.

This study also implemented the 'Taguchi' philosophy, but used separate mean and standard deviation values instead of the signal-to-noise ratios therefore it shows how altering a factor's average response could affect the process variation. The general alias structure for the main effects and two-level interactions in such a design is

Table 1. The fractional experimental design of the experiment.

Random order of the trials	Standard order of the trials	Level of Factor A	Level of Factor B	Level of Factor C	Level of Factor D	Level of Factor E	Level of Factor F	Level of Factor G
5	1	−1	−1	−1	1	1	1	−1
2	2	−1	−1	1	1	−1	−1	1
4	3	−1	1	−1	−1	1	−1	1
1	4	−1	1	1	−1	−1	1	−1
6	5	1	−1	−1	−1	−1	1	1
7	6	1	−1	1	−1	1	−1	−1
3	7	1	1	−1	1	−1	−1	−1
8	8	1	1	1	1	1	1	1

given by the following [13]:

$$\left\{\begin{array}{l} A = B*D = C*E = F*G; \\ B = A*D = C*F = E*G; \\ C = A*E = B*F = D*G; \\ D = A*B = E*F = C*G; \\ E = A*C = B*G = D*F; \\ F = A*G = B*C = D*E; \\ G = A*F = B*E = C*D \end{array}\right\}. \tag{1}$$

This alias structure gives the factors and interactions which are confounded. Levels (−1) and (+1) of the factors were identified by practical restraints such as machine speeds, availability of materials, etc.

The strategy that was used to deal with the alias structure was the use of Pareto charts and probability plots to reduce the alias structure to simple forms [13]. The reduced, simplified alias structure was dealt with using knowledge of fancy yarn structure and its method of manufacture on hollow-spindle machines to obtain the final real factors and interactions [10,12]. For factors which appear to have a high effect on the Pareto chart but appear to be weak on probability plots, probability plots take precedence and the factors will normally have weak individual effects [13]. However, it is wise to recognise their interactions as real factors should such interactions appear.

Materials of different types were used in this study, all of which were yarns: single, plied, and multi-filament. These yarns were made on different manufacturing systems therefore they had different structures or tensile properties as shown in Table 2 which also gives the hollow-spindle machine settings. The input yarns were preconditioned, then conditioned in accordance with British Standard BSI: BS EN ISO 139:2005. Following this, they were tested in accordance the British Standard BSI: BS EN ISO 2062:2009 to obtain their tensile properties (Tab. 2).

The gimp yarns were produced on a Gemmill & Dunsmore 3 hollow-spindle spinning machine (UK). The eight experimental trials were randomised to minimise relation bias. The experimental design (i.e. all trials) was repeated five times (i.e. five replicates) on three successive days, in the same random order of the first replicate. For each replicate, samples of 20 specimens each were randomly selected from the fancy yarns to test them. Those specimens were first pre-conditioned and then conditioned in accordance with British Standard BSI: BS EN ISO 139:2005. Following this, they were tested on an Instron Tester in accordance with the British Standard BSI: BS EN ISO 2062:2009 thus values of maximum load imposed on the gimp yarns were obtained when they broke.

3 Results and analysis

The data collected from the five replicates related to maximum load are given in Table 3 where the individual results of the replicates were averaged from 20 measurements. The average and standard deviation for each trial were calculated by considering the averages of the replicates horizontally across Table 3.

To estimate the contribution of each factor level, and each factor, to maximum load a *response table* (Tab. 4) was used [12,13]; Suitable statistical software can also be used instead of response tables for the same purpose. The average values of the trials given in Table 3 regarding maximum were used to complete Table 4. The estimated effects for the first level (−1) and the second level (+1) of each factor are given in the second bottom row of Table 4. The estimated effect of a factor when its value changes from level −1 to level +1 can be calculated by subtracting its response at level −1 from the response at level +1. By doing so, the estimated values of each factor level on maximum load are given in the bottom row of the response table (Tab. 4). A similar procedure was followed regarding the standard deviations for this property.

