

COMPARATIVE STUDY OF NEEDLE PENETRATION FORCES IN SEWING HEMS ON TOWELING TERRY FABRICS: INFLUENCE OF NEEDLE TYPE AND SIZE

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Abstract:

In this paper, an industrial case study comparing the use of different needles in the production of hems in towels is presented. The study aims to assess the sewability of the fabrics, quantified by needle penetration forces. The market offers an interesting range of options for the needle, regarding the geometry of the needle point, surface finishing, and sizes. However, in practice, the choice is difficult, namely due to the lack of quantitative data that may support the empirical evaluation made by the sewing technicians. The work aims to assess how the needle type and size relate to the resulting needle penetration forces. Three terry fabric structures, produced by a home textiles manufacturer, were tested using needles of different sizes, points, and coatings. Needle penetration forces were measured on a sewability tester prototype, previously designed and developed, based on an instrumented overedge sewing machine. It was found that needle penetration forces present very significant differences with small size increments, needle coating also influences forces significantly, and different needle points produce only slight differences, significant only on some of the fabrics that were tested.

Keywords:

sewing, sewability, needle penetration forces, sewing needles

1. Introduction and objectives

Sewing production efficiency is of paramount importance for apparel manufacturing. Among the different sewing process variables, needles play a key role in determining product quality and process productivity. This study, carried out in cooperation with a terry towel manufacturer, aimed at the selection of the most adequate needles to use in automatic hem seaming machines. The seam under study is the double-fold hem, produced by a 401 double chain stitch (Figure 1), using overedge sewing heads integrated in an automatic production line. This portion of the fabrics has normally a different structure than the main towel area, for decorative purposes.

The selection of needles is normally based on experience, as was the case studied in this work, rather than on a direct, quantitative assessment of needle sewing performance.

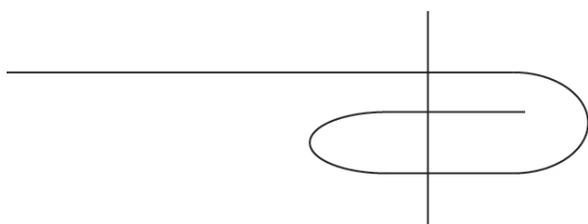


Figure 1. Double-fold hem used in this study.

Measurement of needle penetration forces may provide support in choosing the most adequate needle, considering both the type and the size. In this study, the data obtained from the measurement of needle penetration forces in three fabrics, commonly produced by the manufacturer, are analyzed. The relation with needle sizes, needle points, and surface finishing of the needles is evaluated on the basis of these data.

2. Literature review: measurement of the forces acting during needle penetration and their relation to sewability

Measurement of process variables during sewing using instrumented sewing machines is a theme that has been addressed by several researchers over the years [1–3].

Needle penetration forces, in particular, have been studied since the 1960s, with attention on aspects such as theoretical modeling of the forces, fabric damage by needles, needle heating during sewing, and measurement methods to quantify the intervening variables.

Hurt and Tyler [4, 5] described the significant relation between fabric finishing processes and their influence on needle

penetration forces and resulting damage, by modification of the fabric's frictional properties.

Leeming and Munden [6] contributed decisively to the research in this area with the development of the L&M sewability tester (Testing fabric sewing properties, US Patent 3979951, 1976). This device has been used by several researchers studying needle penetration forces in textiles. Using this equipment, Leeming and Munden described the effect of lubricant or softener on needle penetration forces [7], observing a direct relation between penetration forces and damage to the fabrics. Fabrics that produced lower penetration forces were found to be less prone to damage.

Significant works involving theoretical modeling and numerical simulation of the needle penetration process were also published. Lomov presented a mathematical model to predict the needle penetration force in woven fabrics [8]. Mallet and Du [9] predicted penetration forces in fabrics using finite element modeling techniques.

Later, Carvalho [10, 11] developed new techniques for measuring, processing, and classifying process variables on industrial sewing machines. One of the parameters included was needle penetration and withdrawal forces. In this work, a Singer 882 overedge sewing machine instrumented by Rocha [1] was used. A comprehensive description of this subject is given in Carvalho [11] and Carvalho et al. [12]. The measurement of the forces is obtained using a piezoelectric sensor introduced into the machine's needle bar. A process of filtering and feature extraction allows determining needle penetration and withdrawal forces [10]. The signals measured [11, 12] show a needle penetration force waveform that is very similar to the one predicted by Mallet and Du [9]. Three phases can be observed in the signal: The first one occurs when the needle first touches the fabric; the second when the needle body penetrates; and the third when the needle is withdrawn.

It has been shown that needle penetration forces differ significantly between fabrics in different finishing states. They also increase with the number of fabric layers and with needle size [12]. Different softeners and concentrations have a fundamental influence on these forces [13].

