# Evaluation of Woven Denim Fabric Sewability based on Needle Penetration Force

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## ABSTRACT

This paper investigates the sewability of the woven denim fabrics based on needle penetration force (NPF). For this purpose, the effects of fabric weight, number of fabric layers, needle size, and the interaction effect of these parameters on NPF in twill denim fabrics were investigated. In addition, the influence of weave pattern on NPF was studied. The statistical analysis results show that NPF is influenced by these parameters. Fabric weight has a greater effect on NPF than other parameters. With increasing fabric weight, number of fabric layers, and needle size, the NPF increases. The trend of this increase is nonlinear as predicted by a cubic regression equation. The fabric sewability is also influenced by the mentioned parameters. The fabric sewability becomes poor with increasing fabric weight, needle size, and number of fabric layers. Generally, lighter fabrics sewn with finer needles have better sewability.

**Keywords**: Denim fabric, Needle penetration force, Fabric sewability, Fabric weight, Needle size

## INTRODUCTION

The garment industry is one of the main economic sectors, which has an important role in everyday life and global economics [1]. Among woven fabrics the usage of denim, as a main part of garment fashion, is greatly increasing every year [2-3]. In the garment manufacturing industry, pressure on manufacturers has increased due to competition in global markets [4]. The proper quality of garments depends on fabric quality, machine parameters, and fabric sewability. Sewability can be defined as ease of formation of shell structures and the ability of material to be seamed effectively without fabric damage, and also to provide suitable end-use performance [5-6].

The problems related to sewability are not restricted to a particular section of the sewing industry; it is widely considered in the whole of the apparel manufacturing processes. The study of sewability can help better understanding of the interaction between one or more plies of fabric, which are sewn with sewing thread [7-8]. In addition to seam efficiency, puckering, slippage, damage and appearance, the needle penetration force (NPF) is another main factor which is used to determine fabric sewability. A fabric with high penetration force is more susceptible to damage. Fabric damage has directly negative effects on garment quality; therefore, the quantitative value of NPF and fabric sewability could be used to determine the damage of sewn fabrics during the sewing process [5,9]. The subject of NPF has been studied by several researchers. In order to evaluate the influence of the geometrical and physical parameters of fabrics on the sewability of the shirting fabrics, some sewing trials were applied by McLoughlin *et al.* [8]. This research concluded that fabrics with lower shear rigidity could be easily deformed during sewing. The fabrics with higher shear rigidity rarely deform into three-dimensional shapes and cause problems in fabric sewing.

The type of material, weave pattern, sewing needle size, shape of needle point, and number of fabric layers have a profound effect on the NPF. Also, the friction between the fabric and sewing needle has a great effect on the NPF. Needle penetration force increases proportionally with needle size. There is no noticeable difference in NPF when the samples are sewn with or without sewing thread [9]. A system that measures the parameters of needle penetration and withdrawal forces during high-speed sewing was developed by Carvalho *et al*. [10]. By this system, it is possible to find the relationship between penetration force and needle size for a particular fabric and also evaluate fabric sewability by different needles and other sewing conditions.

To measure the NPF, the L&M Sewability Tester has been used in many studies [11-14]. This equipment simulates a sewing machine without needle sewing thread at a rate of 100 penetrations per minute, and it allows many laboratorial studies to be developed.

The effects of elastane yarn type and fabric density on the NPF of PET/ elastane woven fabrics were investigated. Needle penetration force was measured on the L&M Sewability Tester for evaluating seam performance. Additionally, the needle damage index was calculated. The weave type, elastane yarn type, and fabric density were found to have significant influence on the NPF and needle- related damage in PET / Elastane woven fabric [11].

The sewability of woven fabrics fused with different woven interlinings was investigated by using the L&M Sewability Tester. It was found that the sewability of fabric decreases when the weight and thickness of fabrics increase. Also, the NPF increases proportionally with weight and thickness. Because of the high resistance during the sewing process, the fabric will be damaged during sewing process [12]. The effects of the elastane draw ratio, pre-setting temperature, and finishing process on the NPF and damage of elastane fibre during sewing of cotton/elastane fabrics were investigated [13]. It was found that pre-setting temperature and finishing process had meaningful effect on the NPF and fibre damage. Also, Gurarda [14] presented an experimental study of seam performance of the PET/nylon elastane woven fabrics. To evaluate the seam performance, the seam strength, seam slippage, seam efficiency, and NPF were obtained. Seam performance was found to be influenced by weave type and weft density.

To determine the damage of cotton/polyester woven fabric in garments, the effects of fabric construction on the sewability (NPF) of untreated and treated fabrics were investigated [15]. The weave pattern and weft density were found to influence NPF in both weft and warp directions.

According to newly developed processes in garment manufacturing, particularly in the denim garment, the study of denim sewability in clothing manufacture is important. In the sewing process, a fabric with a high density, thickness, and weight such as denim fabric is more prone to damage [5]. At the same time, if the sewing needle is not correctly selected with respect to the fabric construction, the sewability of fabric becomes poor in the final product.

This study aimed to statistically analyze the effect of fabric weight, needle size, number of fabric layers, and weave pattern on the NPF of denim fabrics and to evaluate the sewability of these fabrics based on NPF. The needle penetration force was measured by an Instron tensile tester. Also, in order to investigate sewing damage, the fabric surfaces after removing sewing thread from fabric were observed.

## MATERIALS AND METHODS

### Fabric Sample

In order to investigate the influences of parameters (fabric weight, needle size and number of fabric layers) on NPF and the fabric sewability of denim fabrics, four commercial samples of denim fabrics with Twill 3/1 weave pattern and different weights (D1, D2, D3, and D4), commonly used for clothing, were prepared. In addition, for evaluating the effect of weave pattern on NPF and fabric sewability, another sample with Twill 2/1 weave pattern (D5) which partially has the same weight and cover factor as sample D2 was prepared. The physical characteristics of fabrics are shown in *Table I*. The fabric weight and yarn density were measured according to ASTM Standards D3776 and D3775, respectively. The cover factor of fabrics was calculated based on the count and density of yarns [16].

TABLE I. Physical characteristics of denim fabrics.

| Fabric code | Weight ($g/m^2$) | Yarn count (Tex) | | Yarn density (1/cm) | | Cover factor | Weave pattern |
|---|---|---|---|---|---|---|---|
| | | warp | weft | warp | weft | | |
| D1 | 300 | 59 | 59 | 27.0 | 20.0 | 37.75 | T3/1 |
| <u>D2</u> | <u>370</u> | 74 | 74 | 27.5 | 18.0 | <u>40.86</u> | |
| D3 | 421 | 66 | 74 | 28.0 | 22.5 | 43.91 | |
| D4 | 441 | 66 | 74 | 31.0 | 23.0 | 46.90 | |
| <u>D5</u> | <u>375</u> | 66 | 59 | 27.0 | 22.5 | <u>40.93</u> | T2/1 |

### Measurement of Needle Penetration Force

Measurement of NPF was performed on an Instron 5566 Tensile Tester. In order to hold the fabric samples on the Instron, a ring was used. The ring was mounted on the bottom jaw of the Instron. The needle was attached to the upper jaw of the Instron by using a special eccentric needle bar, so it was possible to have different places on the fabric samples during needle penetration by rotating the ring [17].