The estimated effects of the factors on maximum load were represented in a Pareto chart in Figure 1. This chart indicated that the weakest factor was Factor B (the binder). This factor was deleted from the analysis because it was not expected to be involved in any two-factor interaction [13].

Initially, it was difficult to use the knowledge of the manufacturing process to define whether the factors or

Table 2. Factors' description and their levels.

Factor	Level	Description	Usage	Elongation at maximum load (mm)	Extension at maximum load (%)	Maximum load (cN/tex)
A	−1	An open-end rotor-spun cotton yarn; Ne = 20s	Core component	19.23	7.6	327.74
	1	Two-ply combed ring-spun cotton yarn; Ne = 30 s/2		23.90	9.5	540.91
B	−1	A textured multi-filament polyester yarn, 34 filament; 16.7 tex/34 f	Binder	103.32	40.9	609.04
	1	A multi-filament nylon yarn, 77 filaments; 14.5 tex/77 f		86.77	34.7	418.36
C	−1	A three-ply ring-spun yarn made of chemically spun bamboo fibres; Ne = 24 s/3	Effect component	44.85	17.9	980.6
	1	A three-ply carded ring-spun cotton yarn; Ne = 30 s/3		24.59	9.8	942.3
D	−1	85 m/min	Supply speed	Not relevant	Not relevant	Not relevant
	1	95 m/min		Not relevant	Not relevant	Not relevant
E	−1	16 000 rpm	Rotational speed	Not relevant	Not relevant	Not relevant
	1	21 000 rpm		Not relevant	Not relevant	Not relevant
F	−1	60 m/min	Delivery speed	Not relevant	Not relevant	Not relevant
	1	70 m/min		Not relevant	Not relevant	Not relevant
G	−1	Not using the false-twist hook	Usage of false twist	Not relevant	Not relevant	Not relevant
	1	Using the false-twist hook		Not relevant	Not relevant	Not relevant

Table 3. The results of the five replicates of the main experimental design related to maximum load of the fancy yarns.

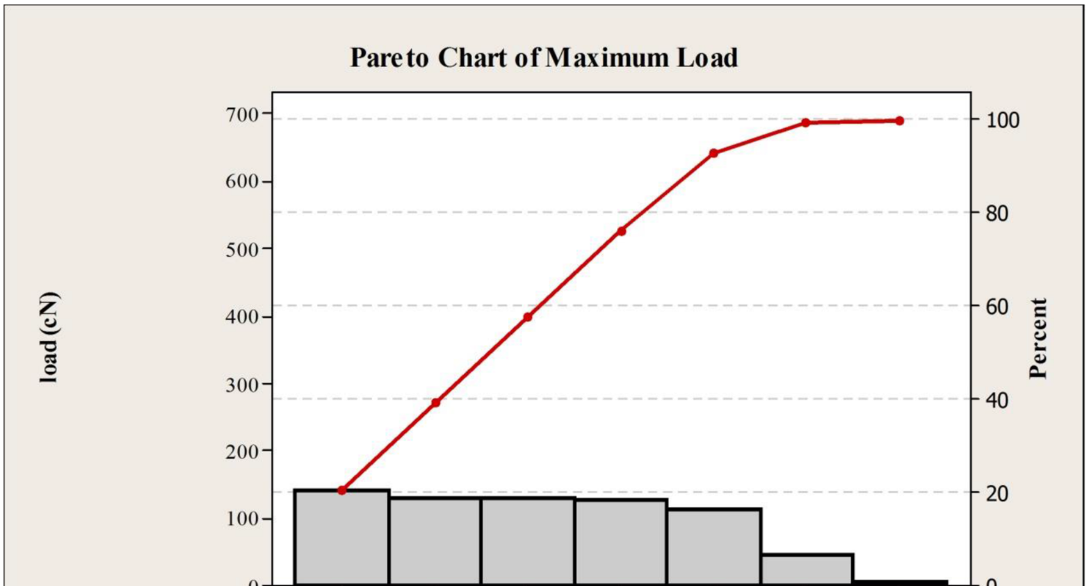
Standard-order trial number (randomised-order trial number)	Value measured for						
	Replicate 1	Replicate 2	Replicate 3	Replicate 4	Replicate 5	Average of trial	Standard deviation of trial
1 (5)	1016.93	907.72	995.60	976.29	1030.99	985.51	48.20
2 (2)	1046.49	1081.45	1070.57	1051.28	1084.96	1066.95	17.41
3 (4)	1021.74	905.23	987.07	905.82	954.09	954.79	50.94
4 (1)	1376.67	1389.59	1380.50	1427.77	1364.42	1387.79	24.11
5 (6)	1102.24	1122.55	1082.61	1072.29	1099.88	1095.91	19.37
6 (7)	1042.05	1019.47	987.91	996.78	1000.72	1009.39	21.59
7 (3)	885.21	882.05	875.73	863.90	869.42	875.26	8.78
8 (8)	985.61	903.62	932.95	958.98	1010.16	958.26	42.04