Another measurement setup was proposed by ITV-Denkendorf using a PFAFF 1053 lockstitch machine. A sensor applied on the machine's throat plate is able to measure the forces that take place when the needle pushes the fabric against the plate. Using this equipment, Grancaric, Lima, Vasconcelos, and Tarbuk studied the relationship between fabric finishing and needle penetration forces, namely the effect of pre-treatment in cotton fabrics [14]. The influence of enzymatic scouring [15] and the sewability of fabrics treated with zeolite nanoparticles [16] have been studied by Grancaric, Ujevic, Tarbuk, and Sajatovic.

Using a similar measurement system, Ujevic, Rogale, Kartal, and Šajatović performed several other studies, in which once again the essential relation between needle properties, needle penetration forces, and sewing damage could be shown [17].

The main factors affecting needle penetration forces were found to be the number of fabric layers, the size of the needles, and fabric properties. The presence of thread in the needle did not produce significant differences in needle penetration force. Although two types of needle points (Groz-Beckert SES and SUK) and a special type of needle (Groz-Beckert SAN 10) were used, no clear trends of needle penetration force variation were evident from the data presented.

Finally, another method for measurement of needle penetration forces was proposed by Haghghat, Etrati, and Najar [18]. In this case, an Instron 5566 Tensile Tester is used. The fabric is held in a ring, and a special mechanical setup is used to allow the needle to penetrate in different places of the fabric. In this research, besides the size of the needles and the number of fabric layers, the weight of the fabric was pointed out as another factor significantly influencing needle penetration forces.

In most of the studies on the above-mentioned needle penetration force, the main aspects of the needle penetration process and the factors influencing them are investigated, such as fabric mass, number of layers, and needle size. Additionally, fabric finishing and their influence on needle penetration forces are also studied.

A specific study on needle penetration forces to support needle choice on industrial settings, based on needle size, as well as needle point and surface finishing, is still lacking in the literature, especially in what concerns surface finishing with titanium nitride (TiN), which is used in the most demanding sewing tasks. This work, besides new case studies regarding needle size and points, has the objective of studying the behavior of TiN-coated needles when compared to the normal chrome-plated surface finish.

3. Experimental details

3.1. Materials

The sample used for this study is a convenience sample selected by the towel manufacturer that proposed the study. Three toweling terry woven fabrics were chosen with which the manufacturer has observed very different sewing behavior. The criterion for selection was an empirical and indirect assessment of the sewability of the fabrics based on observation and production efficiency indicators, namely production stops related to sewing defects and needle breakage. The manufacturer selected three fabric specimens and classified them as difficult-to-sew (material A), easy-to-sew (material B), and medium difficulty (material C), according to their own experience and the above-mentioned production indicators. The objective of the study was to analyze how these indicators and factors related to material properties and needle choice are conveyed by objective measurement of needle penetration forces.

The characteristics of the materials to be sewn, which correspond to the edges of the fabric specimens (where the

hems are produced in the manufacture of towels), are listed in Table 1.

Fabric porosity is calculated using equation (1), according to Hsieh [19]

$$P(\%) = \left(1 - \frac{m/t}{d}\right) \cdot 100 \tag{1}$$

with

P(%): Porosity (in percentage)

m: Mass per unit area

t: Fabric thickness

d: Fiber density

3.2. Sewing needles

Needle size and type were selected according to the towel manufacturer’s practice and needle manufacturer’s recommendation. Needle sizes 110 and 120 were considered for the study. Two different needle points were tested: the RG point (a round point combined with a light ball point) and the FFG point (a light ball point).

Regarding needle finishing, for the sewing operation considered, the towel manufacturer usually selects TiN-coated needle, expecting them to be less prone to problems.

According to the needle manufacturers, such as Groz-Beckert, needles coated with this material are more resistant to wear than normal chrome-plated needles [20]. The effect of the TiN coating on the sewing process, namely on needle penetration forces, is not yet studied, and the authors were unable to find any work regarding this subject.

This study proposes to provide some insight on this subject. The main characteristics of the needles used are shown in Table 2.

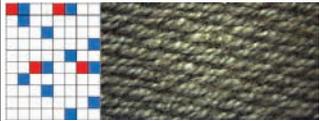
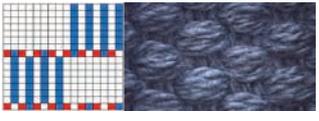
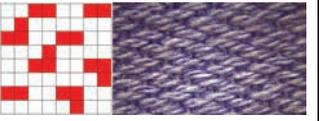
3.3. Test method: evaluation of needle penetration force

To measure the needle penetration forces, the above-mentioned sewing rig using a Singer 882 three-thread overedge sewing machine was used. The machine is equipped with a piezoelectric force sensor (Kistler) fitted into the needle bar (Figure 2). The sensor is connected to specific signal condition hardware, namely a charge amplifier, which, in turn, connects to a National Instruments LAB-PC+ data acquisition board in a PC (Figure 3). A software acquires and processes the data automatically as described next.