To simulate the motion of the needle in a sewing machine, the cyclic needle penetration was performed five times for each fabric sample. Five samples were tested for each case. As a result, the number of needle penetration cycles for each case was 25 times on the different places of fabric samples. The needle insertion speed was adjusted at 460 mm/min. This technique is useful to simulate the NPF to compare the effects of different parameters on the NPF, and also to estimate the fabric sewability.

To evaluate the effect of needle size, according to fabric weight, five *set cloth point* needles with different sizes (80, 90 100, 110, 120 *Nm*) were selected. According to the fabric type (5 different fabrics), number of fabric layers (4 levels), and needle size (5 levels), the number of cases tested was 100. As mentioned, for each case five samples from different places of fabrics were tested. Therefore, the total number of examined samples was 500.

In order to determine the NPF, at first the maximum needle penetration force in each cycle was defined. Then the average of these values in 25 cycles was taken into account as NPF for each case. *Table II* shows the average of experimental values of NPF for different cases.

In this study, for calculating the sewability values, a threshold of NPF was determined based on fabric mass per unit area and the total average of needle penetration forces, when different needles pierce into one layer of fabrics. According to total average of NPFs (476 *cN*) and fabric weights, the threshold value was defined approximately close to total average, which was 400 *cN*. The number of times that the achieved NPF was greater than the threshold value was counted. The sewability values were obtained from the ratio of the numbers of points that exceed the threshold to all tested points and expressed as a percentage [12].

When sewability value ranges between 0 and 10%, the fabric sewability is considered good; between 10 and 20%, the fabric sewability is considered to be only fair, even though no main difficulties arose during sewing process. When sewability value is more than 20%, sewability is considered to be poor [18]. The sewability values are given in *Table II*.

In order to evaluate the sewing damage as a result of the needle penetration process, some pictures were captured from fabric surface by using a proper digital lens (Dino Capture) connecting to the PC.

TABLE II. The experimental values of needle penetration force and sewability values in different cases.

| Number of fabric layers | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | 2 | | | | 3 | | | | 4 | | | |
| FC | NS (*Nm*) | NPF (*cN*) | SV (*%*) | FC | NS (*Nm*) | NPF (*cN*) | SV (*%*) | FC | NS (*Nm*) | NPF (*cN*) | SV (*%*) | FC | NS (*Nm*) | NPF (*cN*) | SV (*%*) |
| | 80 | 131 | 0 | | 80 | 229 | 4 | | 80 | 350 | 32 | | 80 | 632 | 92 |
| | 90 | 174 | 0 | | 90 | 329 | 20 | | 90 | 463 | 60 | | 90 | 525 | 88 |
| D1 | 100 | 183 | 0 | D1 | 100 | 331 | 24 | D1 | 100 | 550 | 100 | D1 | 100 | 660 | 100 |
| | 110 | 288 | 16 | | 110 | 579 | 100 | | 110 | 896 | 100 | | 110 | 1016 | 100 |
| | 120 | 334 | 20 | | 120 | 629 | 100 | | 120 | 1014 | 100 | | 120 | 1215 | 100 |
| | 80 | 217 | 0 | | 80 | 422 | 44 | | 80 | 646 | 100 | | 80 | 818 | 100 |
| | 90 | 253 | 4 | | 90 | 498 | 80 | | 90 | 811 | 100 | | 90 | 986 | 100 |
| D2 | 100 | 331 | 20 | D2 | 100 | 667 | 100 | D2 | 100 | 982 | 100 | D2 | 100 | 1156 | 100 |
| | 110 | 500 | 68 | | 110 | 1019 | 100 | | 110 | 1372 | 100 | | 110 | 1779 | 100 |
| | 120 | 534 | 76 | | 120 | 1074 | 100 | | 120 | 1712 | 100 | | 120 | 1869 | 100 |
| | 80 | 322 | 20 | | 80 | 604 | 96 | | 80 | 959 | 100 | | 80 | 1068 | 100 |
| | 90 | 422 | 68 | | 90 | 823 | 100 | | 90 | 1228 | 100 | | 90 | 1481 | 100 |
| D3 | 100 | 372 | 32 | D3 | 100 | 857 | 100 | D3 | 100 | 1222 | 100 | D3 | 100 | 1570 | 100 |
| | 110 | 509 | 84 | | 110 | 1104 | 100 | | 110 | 1665 | 100 | | 110 | 2017 | 100 |
| | 120 | 690 | 100 | | 120 | 1265 | 100 | | 120 | 1877 | 100 | | 120 | 2285 | 100 |
| | 80 | 479 | 84 | | 80 | 982 | 100 | | 80 | 1408 | 100 | | 80 | 1763 | 100 |
| | 90 | 681 | 100 | | 90 | 1323 | 100 | | 90 | 1835 | 100 | | 90 | 2099 | 100 |
| D4 | 100 | 731 | 100 | D4 | 100 | 1329 | 100 | D4 | 100 | 1979 | 100 | D4 | 100 | 2340 | 100 |
| | 110 | 955 | 100 | | 110 | 1733 | 100 | | 110 | 2435 | 100 | | 110 | 3155 | 100 |
| | 120 | 1014 | 100 | | 120 | 1979 | 100 | | 120 | 2694 | 100 | | 120 | 3481 | 100 |
| | 80 | 366 | 20 | | 80 | 663 | 100 | | 80 | 985 | 100 | | 80 | 1248 | 100 |
| | 90 | 500 | 64 | | 90 | 979 | 100 | | 90 | 1339 | 100 | | 90 | 1667 | 100 |
| D5 | 100 | 524 | 92 | D5 | 100 | 960 | 100 | D5 | 100 | 1441 | 100 | D5 | 100 | 1743 | 100 |
| | 110 | 632 | 100 | | 110 | 1207 | 100 | | 110 | 1830 | 100 | | 110 | 2260 | 100 |
| | 120 | 766 | 100 | | 120 | 1444 | 100 | | 120 | 2117 | 100 | | 120 | 2670 | 100 |

FC: fabric code, NS: needle size, NPF: needle penetration force, and SV: sewability value

To statistically evaluate the interaction as well as individual effects of each parameter on the NPF (while the other parameters were constant), the General Linear Model, and One-Way ANOVA at confidence intervals of 95%, were applied. Then, to determine which means of groups differ significantly, the Tukey test was performed by using software SPSS Version. 20.

## RESULTS AND DISCUSSION

### Needle Penetration Force

#### *The Variation Trend of Needle Penetration Force in Each Cycle*

*Figure 1* shows a typical result of NPF versus cycles obtained on the Instron tensile tester. The parts of sewing needle are given in *Figure 2*.

The points *a*, *b*, *c*, *d*, *e*, and *f* on *Figure 1* in cycle 1 are specified as following:

a: global maximum NPF when needle eye penetrates into the fabric.
b: local minimum NPF in needle scarf zone.
c: local maximum NPF when needle shaft pierces into the fabric.
d: local maximum needle withdrawal force (NWF) when needle shaft withdraws from the fabric.
e: local minimum NWF in needle scarf zone.
f: global maximum NWF when needle eye withdraws from the fabric.