their confounded interactions were responsible for the effect on maximum load. Subsequently, to analyse those results, the probability plot in Figure 2 was used instead. The factors which deviate from the normal line usually have real effects whereas factors which are close to the normal line or located on it might not be important factors and should be discarded from the analysis [13].

The point representing Factor *B* was tangent to the probability line therefore it confirmed the weakness of the binder. The point representing the false twist (*G*) was also close to the probability line which indicates that it was a relatively weak factor. The point representing Factor *F* was on the probability line therefore this factor was not real and one of its alias structures may claim the effect on maximum load. The point representing the rotational speed (*E*) was also close to the probability line, so this factor was not real [13]. The influence of Factors *F* and *E* on the maximum load appeared to be high on the Pareto chart but they are

Table 4. Response table for maximum load.

Random order trail number	Standard order trail number	Response observed values	Factor A The core yarn (Ne)		Factor B The binder yarn (dtex/filaments)		Factor C The effect or profile yarn (Ne)		Factor D Supply speed (m/min)		Factor E Rotational speed (rpm)		Factor F Delivery speed (m/min)		Factor G False twist	
			Level −1 2 × 20 Cotton	Level +1 30/2 Cotton	Level −1 Polyester 167/34	Level +1 Nylon 145/77	Level −1 24/3 Bamboo	Level +1 30/3 Cotton	Level −1 85	Level +1 95	Level −1 16 000	Level +1 21 000	Level −1 60	Level +1 70	Level −1 No	Level +1 Yes
5	1	985.51	985.51		985.51		985.51			985.51		985.51		985.51	985.51	
2	2	1066.95	1066.95		1066.95			1066.95		1066.95	1066.95		1066.95			1066.95
4	3	954.79	954.79			954.79	954.79		954.79			954.79	954.79			954.79
1	4	1387.79	1387.79			1387.79		1387.79	1387.79		1387.79			1387.79	1387.79	
6	5	1095.91		1095.91	1095.91		1095.91		1095.91		1095.91			1095.91		1095.91
7	6	1009.39		1009.39	1009.39			1009.39	1009.39			1009.39	1009.39		1009.39	
3	7	875.26		875.26		875.26	875.26			875.26	875.26		875.26		875.26	
8	8	958.26		958.26		958.26		958.26		958.26		958.26		958.26		958.26
Total		8333.86	4395.04	3938.82	4157.76	4176.1	3911.47	4422.39	4447.88	3885.98	4425.91	3907.95	3906.39	4427.47	4257.95	4075.91
Number of values		8	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Average		1041.73	1098.76	984.71	1039.44	1044.03	977.87	1105.60	1111.97	971.50	1106.48	976.99	976.60	1106.87	1064.49	1018.98
Effect of each factor				−114.055		4.585		127.73		−140.475		−129.49		130.27		−45.51



Factors	D	F	E	C	A	G	Other
maximum Load (cN)	140.5	130.3	129.5	127.7	114.1	45.5	4.6
Percent	20.3	18.8	18.7	18.5	16.5	6.6	0.7
Cum %	20.3	39.1	57.8	76.3	92.8	99.3	100.0

Fig. 1. Pareto chart of maximum load of the fancy yarns showing the individual effect of factors (bars) and cumulative effect (%) of factors (red line).