The signals obtained are divided into three penetration phases: First phase—first contact of the needle tip with the fabric; second phase—penetration of the needle eye and body; and third phase—needle withdrawal. Force peaks in phases 1 and 2, as well as the force valley produced in phase 3, are computed automatically from the acquired signals.

The mechanical setup used implies that the signals obtained by the sensor result from several forces, not only needle penetration and withdrawal forces. Specifically, the signals

Table 1. Characteristics of the specimens: edges of the terry toweling fabrics

Property	Material A	Material B	Material C
Weave pattern			
Fiber content	100% cotton	100% cotton	100% cotton
Weft yarn linear density (tex) ¹	48.5	73.1	43.0
Warp density (ends/cm)	58.0	44.0	41.7
Weft Density (picks/cm)	29.3	28.0	24.3
Mass per unit area (g/m ²)	467.2	540.3	317.8
Thickness (mm)	1.22	1.63	0.90
Fabric porosity (%)	75.1	78.5	77.1

¹ Data not available for the warp, due to the small dimension of the specimen in this direction

Table 2. Characteristics of the needles (Image Source: Groz-Beckert)

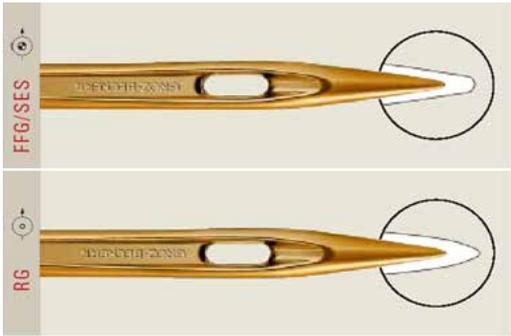
System:	Groz-Beckert B-27 system	
Size:	110 and 120	
Points:	RG and FFG/SES (FFG/SES point not available with TiN coating)	
Coating:	Normal chrome plating and TiN coating (GEBEDUR)	



Figure 2. Setup of the piezoelectric sensor in the machine’s needle bar.

contain components related to needle-bar acceleration and thread forces, which are not interesting and have thus to be eliminated. To eliminate the forces related to thread movement, the machine is unthreaded and the fabric is stitched without thread. The results are not significantly affected by this procedure. It has been shown that the influence of the thread in the needle on fabric damage is not relevant [21]. The other component, related to acceleration forces, is filtered by signal processing, a procedure that is comprehensively described in Carvalho et al. [10]. A residual error results from this process, which is dependent on sewing speed and affects mainly the values of forces measured in the needle withdrawal phase. Forces measured in this phase are the lowest and thus more easily masked by this mechanical noise. Peak forces measured in the first two phases are only minimally affected up to medium sewing speeds. Values of residual noise at a speed of around 3000 spm are in the order of a few tens to a

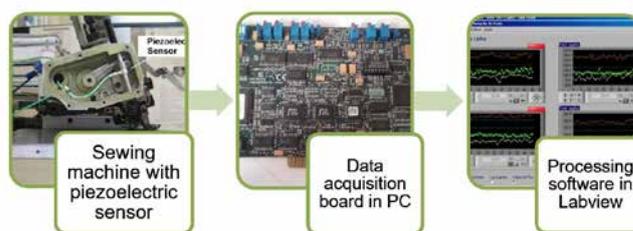


Figure 3. Simplified measurement system diagram.

hundred cN, whereas penetration forces are generally an order of magnitude higher. The measurement hardware and signal processing methods are described in detail in Carvalho [11] and Carvalho et al. [12].

The evaluation of needle penetration forces on the three fabric specimens was focused on force peaks in phase 1—peak 1 (first contact) and in phase 2—peak 2 (during penetration) and was carried out according to the conditions listed in Table 3.

3.4. Data analysis

After the extraction of the relevant peak values of the signals, as described before, the data were tested for normal distribution using the Shapiro–Wilk test (95% confidence interval). This allowed the selection of an adequate method for comparing the means of the datasets. As only two datasets were found to be normally distributed (see Results Section), the Kruskal–Wallis nonparametric test was used to carry out the comparison of means (95% confidence interval).

Table 3. Test conditions

Sewing speed	3000 stitches per minute
Number of fabric layers	Three layers
Stitch length	Approx. 2.5 mm
Number of stitches for each fabric–needle combination	204 stitches Needle change upon every change in fabric–needle combination
Fabric stitching direction	Weft

4. Results and discussion

The experiments conducted generated a large amount of data. To allow the study to be comprehensive, but not too exhaustive, a selection of the data is presented here. The intention is to analyze three fundamental parameters in needle choice: size, point, and surface finishing. The results are thus presented as three independent experiments, each one addressing one of the parameters involved.