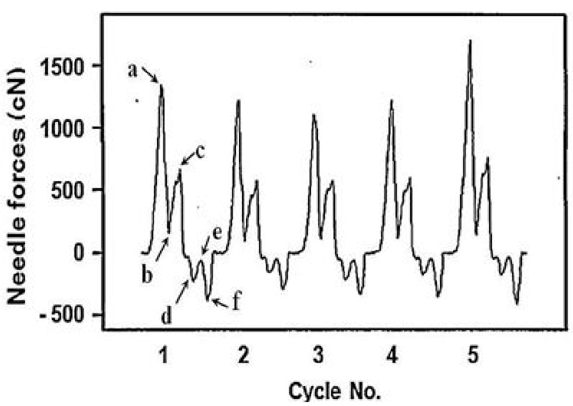

FIGURE 1. A typical needle forces at five cycles loading.

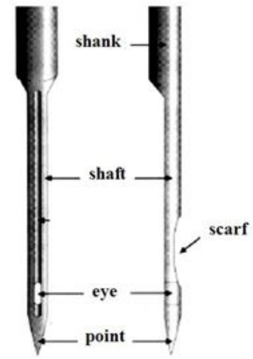

FIGURE 2. The parts of sewing needle.

The highest NPF value occurs when the needle eyelet penetrates into the sewn fabric layer (point *a*), because the diameter of needle eyelet is greater than the diameter of the other part of needle. Therefore, the needle passes through the sewn fabric at a larger gap due to the needle profile changes. Accordingly, a high friction force against the sewing needle results. As a consequence, the NPF increases. Moreover, the NPF is higher than NWF, because when the sewing needle goes away from the fabric, the friction force decreases. So the needle leaves the part of sewn fabric that previously was punctured. Accordingly, the forces applied to a sewing needle by the fabric are considerably reduced.

#### *The Statistical Analysis of the Results*

The statistical analysis of the results shows that fabric weight (FW), number of fabric layers (NFL), and needle size (NS) have a significant effect on the NPF. Also, the interaction effects of parameters on the NPF are meaningful (*Table III*). According to values of *F* in *Table III*, the FW and NFL have the highest effect on NPF among all parameters.

TABLE III. The effect of FW, NFL, and NS on the needle penetration force of denim fabrics.

| Source | F | Sig. |
|---|---|---|
| FW | 3071.491 | 0.000 |
| NFL | 3015.430 | 0.000 |
| NS | 1036.469 | 0.000 |
| NS * FW | 29.472 | 0.000 |
| NFL * NS | 54.565 | 0.000 |
| NFL * FW | 144.794 | 0.000 |
| NFL * NS * FW | 3.261 | 0.000 |

F: the ratio of mean square of each parameter to mean square of error.

As explained before, the General Linear Model could help to have a better comprehending of interaction effects of FW, NFL, and NS on the NPF.

Statistical analysis of the results show that the interaction between NFL * FW has higher influence than NFL* NS, FW * NS and NFL* FW* NS on the NPF. Generally, the trend of these effects is as follows:

FW>NFL>NS>NFL*FW>NFL*NS>FW*NS>NFL* FW*NS

In order to analyze the relationship between FW, NFL, NS, and NPF, surface plots were extracted. Using the surface plots, it is possible to investigate the interaction influences of mentioned parameters on the NPF. The surface plots are shown in *Figures 3-5.*

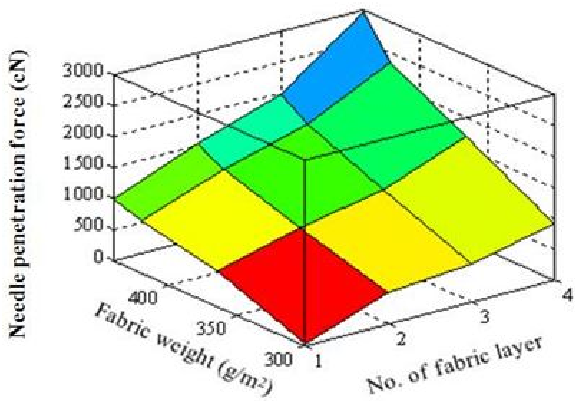


FIGURE 3. The surface plot of needle penetration force against fabric weight and number of fabric layer.

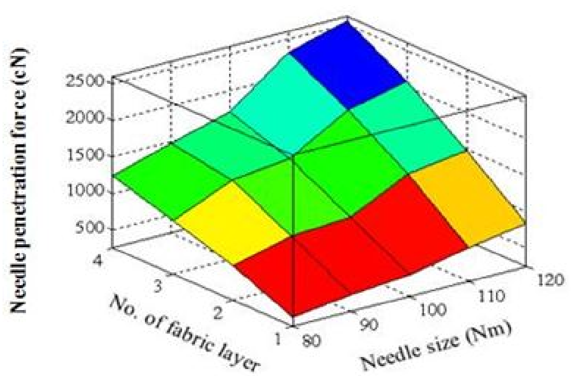


FIGURE 4. The surface plot of needle penetration force against number of fabric layer and needle size.

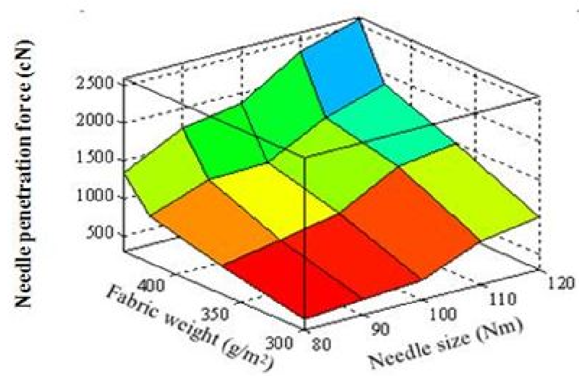


FIGURE 5. The surface plot of needle penetration force against fabric weight and needle size.

*Figure 3* shows that the NPF increases with FW and NFL. At higher values of FW and NFL, the increasing of NPF is greater. When a coarser needle pierces in the several layers of fabric, NPF raises. *Figure 4* shows that the influence of NFL on the NPF is higher than NS, because the slope of graph in left hand side is greater than right hand side, as expected. Considering the surface plots, it can be realized that the effect of FW and NFL on the NPF is more pronounced than the NS, because the maximum value of NPF is observed in the *Figure 3.*

Multiple nonlinear regressions were fitted on experimental values of NPF in terms of parameters including FW, NS, and NFL. According to the results, the cubic equation (Eq. (1)) has the best goodness of fit among the other multiple nonlinear equations ($R^2$=0.972).

$$\text{NFL } (cN) = -124456 + 2955.7*NFL - 231.05*NS + 1091.26*FW - 23.15*NFL*NS - 14.73*NFL*FW + 0.0006*NS*FW + 204.32*NFL^2 + 2.39*NS^2 - 2.97*FW^2 + 0.037*NFL*NS*FW - 0.271*NFL^2*FW + 0.081*NFL*NS^2 + 0.02*NFL*FW^2 - 18.09*NFL^3 - 0.008*NS^3 + 0.003*FW^3 \quad (1)$$

The individual effects of these parameters (when only one parameter is changed and the other parameters are constant) were investigated by using One-Way ANOVA**.**

***The Effect of Fabric Weight on the Needle Penetration Force***

The results of data analysis show that fabric weight has a significant influence on NPF, when the number of fabric layers and needle size are constant. According to *Figure 6,* the values of NPF increase with fabric weight, particularly for higher fabric layers.