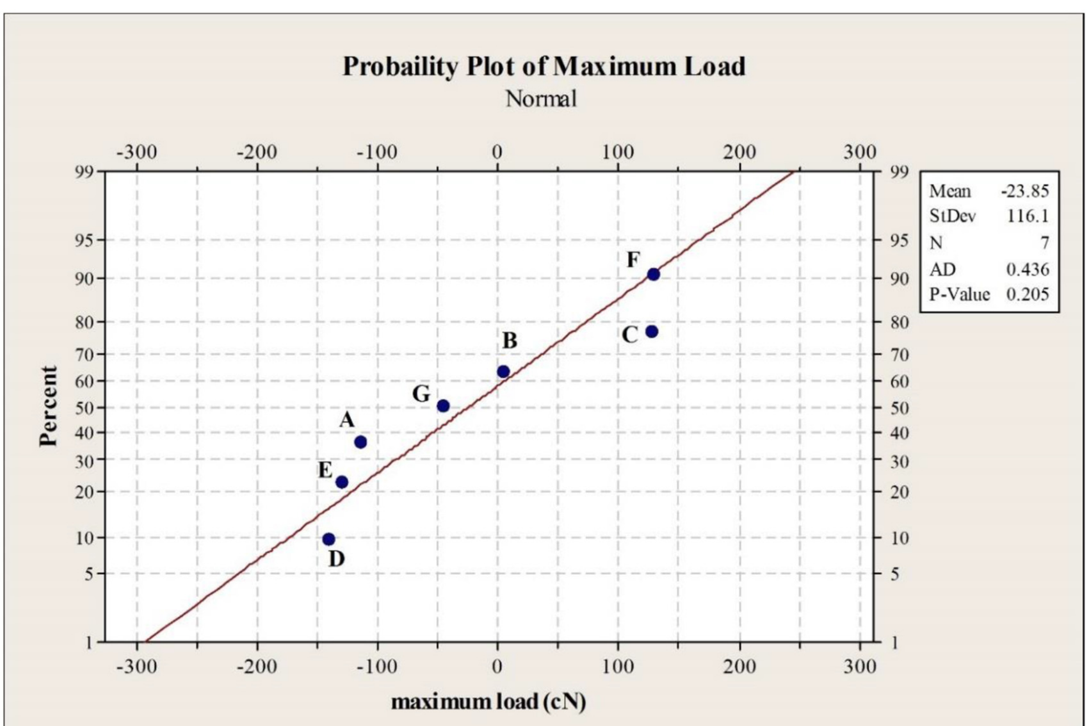


Fig. 2. Normal probability plot of maximum load.

Table 5. The results of the statistical study of the regression model of maximum load.

Predictor	Coefficient	t-test	p-value of the t-test	Accuracy of the fitted regression line	p-value of the ANOVA test
Constant	1716.98	29.07	0.022	SE = 6.48	0.030
A	−22.8110	−24.88	0.026		
C	63.865	27.86	0.023		
D (=E*F)	−14.0475	−30.64	0.021	$R^2 = 100.0\%$	
E (=A*C)	−0.0258980	−28.24	0.023		
F (=D*E)	13.027	28.41	0.022	R^2 (adj) = 99.8%	
G (=C*D)	−45.51	−9.93	0.064		

weak on probability plots. Therefore, F and E were considered to represent a strong interaction pattern. After eliminating the weak factors B, F, G, and E, the previous full alias structure was reduced to:

$$\left\{\begin{matrix} A = C * E; \quad C = A * E; \quad D = E * F; \\ A * C = D * F; \quad D * E \end{matrix}\right\}. \qquad (2)$$