4.1. Statistical distribution of the data

Table 4 shows the results of the normality test achieved using the Shapiro–Wilk test.

Table 4. Results of the Shapiro–Wilk normality tests

Dataset	Peak 1	Peak 2
	p value	p value
A.FFG/SES.110	0.132	0.004
A.FFG/SES.120	0.000	0.000
A.TIN.RG.110	0.040	0.002
A.TIN.RG.120	0.000	0.011
A.RG.120	0.444	0.013
B.FFG/SES.110	0.000	0.000
B.FFG/SES.120	0.001	0.000
B.TIN.RG.110	0.000	0.000
B.TIN.RG.120	0.001	0.029
B.RG.120	0.000	0.000
C.FFG/SES.110	0.000	0.000
C.FFG/SES.120	0.020	0.000
C.TIN.RG.110	0.000	0.001
C.TIN.RG.120	0.000	0.000
C.RG.120	0.001	0.003

As can be seen, the *p* value is higher than 0.05 only for two of the datasets. For the remaining ones, the null hypothesis that the distribution is normal has to be rejected. The Kruskal–Wallis nonparametric test was thus selected to compare the equality of population of the datasets.

4.2. Effect of needle size on needle penetration forces

In this study, the penetration forces of 110- and 120-sized needles, with FFG/SES light ball points and normal chrome-plated finishing, were compared and analyzed.

Figures 4–6 show the needle penetration forces obtained for materials A, B, and C. All the penetrations, represented by the symbols specified in the legend, are plotted on an X-Y graph with peak 1 and peak 2 as x- and y-coordinates, respectively.

This representation allows the analysis of trends and relations between the measurements of peak 1 and peak 2.

A clear relation between peak 1 and peak 2 of needle penetration forces can be observed in these graphs, particularly in material

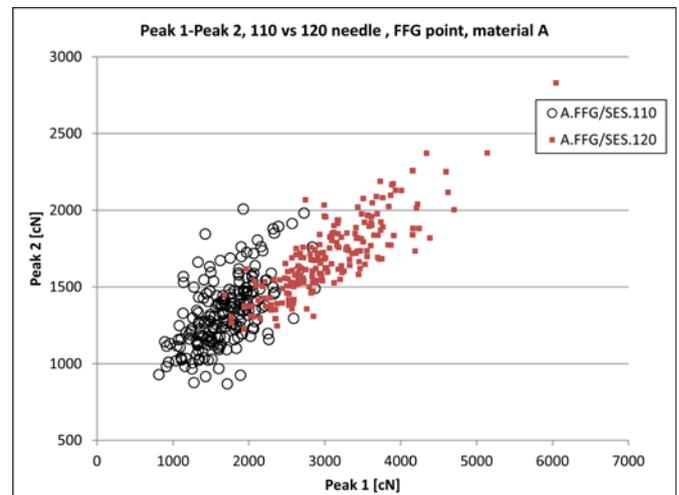


Figure 4. Peak 1–peak 2 graph of needle penetration force on material A, obtained with 110 and 120 needle sizes, light ball points, normal chrome-plated needles.

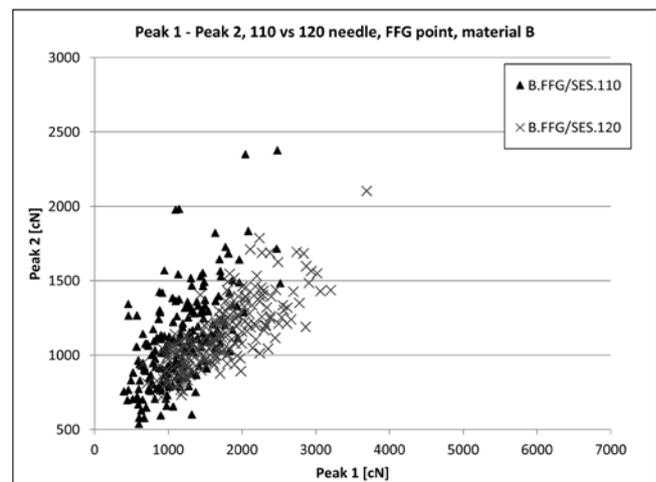


Figure 5. Peak 1–peak 2 graph of needle penetration force on material B, obtained with 110 and 120 needle sizes, light ball points, normal chrome-plated needles.