In higher fabric layers, the slope of rising of NPF is more than the lower level. It is reasonable to say that by increasing fabric weight, the cover factor of fabric increases (*Table I*). This means that the free space between warp and weft yarns is reduced. Therefore, the resistance of heavier fabric against needle penetration is more than it is for lighter fabrics, which causes the values of NPF to rise. However, in some cases where the weights of fabrics are close to each other (300 - 370 and 370 - 421, g/m$^2$), the NPF of these fabrics are statistically in one group (*Table IV*).

As it is shown in *Table IV*, in *cases N90L1* (NS= 90 *Nm*, NFL=1), and *N80L4* (NS= 80 *Nm*, NFL=4) there is no meaningful difference between NPF in fabrics 300 and 370. Also, in cases *N100L1*, *N110L1*, *N110L2*, and *N120L3* there is no significant difference between NPF in fabrics 370 and 421.

In order to determine the trend of NPF increasing with fabric weight, the linear and nonlinear (cubic and exponential) curves were fitted on the obtained values of NPF.

TABLE IV. Multiple comparison results (Tukey test) for fabric weight changes.

| Code | N80L1 | | | | N90L1 | | | N100L1 | | | N110L1 | | | N120L1 | | | | N80L2 | | | | N90L2 | | | | N100L2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| FW (g/m²) 300 | * | | | | * | | | * | | | * | | | * | | | | * | | | | * | | | | * | | | |
| 370 | | * | | | * | | | | * | | | * | | | * | | | | * | | | | * | | | | * | | |
| 421 | | | * | | | * | | | * | | | * | | | | * | | | | * | | | | * | | | | * | |
| 441 | | | | * | | | * | | | * | | | * | | | | * | | | | * | | | | * | | | | * |

| Code | N110L2 | | | N120L2 | | | | N80L3 | | | | N90L3 | | | | N100L3 | | | | N110L3 | | | | N120L3 | | | N80L4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 1 | 2 | 3 |
| FW (g/m²) 300 | * | | | * | | | | * | | | | * | | | | * | | | | * | | | | * | | | * | | |
| 370 | | * | | | * | | | | * | | | | * | | | | * | | | | * | | | | * | | * | | |
| 421 | | * | | | | * | | | | * | | | | * | | | | * | | | | * | | | * | | | * | |
| 441 | | | * | | | | * | | | | * | | | | * | | | | * | | | | * | | | * | | | * |

| Code | N90L4 | | | | N100L4 | | | | N110L4 | | | | N120L4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | N80, N90, N100, N110, and N120: needle size, 80, 90, 100, 110 and 120 (Nm), respectively. L1, L2, L3, and L4: number of fabric layers, 1, 2, 3, and 4, respectively. |
| FW (g/m²) 300 | * | | | | * | | | | * | | | | * | | | | |
| 370 | | * | | | | * | | | | * | | | | * | | | |
| 421 | | | * | | | | * | | | | * | | | | * | | |
| 441 | | | | * | | | | * | | | | * | | | | * | |

Linear and nonlinear regressions estimate the coefficients of the equation, involving one or more independent variables that predict the value of the dependent variable. For instance, the exponential fitted curves are shown in *Figure 6a*. The goodness of fit is estimated in terms of $R^2$ (determination coefficient). The average values of $R^2$ are presented in *Table V*. Generally, the cubic curve has a greater $\bar{R}^2$ compared to exponential and linear curves:

$$\left(\bar{R}^2_{cubic} = 1\right) > \left(\bar{R}^2_{exponential} = 0.972\right) > \left(\bar{R}^2_{linear} = 0.951\right)$$

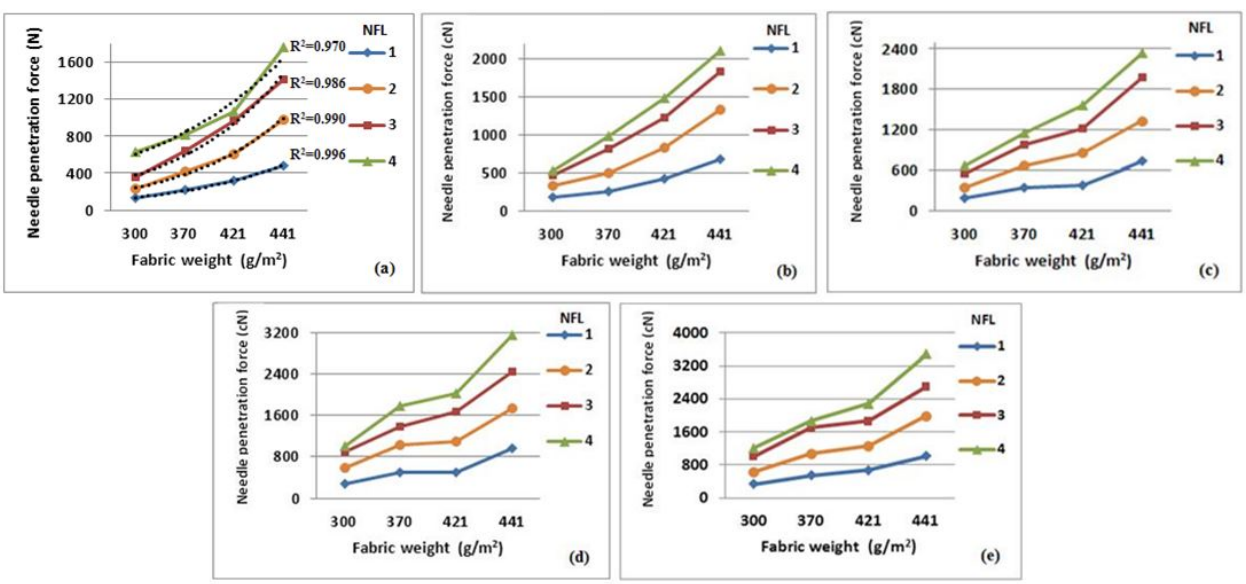


FIGURE 6. The effect of fabric weight on the needle penetration force under sewing with different number of fabric layers and needle sizes (Nm): (a): 80, (b): 90, (c): 100, (d): 110, (e): 120.

TABLE V. The $R^2$ values of fitted curves of needle penetration force against fabric weight for different number of fabric layers and needle size.

| No of fabric layers | | Values of $R^2$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Linear | | | | Exponential | | | | Cubic | | | |
| | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Needle size (*Nm*) | 80 | 0.981 | 0.962 | 0.989 | 0.902 | 0.996 | 0.990 | 0.986 | 0.970 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 90 | 0.946 | 0.955 | 0.983 | 0.995 | 0.996 | 0.998 | 0.993 | 0.980 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 100 | 0.876 | 0.974 | 0.952 | 0.981 | 0.943 | 0.963 | 0.974 | 0.985 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 110 | 0.855 | 0.927 | 0.965 | 0.942 | 0.907 | 0.934 | 0.982 | 0.965 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 120 | 0.975 | 0.949 | 0.948 | 0.954 | 0.988 | 0.968 | 0.936 | 0.982 | 1.000 | 1.000 | 1.000 | 1.000 |
| Average of $R^2$ | | 0.927 | 0.953 | 0.968 | 0.955 | 0.966 | 0.971 | 0.974 | 0.977 | 1.000 | 1.000 | 1.000 | 1.000 |
| Total average of $R^2$ | | 0.951 | | | | 0.972 | | | | 1.000 | | | |

***The Effect of Needle Size on the Needle Penetration Force***

The results show that needle size has a significant effect on NPF, when fabric weight and number of fabric layers are constant. *Figure 7* shows that with increasing of needle sizes, the values of NPF increase. The needle with a higher size has a greater diameter. Thus, during needle penetrating into the fabric structure, a larger force exists between fabric and needle. However, in some needle sizes, the applied forces by needle are very close to each other.