To further identify the main factors and interactions, the knowledge of gimp yarn structure and its manufacturing process on hollow-spindle spinning machines was used define the real factors and interactions of the reduced alias structure. Since using stronger materials for the components usually increases the strength of the final gimp yarn, the core component (Factor A) and the effect yarn (Factor C) had real main effects on maximum load. Consequently, both the core component and the effect component had a real two-factor interaction therefore the interaction $A * C$ was responsible for the effect instead of the interaction $D * F$. Further, the structure of multi-thread gimp yarn is fastened and stabilised due to the wraps of the binder therefore the interaction $E * F$, which represents the number of wraps, was responsible for the effect on maximum load instead of Factor D.

In summary, the factors and interactions which had real influence on the maximum load were: Factors A and C; interactions $E * F$, $A * C$, and $D * E$. These factors and interactions were used to build up a regression model for maximum load using Minitab 15 as follows:

$$\begin{aligned} \text{Maximum load (cN)} = 1717 - 22.8\,A + 63.9\,C \\ - 14.0\,D - 0.0259\,E \\ + 13.0\,F - 45.5\,G \end{aligned} \qquad (3)$$

where A, B, and C are the English Counts based on the Cotton System (Ne) for the core, the binder, and the effect yarns, respectively (h/lb). The choice of the English count was only to account for the weight of the yarns and the Titre-tex system or the metric system can be used instead; D and F are supply speed and delivery speed, respectively (m/min); E is the rotational speed of the hollow spindle (rpm); and G represents the false twist and it takes the value (+1) if used or (−1) if not.

The results of the statistical studies of this model are given in Table 5. The overall significance of the model was secured since the p-value of the ANOVA testing was smaller than the significance $\alpha = 0.05$. This p-value meant that this model did explain significant portions of the variation in the output value by the variation in the input values. Additionally, the significance of the individual terms included in the model was secured since the p-values of the t-test were smaller than $\alpha = 0.010$. Moreover, the fitness of the regression line to the data was also high since the value of the c*oefficient of determination* (R^2) was also high. The value of the s*tandard error of estimate* (SE) was compared with the constant of the process regarding the maximum load, as given in Table 4.

The standard deviation (SD) of the process regarding the maximum load was 29.6 cN while the average was 1041.73 cN therefore the value of coefficient of variation (CV) was 2.86%. The sources of this variability were: Factor E by 37.9%, Factor A by 19.9%, Factor F by 14.2%, and Factor G by 11%. The contribution of these factors was 83% of the value of standard deviation.

It is worth mentioning that for those fancy yarns, the linear density was considered and analysed in previously published work [12] while the count and size of their fancy projections were also provided and analysed in another study concerning the structure of fancy yarn [10].

4 Discussion

To implement the philosophy of Taguchi, the objective of this discussion was to use the concept Larger-the-Better for the mean value of maximum load, by maximising it. Additionally, the concept Smaller-is-Better was used for the variability of maximum strength.