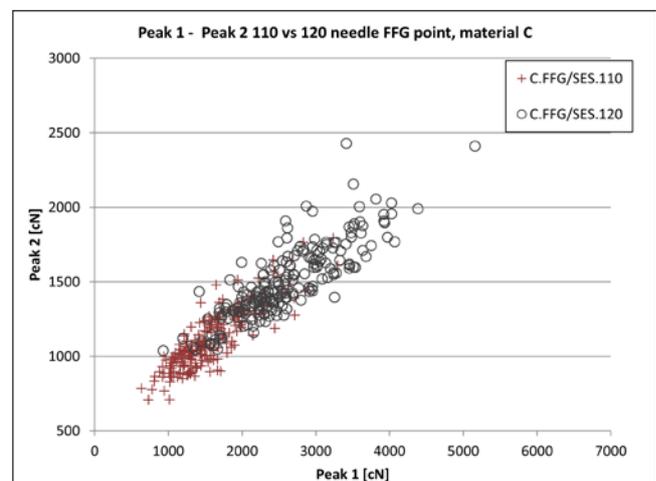


Figure 6. Peak 1–peak 2 graph of needle penetration force on material C, obtained with 110 and 120 needle sizes, light ball points, normal chrome-plated needles.

specimens A and C. The higher dispersion that was observed on material specimen B might be due to the different texture of the fabric surface, imparted by the weave pattern.

The values of peak 2, related to needle passing through the fabric, tend to follow peak 1 behavior. For the three material specimens, needle penetration forces are clustered according to the needle size used and tend to increase when stitching with 120 needle size.

The measurements of needle penetration forces normally result in values with a great spread, with coefficients of variations up to 50%. This has been found in other studies as well, carried out by the authors and by other researchers using different measurement equipment (for instance [14]).

The needle penetration forces of the three fabric specimens, assessed by the mean force peaks values in phases 1 and 2, are shown in Figure 7.

The results of the Kruskal–Wallis test are shown in Table 5.

Table 5. Comparison of means for experiment with different needle sizes

Dataset	p for peak 1	p for peak 2
A.FFG/SES.110 vs A.FFG/SES.120	0.000	0.000
B.FFG/SES.110 vs B.FFG/SES.120	0.000	0.011
C.FFG/SES.110 vs C.FFG/SES.120	0.000	0.000

As can be observed in Figure 7, peak 1, which is related to needle first contact with the fabric, is statistically different, being considerably higher with needle 120, especially for fabrics A and C. An increase between 50% and 80% in the penetration force was observed with an increase in only about 9% on needle diameter. This factor should be carefully considered when choosing a needle. In what concerns peak 2, the differences obtained between 110 and 120 needle sizes are lower, being not significant with material B ($p = 0.011$ in the Kruskal–Wallis test).

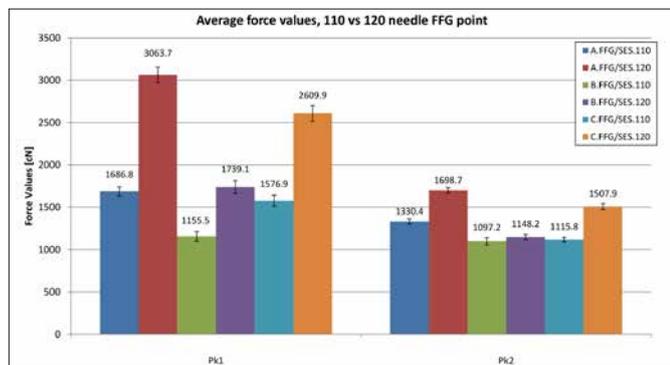


Figure 7. Average values of peaks 1 and 2 of needle penetration force on materials A, B, and C obtained with 110 and 120 needle sizes, light ball points, normal chrome-plated needles.

The results presented are consistent with previous work [12, 17, 18], with the exception of peak 2 with material B. Still, the general trend is a clear increase in needle penetration force with needle size. It has to be added, though, that the results are not directly comparable, given that in this work two force peaks are extracted for each stitch while other authors consider only one.

From the results obtained, it is also apparent that needle penetration forces are closely related to fabrics constructional parameters, with fabric porosity playing a key role. Fabric specimen A with lower porosity (75.1%) demonstrated the highest needle penetration forces for both needle sizes, followed by fabric specimen C (77.5% porosity) and fabric specimen B (78.5% porosity).

The ranking of fabrics sewability based on the needle penetration forces is consistent with the empirical and indirect assessment provided by the manufacturer. It also supports the conclusions of Lemming and Munden [7], stating that fabrics producing higher penetration forces are more prone to sewing damage or other problems.

Results obtained with the RG point are very similar. Actually, as will be seen in the next section, the differences due to the needle point are much smaller than the ones produced by increasing the needle size.

4.3. Effect of needle point on needle penetration forces

From previous studies and results obtained by other researchers [17], the effect of needle point on penetration forces is not yet clearly demonstrated. To maximize possible differences in needle penetration forces due to the needle’s point, the highest needle size, 120, was selected for this experiment. RG (round point combined with a light ball point) and FFG/SESS (light ball point) point needles were used.

