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Heating Of Sewing Needle and Its Impact on Sewing Process

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ABSTRACT

The sewing process is the major operation of any clothing manufacturing industry, from classical garments to technical textiles there is intensive usage of the sewing machine. When the products are made millions a day, any small improvement can bring significant benefits and the role of sewing machines cannot be neglected. Lots of products ranging from shoes, covers for car seats, clothing, technical textiles etc. are stitched every day. The latest sewing machines runs fast and can significantly reduce the production time, however there are multiple areas which lacks improvement including needle design, lubrication system, ambient conditions, optimising of the cooling system etc. All these fields of research are uniquely connected to the performance of sewing. The focus of thesis is to realize the causes of the problem through sewing process. Identify the factors affecting sewing process, propose new innovative improvement of the process, theoretical explanation to problems and optimise the process.

Firstly, it is about sewing needle heating; it is one of the most common factors that is root cause of thread damage, spots on fabric and significant decrease in productivity due to machine stoppage. The sewing needle heating is one of the limiting factors for the reduction in in garment production, as the needle heat and the abrasion from the mechanical parts of the sewing machine causes significant damages to the thread and the fabric that majority of the companies run the machine at lower speeds and stand the loss of lower production. It is important to identify factors that significantly affect the needle temperature and later find economical options to reduce the damage caused. In this thesis different methods are compared for the measurement of needle temperature. Factors like speed of machine, ambient conditions, textile material properties, needle structure, stitching parameters etc. are all tested to identify the real cause of heating. The research work includes experimental and theoretical measurement of needle temperature.

Most common techniques used by the industry to cool down needle are compressed air flow, coating for needle, surface finishes of textile fabric and lubrication of sewing threads. The compressed air flow is costly in terms of continuous use of compressor but out of all is the easiest approach. It is important understand how much needle temperature is dropped and how to optimize the performance of air flow with low usage of compressed air. Thread lubrication is mostly used in the form of uncontrolled addition to the thread by passing the thread through the silicon oil. It needs to be researched if this technique is really helpful and how much oil is

enough for the lubrication and needle heating reduction. Fabric finishes on the other hand is not supported by the clients as it either changes the surface feel or the colour of the fabric. Lastly the needle coatings are marketed by the needle producers with coatings like Chromium, Ceramic or Titanium Nitride etc. It is important to compare them with Diamond Like Carbon (DLC) coated needles and check performance after multiple usage.

Finally, impact of the sewing performance on the textiles, including fire fighter clothing (technical textile) and the car seat covers is discussed. These materials are made for higher performance and the durability or life time is very important. In this research work the damage caused by the needle heat and sewing process on the strength of thread and seams is discussed. It includes the effect of friction, abrasion, fatigue on the sewing thread, also which section of the thread is highly impacted and how much strength is lost during sewing process. Research also includes the effect of pretension of thread on the final seam strength. The thesis provides very useful information for the clothing industry and academia.

ABSTRAKT

Šicí proces se skládá ze šicího stroje, operátora, šitých materiálů (šicí nitě a látky) a také příslušenství, které nepřímo napomáhá procesu. Cílem práce je pochopit a zlepšit celý proces. Šicí stroje jsou důležité pro každou oděvní firmu zabývající se kompletací klasických textilních materiálů nebo i vysoce funkčních pružných materiálů. Každý den se šijí miliony výrobků od bot, potahů autosedaček, oděvů, technických textilií atd. Nejnovější šicí stroje jsou rychlé a mohou výrazně zkrátit dobu výroby, avšak existuje několik oblastí, které postrádají zlepšení, mezi ně patří i problematika teploty jehel v procesu šití, mazacího systému, okolních podmínek, optimalizace chladicího systému atd. Všechny tyto oblasti výzkumu přímo souvisejí s produktivitou šicího procesu. Těžištěm práce je analyzovat celý šicí proces a nalézt souvislosti vlivu jednotlivých faktorů šití. Výzkumná práce identifikujte faktory ovlivňující proces šití, navrhuje nová inovativní vylepšení procesu a teoretické vysvětlení problémů a optimalizuje celý proces.

Mezi nejdůležitější faktory patří ohřev šicí jehly; je to jeden z nejčastějších příčin, který způsobuje poškození nitě, chyb na textilii a výrazné snížení produktivity v důsledku zastavení stroje. Ohřev šicí jehly je jedním z limitujících faktorů snižující produktivitu a zapříčiňuje provoz stroje při nižší rychlosti. Tření mezi jehlou a nití způsobuje enormní zahřívání na špičce jehly a dříku a způsobuje poškození textilního materiálu. Pro pochopení problému zahřívání šicí jehly je důležité nejprve umět změřit teplotu jehly během šití a identifikovat faktory, které významně ovlivňují teplotu jehly, a později najít ekonomické možnosti, jak snížit způsobené škody. V této práci jsou porovnány různé metody měření teploty jehly. Faktory, jako rychlost stroje, okolní podmínky, vlastnosti textilního materiálu, struktura jehly, parametry šití atd. jsou testovány, aby se zjistila skutečná příčina zahřívání. Výzkumná práce zahrnuje experimentální měření a teoretický model teploty jehly.