The maximum load was associated with the rupture of the core yarn, but although the core component ruptured several times, the maximum load was reached only once. Further, the point of maximum load was identified on the load axes of the load-extension charts as a mean value with margins, but the other ordinate on the extension axes varied considerably to the degree it was not possible to identify an average location for this property on load-extension charts. For a few specimens, the maximum load was reached when the core yarn ruptured for the first time, while for other samples, it was reached for the second, the third or other rupture of the core yarn. In all those cases, however, the maximum load was always reached when the binder broke for the first time, given the fact that the binder also broke several times similar to the core yarn. Further, the maximum load value was 984.71 cN in the case of using one combed two-ply yarn for the core of gimp yarn, while it was 1098.76 cN when using two parallel cotton yarns. The higher value which resulted accounted for 3.36 times the value of maximum load for a single cotton yarn of the count Ne = 20 s. The gain in the maximum load in the case of using two parallel cotton yarns for core component of the gimp yarns may have resulted for several reasons. Firstly, the synergy between those two yarns has raised their collective value of maximum load even more than only the sum of the individual values. Secondly, using two yarns in the core gave a more stable structure than using only one two-ply yarn because they increased the number of ruptures of the core component and forced the structure to withstand higher levels of load. Thirdly, using two yarns in the core may make it easier to capture the effect component by the other components within the structure of gimp yarns when stretched therefore all the components may act in unison to resist the load imposed on the fancy yarn and therefore to increase the value of maximum load. Finally, there was the influence of frictional forces generated between the components where higher frictional forces mean that higher loads have to be imposed along the gimp yarn axis to overcome the frictional force. The frictional force may be greater in the case of using two yarns rather than only one two-ply yarn, in the core component, for the following reasons: the single yarns were relatively bulky with greater diameters because they were carded, open-end, rotor-spun yarns. In contrast, the two-ply yarn was relatively thin because it was a ply of two combed yarns. Since the wider the diameter of yarn the greater the outer surface, the contact surface of two individual yarns may have more true points of contact than that of only one two-ply yarn. Further, the single yarns were carded, open-end, rotor-spun yarns; thus, they had a higher degree of hairiness on the yarn surface in comparison with one combed, two-ply yarn. A high level of hairiness means a higher degree of surface roughness which increases the friction coefficient and the frictional force accordingly [14].

The value of maximum load obtained by using the cotton three-ply yarn for the effect component was greater than that resulting from the bamboo three-ply yarn (i.e. 1105.6 cN vs. 977.87 cN) even though Table 2 shows that the bamboo three-ply yarn was stronger than the cotton three-ply yarn. This result indicates that the bamboo three-ply yarn may have contributed individually to the value of maximum load of the whole gimp yarn, while there was an increase in the value of maximum load when using the cotton three-ply yarn. The reasons for that were related to friction and frictional force as presented above. Such friction may have forced the multi-filament binder and the remaining segments of the core to contribute to bearing the load in the case of using cotton yarns for the effect yarn by being locked into the structure while the fancy yarn is being stretched and tested. Once locked into the structure of the fancy yarn, the multifilament binder, mainly, starts to bear its share of the imposed load to contribute to increasing the value of maximum load.

The interaction was understood as follows. The supply rollers do not control the core component on the Gemmil & Dunsmore #3 hollow-spindle spinning machine. Consequently, it was not expected to obtain a real or strong $A*D$ interaction. Further, the effect component did not interact with the core component when considering the load at first break [15], which has the same nature of the maximum load.

The effect component and the supply rollers generally interact with each other because the latter control the former on hollow-spindle spinning machines. To account for the influence of the interaction $E*F$ (which stands for the number of wraps) on maximum load, the line chart of Figure 3 shows the changes in maximum load when both the delivery speed and the rotational speed were changed. Such changes were reflected in different numbers of wraps received by the gimp yarns. Calculations were needed to produce such a line chart and through using the response table (i.e. Tab. 4).

When the number of wraps was near the maximum, i.e. $E_2/F_1 = 21\,000/60 \approx 350$ wpm, the value of maximum load was:

$$\text{Load}_{\max} = \frac{E_{+1} + F_{-1}}{2} = \frac{954.79 + 1009.39}{2} = 982.1 \text{ cN}. \tag{4}$$

Reducing the number of wraps to $E_2/F_2 = 21\,000/70 = 300$ wpm, marginally decreased the value of maximum load to:

$$\text{Load}_{\max} = \frac{E_{+1} + F_{+1}}{2} = \frac{985.51 + 958.26}{2} = 971.8 \text{ cN}. \tag{5}$$

Further reduction in the number of wraps to $E_1/F_1 = 16\,000/60 = 267$ wpm did not bring about any tangible change to the value of maximum load because the value was almost identical to the previous level of wraps:

$$\text{Load}_{\max} = \frac{E_{-1} + F_{-1}}{2} = \frac{1066.95 + 875.26}{2} = 971.1 \text{ cN}. \tag{6}$$