In Figures 8–10, it is possible to observe the needle penetration forces obtained on material specimens A, B, and C, using 120 needles with RG and FFG points.

As can be observed from the graphs, needle penetration forces are not substantially affected by the difference between the two needle points in all material specimens (A, B, and C). It should be noted that the two needle points selected by the manufacturer for the test are very similar. As the needle point is expected to primarily influence the force peak in phase 1 (first contact with the fabric), differences in needle penetration forces should be reflected in this peak. In Figure 8, the mean force peaks values in phases 1 and 2 are depicted.

The results of the Kruskal–Wallis test are shown in Table 6.

It can be observed that only in material A, the most difficult material to sew, a significant difference in peak 1 is obtained. In the other two materials, forces in peak 1 are not significantly different. On the other hand, peak 2 is different on materials B and C and not in material A.

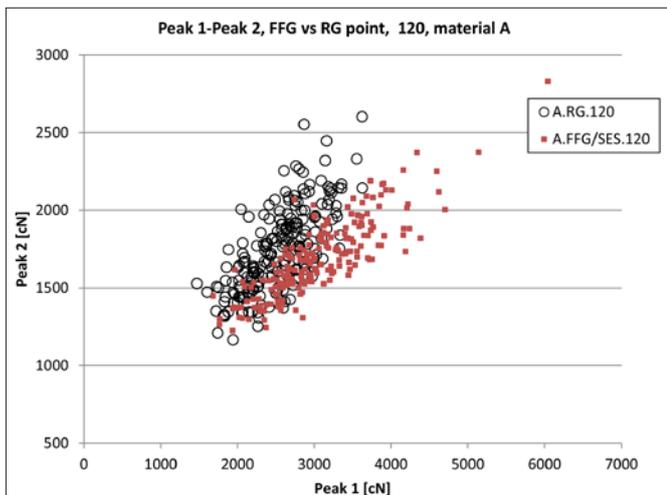


Figure 8. Peak 1–peak 2 graph of needle penetration force comparing FFG with RG points, using normal chrome-plated needle, size 120, material A.

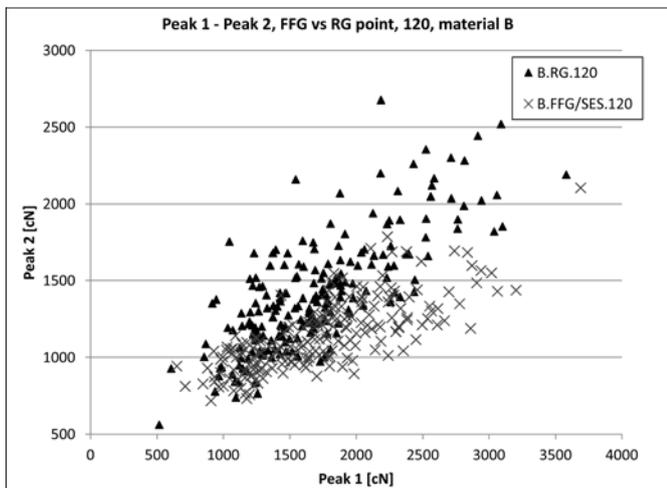


Figure 9. Peak 1–peak 2 graph of needle penetration force comparing FFG with RG points, using normal chrome-plated needle, size 120, material B.

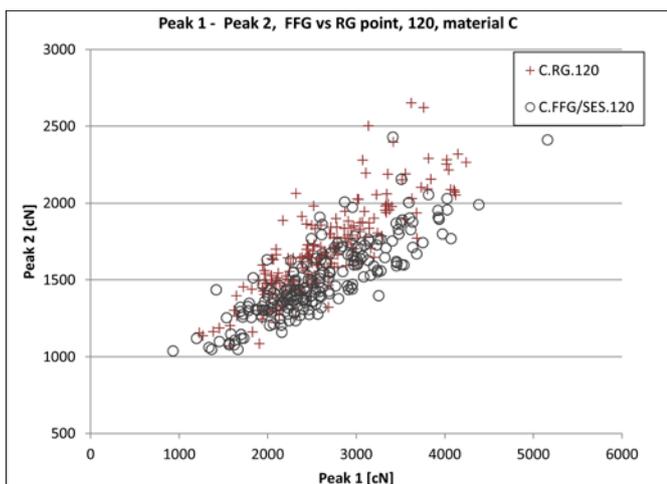


Figure 10. Peak 1–peak 2 graph of needle penetration force comparing FFG with RG points, using normal chrome-plated needle, size 120, material C.