As it is shown in *Table VI*, in cases *D1L1* (FW= 300 g/m$^2$, NFL= 1), *D1L2* (FW= 300, NFL=2), *D1L3* (FW= 300, NFL= 3) and *D1L4* (FW=300, NFL= 4), the differences between NPF in needles 80, 90, and 100 are not meaningful. It could be found from Tukey test (*Table VI*) in all cases except *D4L4*, the differences between NPF values at least for two needle sizes are not significant.

Generally, the effect of needle size in heavier fabric (D4) is more than that of the other fabrics (*Figure 7*). This result is due to that the cover factor value of fabric D4 is the highest among the fabrics; as a consequence there is little gap between yarns in fabric structure, and the needle penetrates into the yarn construction itself. Therefore, the NPF increases considerably compared to the other fabrics, which have a lower cover factor. This is similar to the findings of Carvalho *et al.* [10].

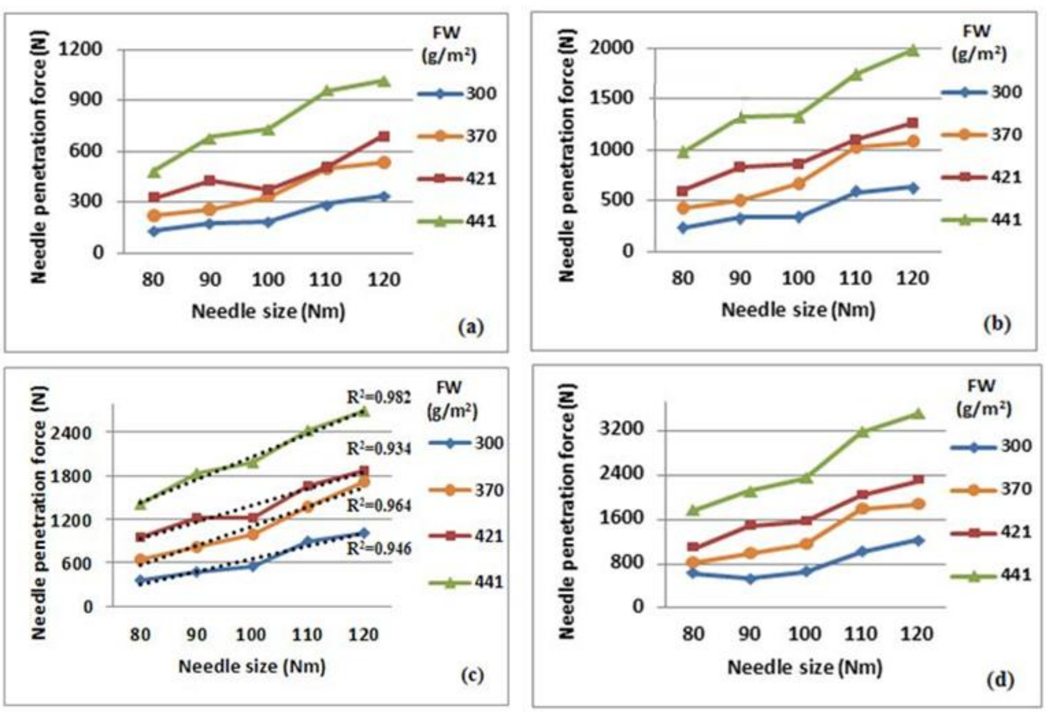


FIGURE 7. The effect of needle size on the needle penetration force under sewing with different fabric weights and number of fabric layers (a): one layer, (b): two layers, (c): three layers, (d): four layers.

TABLE VI. Multiple comparison results (Tukey test) for needle size changes.

| Code | | D1L1 | | D1L2 | | D1L3 | | D1L4 | | | D2L1 | | | D2L2 | | | D2L3 | | | | D2L4 | | | D3L1 | | | D3L2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| NS (Nm) | 80 | * | | * | | * | | * | | | * | | | * | | | * | | | | * | | | * | | | * | | |
| | 90 | * | | * | | * | | * | | | * | * | | * | | | * | * | | | * | | | * | | | | * | |
| | 100 | * | | * | | * | | * | | | | * | | | * | | | * | | | | * | | * | * | | | * | |
| | 110 | | * | | * | | * | | * | | | | * | | | * | | | * | | | | * | | * | | | | * |
| | 120 | | * | | * | | * | | | * | | | * | | | * | | | | * | | | * | | | * | | | * |

| Code | | D3L3 | | | D3L4 | | | | D4L1 | | | D4L2 | | | | D4L3 | | | | D4L4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| NS (Nm) | 80 | * | | | * | | | | * | | | * | | | | * | | | | * | | | | |
| | 90 | | * | | | * | | | | * | | | * | | | | * | | | | * | | | |
| | 100 | | * | | | * | | | | * | | | * | | | | * | | | | | * | | |
| | 110 | | | * | | | * | | | | * | | | * | | | | * | | | | | * | |
| | 120 | | | * | | | | * | | | * | | | | * | | | | * | | | | | * |

D1, D2, D3, and D4: fabric types.
L1, L2, L3, L4: number of fabric layers, 1, 2, 3, 4, respectively

TABLE VII. The $R^2$ values of fitted curves of needle penetration force against needle size for different number of fabric layers and fabric weight.

| | | Values of $R^2$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Linear | | | | Exponential | | | | Cubic | | | |
| No of fabric layers | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Fabric weight ($g/m^2$) | 300 | 0.932 | 0.942 | 0.811 | 0.962 | 0.953 | 0.924 | 0.975 | 0.783 | 0.960 | 0.987 | 0.961 | 0.966 |
| | 370 | 0.906 | 0.940 | 0.963 | 0.951 | 0.961 | 0.958 | 0.993 | 0.952 | 0.927 | 0.987 | 0.970 | 0.961 |
| | 421 | 0.946 | 0.964 | 0.934 | 0.982 | 0.837 | 0.953 | 0.941 | 0.960 | 0.974 | 0.966 | 0.949 | 0.983 |
| | 441 | 0.803 | 0.929 | 0.974 | 0.962 | 0.938 | 0.947 | 0.969 | 0.975 | 0.995 | 0.967 | 0.977 | 0.980 |
| Average of $R^2$ | | 0.897 | 0.944 | 0.921 | 0.964 | 0.922 | 0.946 | 0.970 | 0.918 | 0.964 | 0.977 | 0.964 | 0.973 |
| Total average of $R^2$ | | 0.931 | | | | 0.939 | | | | 0.969 | | | |

The regression analysis result of NPF against needle is depicted in *Table VII.* The cubic curve is a better fit compared to exponential and linear curves. For instance, the linear fitted curves are shown in *Figure 7c*.

***The Effect of Number of Fabric Layers on the Needle Penetration Force***

According to the results, the number of fabric layers has a significant influence on NPF, when fabric weight and needle size are held constant.