When the number of wraps was at its lowest value, i.e. $E_1/F_1 = 16\,000/70 = 228.5$ wpm, the maximum load realised its maximum in this study:

$$\text{Load}_{\max} = \frac{E_{-1} + F_{+1}}{2} = \frac{1387.79 + 1095.91}{2} = 1241.85 \text{ cN}. \tag{7}$$

This meant that high number of wraps had a negative impact on maximum load. This is explained by considering the case of wrap-spun yarns which are, similar to fancy yarns, made on the hollow-spindle system. For a wrap-spun yarn, a sufficient number of wraps are required to give it its

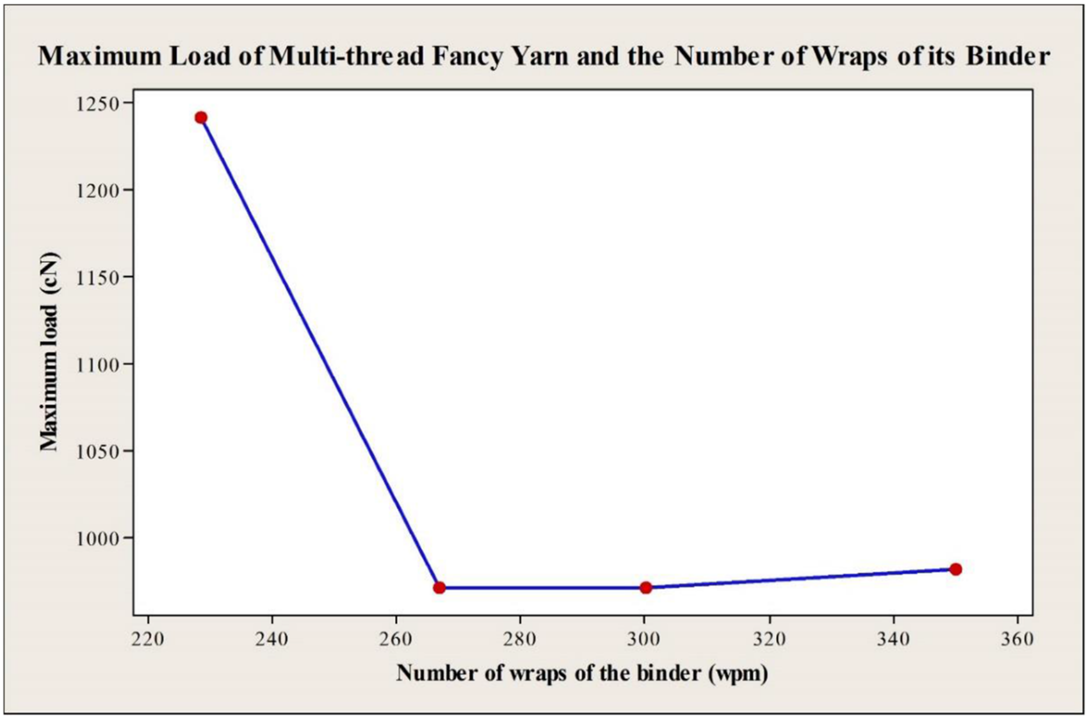


Fig. 3. Line chart of maximum load of the fancy yarns versus wraps.