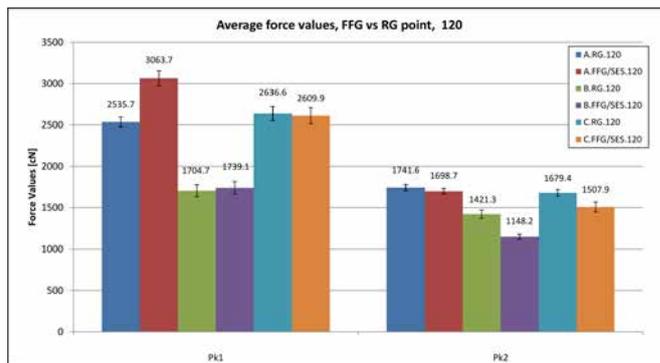


Figure 11. Average values of needle penetration forces on materials A, B, and C obtained with normal chrome-plated needles, size 120, FFG/SES and RG points.

Table 6. Comparison of means for experiment with different needle points

Dataset	p for peak 1	p for peak 2
A.FFG/SES.120 vs A.RG.120	0.000	0.123
B.FFG/SES.120 vs B.RG.120	0.478	0.000
C.FFG/SES.120 vs C.RG.120	0.630	0.000

Although it is possible to observe statistically significant differences between needle points, the results are difficult to explain. It would be expectable to find the differences only in peak 1, being this peak produced when there is interaction between the needle point and the fabric. However, in two cases, a difference is found in peak 2. Moreover, while the RG point shows less penetration force in peak 1 for material A, it results in higher forces in peak 2 for materials A and B. This aspect has to be studied in further work.

4.4. Effect of needle coating on needle penetration forces

In this experiment, the influence of the TiN coating on needle penetration forces was investigated. For this purpose, normal (chrome-plated) and TiN-coated needles of size 120 with RG point were used and the needle penetration forces measured on the three materials. The RG point was selected because TiN-coated needles with FFG point are not produced by Groz-Beckert.

Figures 12–14 illustrate needle penetration force peaks 1 and 2 obtained with material specimens A, B, and C.

As depicted in the graphs, there is a clear influence of needle surface finishing on needle penetration forces, which are clustered according to needle coating. A further analysis of the results reveals that the impact of surface finishing is significant on force peak 2 (during needle penetration through the fabric), but not as important on force peak 1 (first contact with the fabric). Figure 15 shows the mean force peaks values in phases 1 and 2.

The results of the Kruskal–Wallis test are shown in Table 7.

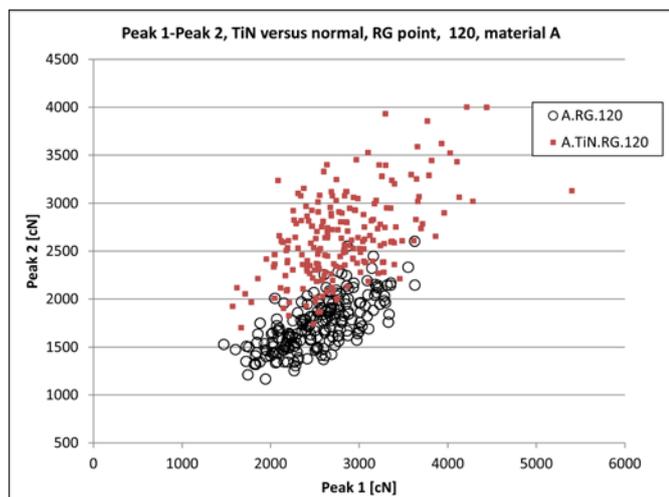


Figure 12. Peak 1–peak 2 graph of needle penetration force comparing TiN-coated needle with normal chrome-plated needle, size 120, RG point, material A.

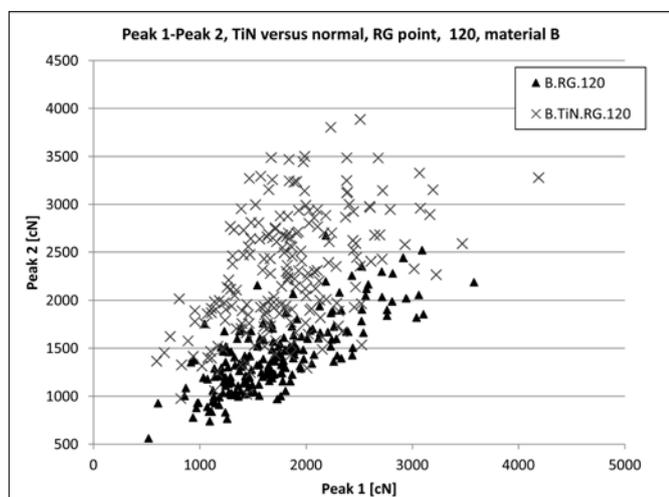


Figure 13. Peak 1–peak 2 graph of needle penetration force comparing TiN-coated needle with normal chrome-plated needle, size 120, RG point, material B.