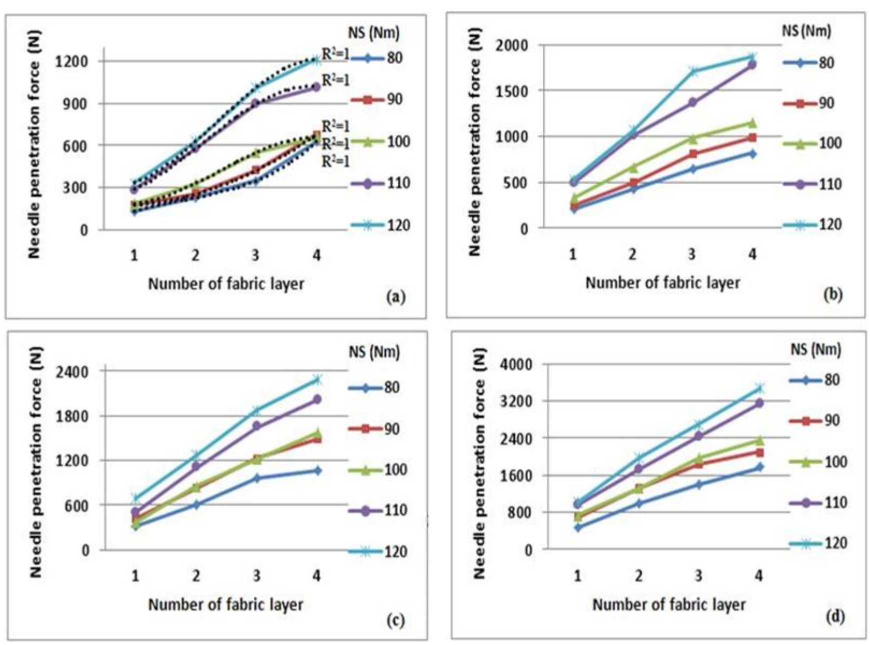


FIGURE 8. The effect of number of fabric layers on the needle penetration force under sewing with different needle sizes and fabric weights ($g/m^2$) (a): 300, (b): 370, (c): 421, (d): 441.

TABLE VIII. Multiple comparison results (Tukey test) for fabric layer changes.

| Code | | D1N80 | | | D1N90 | | | D1N100 | | | | D1N110 | | | D1N120 | | | | D2N80 | | | | D2N90 | | | | D2N100 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| NFL | 1 | * | | | * | | | * | | | | * | | | * | | | | * | | | | * | | | | * | | | |
| | 2 | * | * | | | * | | | * | | | | * | | | * | | | | * | | | | * | | | | * | | |
| | 3 | | * | | | | * | | | * | | | | * | | | * | | | | * | | | | * | | | | * | |
| | 4 | | | * | | | * | | | | * | | | * | | | | * | | | | * | | | | * | | | | * |

| Code | | D2N110 | | | | D2N120 | | | D3N80 | | | D3N90 | | | | D3N100 | | | | D3N110 | | | | D3N120 | | | | D4N80 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 |
| NFL | 1 | * | | | | * | | | * | | | * | | | | * | | | | * | | | | * | | | | * | | |
| | 2 | | * | | | | * | | | * | | | * | | | | * | | | | * | | | | * | | | | * | |
| | 3 | | | * | | | | * | | | * | | | * | | | | * | | | | * | | | | * | | | | * |
| | 4 | | | | * | | | * | | | * | | | | * | | | | * | | | | * | | | | * | | | * |

| Code | | D4N90 | | | | D4N100 | | | | D4N110 | | | | D4N120 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Groups | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| NFL | 1 | * | | | | * | | | | * | | | | * | | | |
| | 2 | | * | | | | * | | | | * | | | | * | | |
| | 3 | | | * | | | | * | | | | * | | | | * | |
| | 4 | | | | * | | | | * | | | | * | | | | * |

D1, D2, D3, and D4: fabric types.
N80, N90, N100, N110, and N120: needle size, 80, 90, 100, 110 and 120 (Nm), respectively

TABLE IX. The $R^2$ values of fitted curves of needle penetration force against number of fabric layers for different fabric weight and needle size.

| | | Values of $R^2$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Linear | | | | Exponential | | | | Cubic | | | |
| Fabric weight (g/m$^2$) | | 300 | 370 | 421 | 441 | 300 | 370 | 421 | 441 | 300 | 370 | 421 | 441 |
| Needle size (*Nm*) | 80 | 0.979 | 0.974 | 0.974 | 0.984 | 0.948 | 0.905 | 0.955 | 0.944 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 90 | 0.966 | 0.963 | 0.983 | 0.965 | 0.916 | 0.935 | 0.925 | 0.962 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 100 | 0.948 | 0.979 | 0.995 | 0.972 | 0.956 | 0.922 | 0.922 | 0.942 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 110 | 0.967 | 0.988 | 0.983 | 0.991 | 0.911 | 0.947 | 0.937 | 0.906 | 1.000 | 1.000 | 1.000 | 1.000 |
| | 120 | 0.985 | 0.949 | 0.994 | 0.988 | 0.996 | 0.955 | 0.942 | 0.936 | 1.000 | 1.000 | 1.000 | 1.000 |
| Average of $R^2$ | | 0.969 | 0.971 | 0.986 | 0.980 | 0.945 | 0.933 | 0.936 | 0.938 | 1.000 | 1.000 | 1.000 | 1.000 |
| Total average of $R^2$ | | *0.976* | | | | *0.938* | | | | *1.000* | | | |

In all fabrics and needles, the values of NPF increase with fabric layers (*Figure 8*). Also, for coarser needles the slope of rising of NPF is more than that of finer needles. On the other hand, the effect of fabric layers on NPF, especially for coarser needles (110, 120), is more pronounced. It is clear that with increasing the number of fabric layers, the needle passes through a thicker structure leading to a higher needle penetration force. In cases *D1N80*, *D1N90*, *D1N110*, *D2N120*, *D3N80*, and *D4N80*, there is no significant difference between NPF in some layers (*Table VIII).* However, in the other cases the differences between NPF for all layers are meaningful. The results of the regression analysis of NPF as a dependent variable and fabric layers as independent variable depict that the cubic curve exhibits higher values of $R^2$ than linear and exponential curves (*Table IX*). The cubic fitted curves for fabric D1 are shown in *Figure 8a*.

***The Effect of Weave Pattern on the Needle Penetration Force***

The statistical analysis shows that weave pattern has a significant effect on the NPF in all cases. According to *Figure 9*, NPF in fabric D5 (Twill 2/1) is higher than fabric D2 (Twill 3/1).

Generally, the weight of fabrics D2 and D5 is partially similar (370 and 375 g/m$^2$), but the count and density of yarns are different. Therefore, the cover factor values of these fabrics were considered as listed in *Table I.*

According to values of cover factor (40.86 and 40.93 for D2 and D5, respectively), it is expected that the NPF of fabric D2 to be equal to D5, but the NPF of D5 is higher than D2. Thus, it can be concluded that the main source for this difference between NPF values in fabrics D2 and D5 is weave pattern. It is deduced that in the 3/1Twill pattern, the interlacing between weft and warp yarns is less than that of the 2/1 Twill. So, there are less resistance forces against needle penetration for this particular structure. Consequently, needle penetration along with yarn bending is much easier, leading to a lower value of NPF.