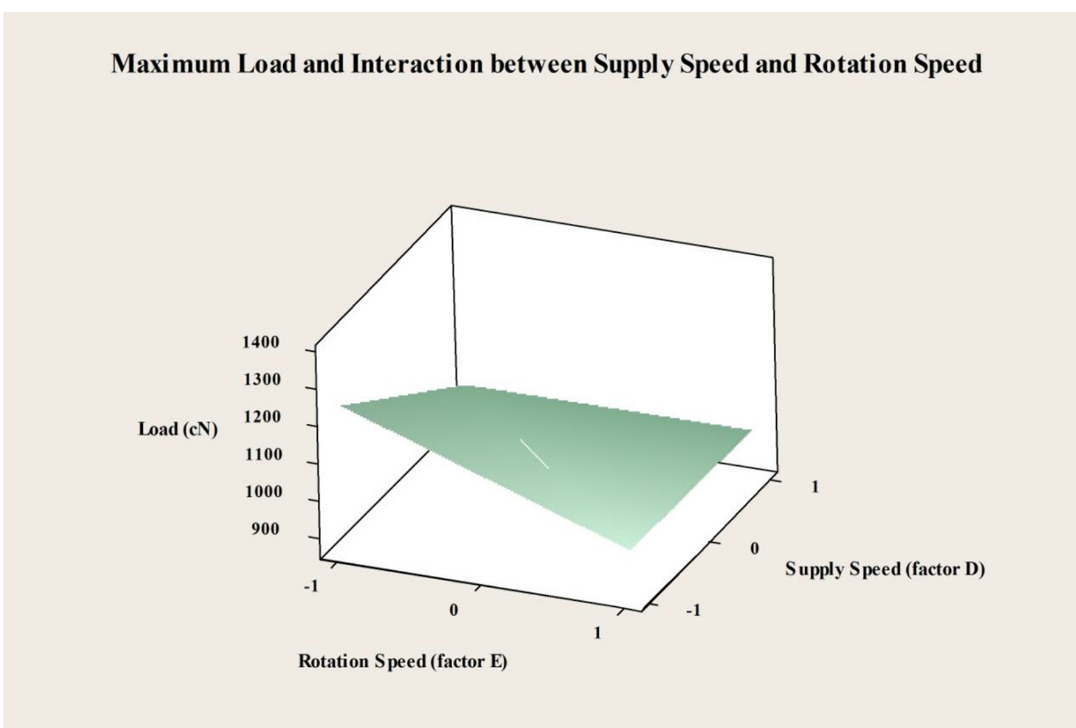


Fig. 4. Surface plot of maximum load versus the supply speed and the rotational speed.

strength through increasing the resistance to the slippage between the components of such a yarn. However, when the wraps were increased to reach a superfluous number, the strength of wrap-spun yarn starts to decrease due to fibre obliquity. Similarly, fibre and yarn obliquity and the bent structure of the components may be responsible for the reduction in maximum load of the fancy yarn. However, it is important to note that high level of wraps had a positive influence on the structure of the gimp yarns by reducing the number of defects on the yarn surface as shown previously [10].

To understand the effect of the interaction between the supply speed and the rotational speed, the surface plot provided in Figure 4 was used. It was shown that the lowest levels selected for these two factors made the strongest gimp yarns with a value exceeding 1200 cN. Low levels for the supply speed made gimp yarns with a lower value of the overfeed ratio and the gimp yarn had a more compact structure therefore its strength was expected to be higher. Further, low levels of the rotational speed meant a lower number of wraps received by the fancy yarns. This in turn was found to give the highest values of maximum load. The images of the fancy yarns made and tested can be found in Figure 3 of reference [16] which is an open access source.

5 Conclusions

In this research, it was possible to study the maximum load of multi-thread-structure fancy gimp yarns and to maximise it. Factors which affected the maximum load were the linear density and material type and form of both the core and the effect components. Using two single yarns in the core component of the gimp yarn instead of one two-ply yarn brought about stronger gimp yarns. The gain in strength was as high as 16% and may be increased further by selecting suitable yarns for the core. Additionally, it was possible to increase the maximum load by about 18% by forcing its effect component to take part in bearing the load. This was achieved by selecting a type of the effect component which has sufficient friction with the other components of the gimp yarn. Moreover, the interaction between both the core component and the effect component contributed a further 18% of the changes to the maximum load. It was also found that the interaction between the supply speed and the rotational speed was responsible for about 18% of the changes in maximum load and the lowest levels selected for these speeds made the strongest gimp yarns. The interaction between the delivery speed and the rotational speed also affected this property since it defines the number of wraps of the binder of the gimp yarns. A sufficient number of wraps, 228 wpm, yielded the strongest gimp yarns, while excessive numbers of wraps, 350 wpm, reduced the maximum load by about 20%.

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