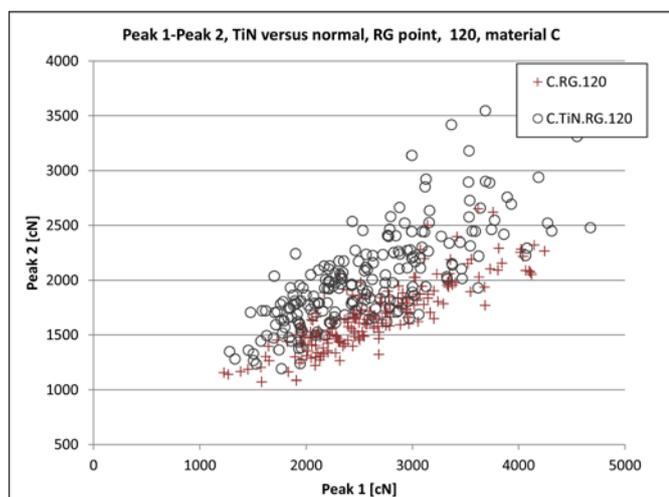


Figure 14. Peak 1–peak 2 graph of needle penetration force comparing TiN-coated needle with normal chrome-plated needle, size 120, RG point, material C.

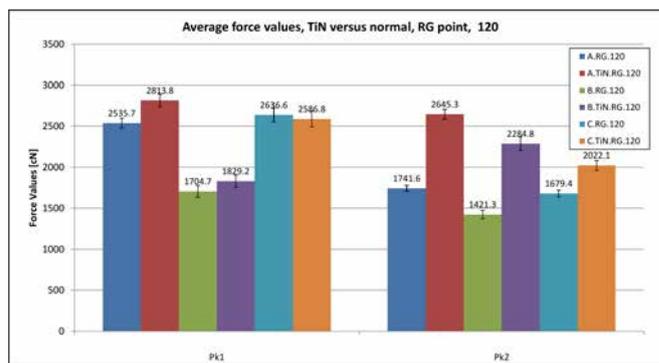


Figure 15. Average values of peaks 1 and 2 of needle penetration force comparing TiN-coated needle with normal chrome-plated needle, size 120, RG point, material C, materials A, B, and C.

Table 7. Comparison of means for experiment with different needle coatings

Dataset	p for peak 1	p for peak 2
A. TiN.RG.120 vs A.RG.120	0.000	0.000
B. TiN.RG.120 vs B.RG.120	0.006	0.000
C. TiN.RG.120 vs C.RG.120	0.229	0.000

It is clear that the TiN coating influences the needle penetration process significantly. In peak 2, all of the experiments show a statistical difference between the needles with different coatings. The trend is to increase needle penetration force through the fabric, in phase 2 of penetration. This can be explained by the properties of the needle surface that apparently produces higher friction between needle and fabric, having a greater importance during the (long) penetration process of the needle body than in the quick first contact.

5. Conclusions

5.1. Summary of results

From the results obtained, several important observations can be made, summarized as follows:

- Needle size clearly affects needle penetration forces, particularly force peak 1. Significant differences were encountered with a minimal increase in needle size.
- The effect of needle point is not clearly demonstrated. Differences in the needle penetration forces were in general not significant, but for material A, a significant difference was encountered in the force peak of phase 1 (first contact with the fabric), whereas differences were also observed in peak 2 using materials B and C.
- Significantly higher needle penetration forces through fabric (force peak 2) were observed when using the TiN-coated needles.

- Fabric constructional parameters demonstrated to be important variables determining needle penetration forces and hence sewability. Fabric porosity, which is dependent on the ratio of fabric mass per unit area and thickness, seems to play a major role.

Furthermore, it should be stressed that the results obtained are consistent with the empirical manufacturer's ranking of the fabrics' sewability.

5.2. Final remarks

The effect of sewing needle characteristics (size, point, and coating) on needle penetration forces was studied with the purpose of developing a support tool to help a terry towel manufacturer on needle selection.

The results presented in this study confirm the relevance and validity of needle penetration forces measurement as a support tool for sewing process optimization. Besides having confirmed the historical data gathered empirically by the manufacturer, this work provides other findings that will allow the manufacturer to improve the process in a more comprehensive and reasoned way. The use of TiN needles may be unnecessary; the reduction of needle penetration force through the reduction of needle size may be sufficient to minimize wear/breakage of the normal needle. This has to be further substantiated.

The need for high productivity, rapid product change, and the great variety of products and materials processed in the sewing industry, pose stronger requirements for well-established process engineering, moving away from empirical, subjective assessments. The measurement of needle penetration forces, as presented in this paper, has the potential to be one of the tools to achieve this, both from academic and industrial perspectives.

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