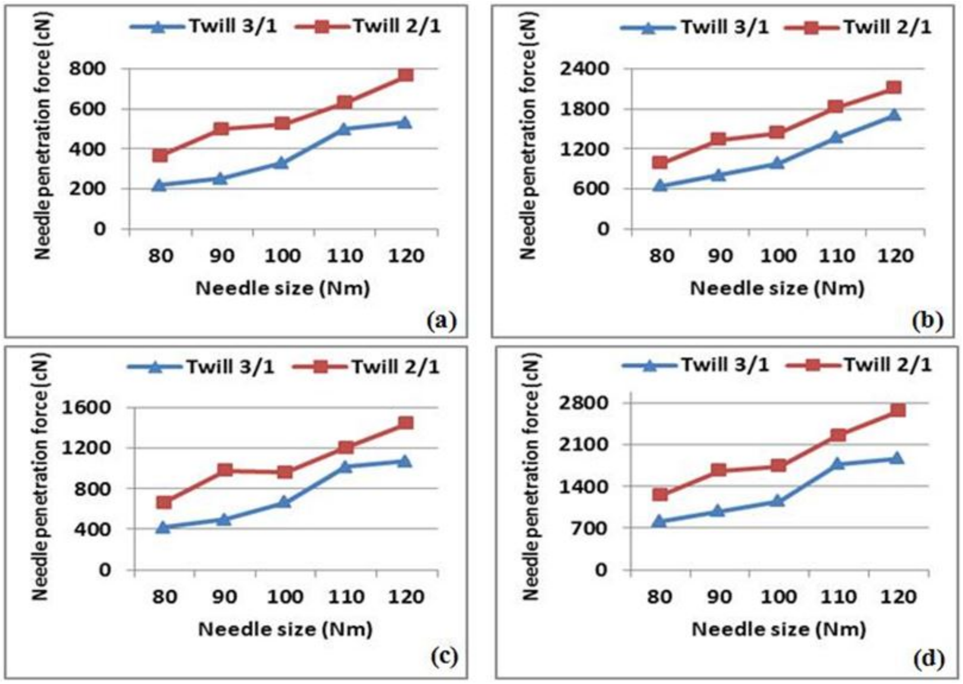


FIGURE 9. The effect of weave pattern on the needle penetration force under sewing with different needle sizes and number of fabric layers (a): one layer, (b): two layers, (c): three layers, (d): four layers.

**The Fabric Sewability**

***The Effect of fabric Weight, Number of Fabric Layers and Needle Size on the Fabric Sewability***

As explained before, the sewability values (SV) were obtained based on defined threshold value.

In *Figure 10*, the sewability values are plotted for different fabric weight, number fabric layers and needle sizes. As it is shown in Figure 10a, for denim fabric with the lowest weight (D1), the fabric sewability for one layer of fabric at three needle sizes of 80, 90, and 100 is good (SV<10%).

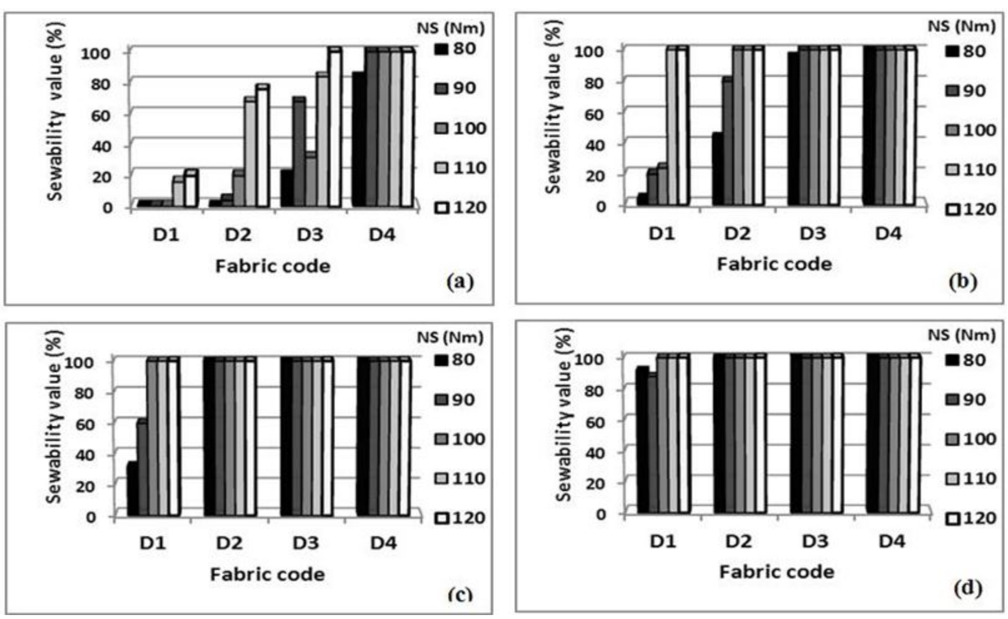


FIGURE 10. The sewability of various fabrics under sewing with different needle sizes and number of fabric layers (a): one layer, (b): two layers, (c): three layers, (d): four layers.

However, the fabric sewability for coarser needle (110 and 120) is fairly good (10% <SV<20%). This result is attributed to the increasing of NPF with needle size as discussed in the preceding section.

For the case of fabric type D2, it is interesting that the sewability trend is partially different. When the fabric is sewn with needle sizes of 80 and 90, the fabric sewability is good. For needle size of 100 is fairly good, whereas for coarser needles (110 and 120), the fabric sewability is not acceptable.

The results indicate that the fabric sewability for fabric type D3 is fairly good with needle 80 for one layer of fabric, and for the other needle sizes the fabric sewability is poor (20% <SV), similar results were obtained for fabric type D4 for one layer of fabric. It was found that for one layer of fabric, the sewability of fabric decreases with increasing of fabric weight.

However, in sample D3 the sewability value for needle 100 is lower than needle 90, but the sewability values of sample D3 with needles 90 and 100 are greater than 20%, so that the fabric sewability is poor for both of these needle types. The reduction of sewability value for needle 100 is due to decreasing of NPF in this needle. This result could explain that the place where the needle penetrates in fabric sample is random. Therefore, in this case, the needle type 100 penetrates into places where the resistance of fabric against the needle is not high. In General, as fabric weight increases the fabric sewability decreases, which possibly results in fabric damage. This finding agrees with the earlier work. [12] Moreover, *Figure 10b* shows that for two fabric layers, the sewability of fabric type D1 with needle size of 80 is good, with 90 is fairly good, and with the other needle sizes is poor. The sewability of fabric types D2, D3, and D4 for all needle sizes is poor for two layers of fabric. By increasing number of fabric layers (3 and 4 layers), the fabric sewability becomes poor for all needle sizes (*Figures 10c and 10d*).

***The Effect of Weave Pattern on the Fabric Sewability***

In *Figure 11*, the sewability values of two different weave patterns (Twill 3/1 and Twill 2/1) for all fabric layers and needle sizes are depicted. The weave pattern influences on the sewability of fabric. Fabric D2 with Twill 3/1 has a better sewability than fabric D5 with Twill 2/1 for one layer of fabric.

As mentioned previously, in fabric D5 the NPF increases due to weave pattern type. Therefore, the sewability value increases, and hence fabric sewability becomes poor. In higher layer of fabric (2, 3, and 4 layers), due to increase the NPF, the sewability of fabrics is poor.

The results show that the fabric sewability for fabric type D5 is fairly good only for one fabric layer with needle 80; however, for the other needle sizes and fabric layers the fabric sewability is poor (20% <SV).

**The Sewing Damage**

The study of sewn fabric surfaces after removing sewing thread from fabric was done using digital microscope. According to captured photos (*Figures 12, 13 and 14)*, the damage mainly occurs at the penetration point of the needle in the stitch.

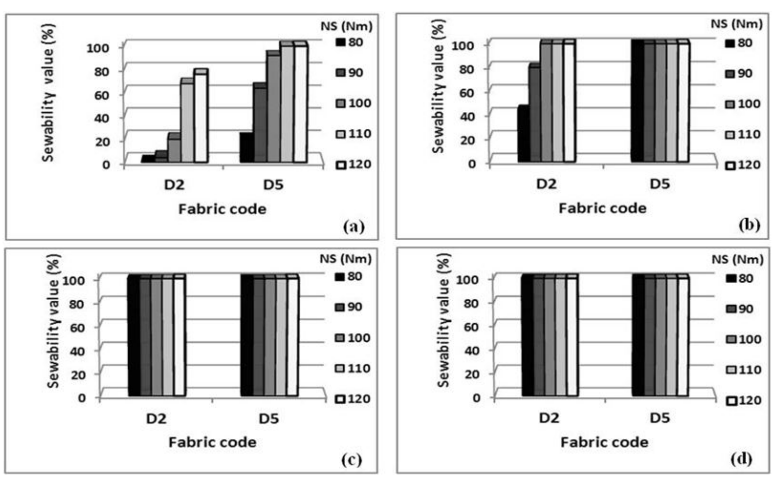


FIGURE 11. The effect of weave pattern on the sewability of fabrics under sewing with different needle sizes and number of fabric layers (a): one layer, (b): two layers, (c): three layers, (d): four layers.

The visual evaluation of photos shows that the sewing damage increases with fabric weight, and needle size. From *Figure 13*, it is clear that the damage of fabric type D3 with needle size 80 for one layer of fabric is not considerable; however, the damage of fabric with the other needle sizes is profound. Moreover, by increasing of needle size, the fabric damage increases. These results confirm that the fabric sewability becomes poor by increasing of needle size.

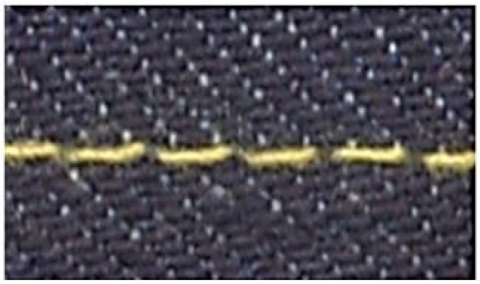

FIGURE 12**.** Appearance of the lockstitch on the surface of fabric type D3.

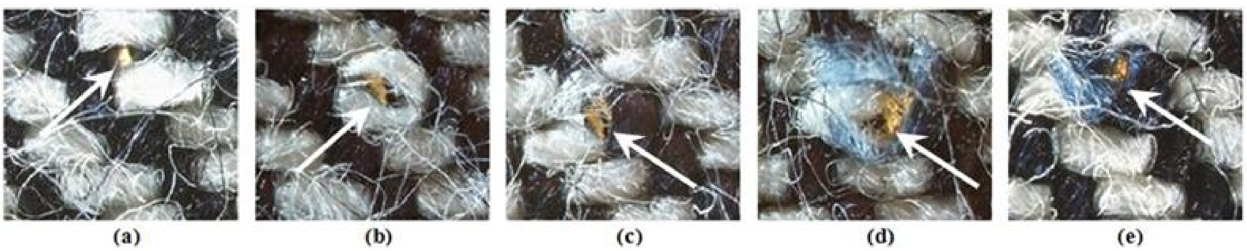


FIGURE 13. Typical photos of needle perforation over fabric surface (type D3) sewn with different needle sizes (*Nm*): (a): 80 (b): 90 (c): 100 (d): 110 (e): 120.

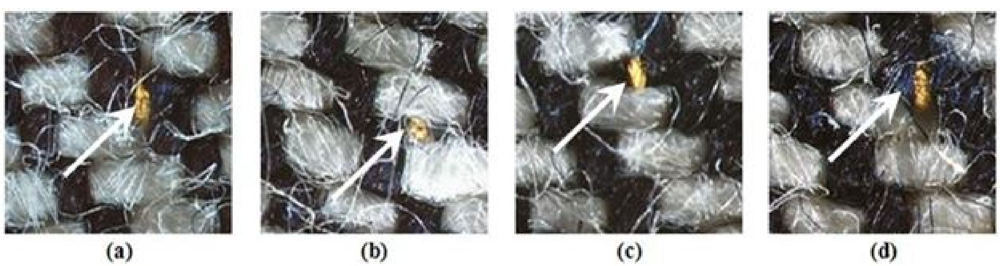


FIGURE 14. Appearance of the needle perforation of fabric D3 sewn as four layers together with needle size 80 *Nm*: (a): first layer (b): second layer (c): third layer (d): fourth layer.

As before found that the fabric sewability will be poor when the number of fabric layers increase. The fabric sewability could be related to fabric damage and ease formation of shell structures. The investigation of fabric damage sewn together as four layers presents that the damage of each layer is partially similar. In *Figure 14*, the damage of each layer (layer 1, 2, 3, and 4) of fabric type D3 with needle sizes 80 was shown. According to *Figure 14* damage of fabric is not profound, but the sewability of fabric sewn as four layers is poor.

Therefore, it can be concluded that when the number of fabric layers increases, the assembled structure is hard deformed into a 3-D structure, which results some problems in sewing process such as needle damage and hence a poor fabric sewability.

**CONCLUSION**

In this study, the effect of fabric weight, needle size, number of fabric layers, and weave pattern on the needle penetration force and fabric sewability were investigated. The results of this work are summarized below:

▪ Statistical analysis of the results shows that fabric weight, number of fabric layers and needle size have significant effects on the needle penetration force. The fabric weight has the greatest effect on needle penetration force, following by the number of fabric layers and needle size.

▪ The values of needle penetration force increase with fabric weight. However, in some cases increasing of needle penetration force is not considerable.

▪ The needle penetration force, in all fabric weights and layers, increase with needle sizes. However, the values of needle penetration force for some needle sizes are partly similar.

▪ By increasing of the number of fabric layers, the values of NPF increase, particularly for coarser needle types.

▪ The needle penetration force in fabric with a Twill 2/1 structure is higher than that of fabric with a Twill 3/1 weave pattern.

▪ The fabrics with various weights have different sewability. When one layer of fabric is sewn, with increasing fabric weight, the sewability value increases, hence the sewability becomes poor. Lighter fabrics (D1 and D2) sewn with finer needles (80, and 90, 100) exhibit better sewability than heavier fabrics (D3 and D4).

▪ The fabric sewability becomes poor when one layer of fabric is sewn with coarser needle. Also, increasing of fabric layers causes a poor sewability of fabric.

▪ The sewability of fabric with a Twill 3/1 weave pattern is better than fabric with a Twill 2/1 structure. When the coarser needles (110 and 120) are utilized in sewing process, weave pattern has no any influence on the fabric sewability.

▪ The trend of NPF increasing with fabric weight, needle size and number of fabric layers is nonlinear: the cubic curve has a greater correlation coefficient compared to exponential and linear curves.

▪ Generally, in order to have acceptable fabric sewability, based on sewing thread and fabric weight, it is suggested that as fine a needle as possible be used.

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