Dále se jedná o zdokonalení a optimalizaci běžně používaných postupů při šití. Zahrnuje za prvé povrchovou úpravu šicí jehly, v tomto výzkumu jsou testovány jehly potažené diamantem jako uhlík (DLC). Za druhé, chlazení Vortex/chlazení stlačeným vzduchem je běžnou praxí v šicím průmyslu, v tomto výzkumu je proces optimalizován pro získání podobné výsledků mnohem hospodárnějším způsobem. Syntetické nitě se pro svou pevnost a odolnost běžně používají k šití. Aby se zabránilo poškození textilie, šicí stroje běží při mnohem nižších otáčkách

a během procesu šití se musí na nitě nanášet vnější mazivo/lubrikace. Tato kapitola také zahrnuje zlepšení lubrikací šicích nití a zvýšení produktivity šití.

Nakonec jsou diskutovány konkrétní příklady a dopady procesu šití na textilie, včetně hasičského oděvu (technického textilu) a potahů autosedaček. Tyto materiály jsou vyrobeny pro vyšší trvanlivost a odolnost nebo životnost je velmi důležitá. V této výzkumné práci je diskutován vliv procesu šití na pevnost švů v tahu. Zahrnuje vliv tření, otěru, únavy na šicí nit a která část nitě je silně namáhána a jak snižuje pevnost během procesu šití. Je také vysvětlen vliv předpětí nitě na konečnou pevnost švu. Výzkum poskytuje velmi užitečné informace pro šicí proces.

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1 State of the art

Industrial lock stitch sewing machine is one of the most common machines used for stitch in in clothing industry. It's a robust machine with possibility to run at extremely high speeds, low maintenance and produces excellent seam quality. The whole process of sewing nevertheless is based on worker experience, many adjustments on machines are done with the expertise of the operator and very little is standardised. The adjustment of tension of upper and bobbin thread, lubrication of thread, machine speed and ambient conditions etc. are all based on the final aesthetic of the seam. Considering technical clothing like protective garments and car seat production where aesthetic and performance are both equally important then it's necessary to identify, improve and standardise the issues. Loss of seam strength with different machines [1-5] and at different sewing speeds is known, but factors involved for this reduction of strength needs to well identified.

In last decade the growth of the sewing process improvement is quite significant. With lots of products produced by sewing every day, any small improvement in the process can bring great advantage for researchers and industrial partners. In sewing process, the abrasion between textile products like thread and fabric with the needle and machine parts is considered to be the main factor causing weaker seam [6]. The functional performance of the seam, productivity loss due to thread breakage and the aesthetic looks of the sewn products are all important especially for the companies producing technical garments. It is necessary to deeply understand the causes and possible improvement to the sewing process.

The increase of the automatic and semi-automatic sewing machines requires more closely controlled parameters of sewing, as higher speeds can easily be achieved. Considering human factor to be removed and machines can self-stitch a garment. The garment industry is known to be labour intensive, in a medium size company there are more than 500 workers just for the sewing operation. These workers are mostly experts for the aesthetic of seam and making a break free operation of the sewing process [7, 8]. The hidden damages like low tensile strength at high speed, poor tension management and high friction needle selection can make faults to the final seam which is not easy to detect during sewing process [9, 10]. It is important to know before the stitching, what is the maximum limits of speed and others parameters of sewing to obtain the strongest bobbin thread with fully functional seam.

The research work includes the technological aspects of better seam quality by industrial lockstitch machine considering the process faults, common developments used at the industry and overall improvement of the seams of classic and technical clothing.

The variety of sewing machine in the apparel sector is quite huge, each with its own specific advantage. Most of the sewing machines are either categorized according to the type of usage or type of stitch formed. All these machines somehow have the similar working drive but differ in the number of thread and type of stitch formed [11]. The focus of the thesis will be majorly on the industrial lock stitch machine due to its versatile usage and particularly usage in the field of technical and functional garments, where the process parameters are of utmost importance.

Lock stitch machine are very versatile machine with stronger seam and often used where high strength is required. Whereas the chain stitch is used for aesthetic and also where the extension of seams is required like the swimwear or underwear seams. Lock stitch is made by looping of needle thread and other thread from the bobbin [12]. The needle thread comes from the spool/bobbin and travels via all the guides/hooks and the tension devices and lastly through the eye of needle. While the thread from shuttle comes from under the sewing machine and make loops with the upper thread. If all parameters are set correctly then a right seam is made in the middle of the two or more layers of fabric, which provides the highest seam strength [13].

1.1 Stitch formation

Sewing machines are usually categorized on the type of application they are used for; they can be for shoe industry, clothing, swim suits or even technical textiles. All machines have the capability of multiple accessories attachments to make the task much easier. Mechanically all the machines are categorized according to the stitch mechanism [14]. Due to high strength and versatile usage the Lock stitch is the first choice to obtain high strength of seam.

1.1.1 Lock stitch machines

The lock stitch has at least two threads. One comes from the upper spool and the other is under the needle inserted in the shuttle. The stitch is made in the middle of the textile material and considered much stronger than the chain stitch; these stitches are top priority when strength is required. Diagram of classical lockstitch sewing machine is labelled below in figure 1.

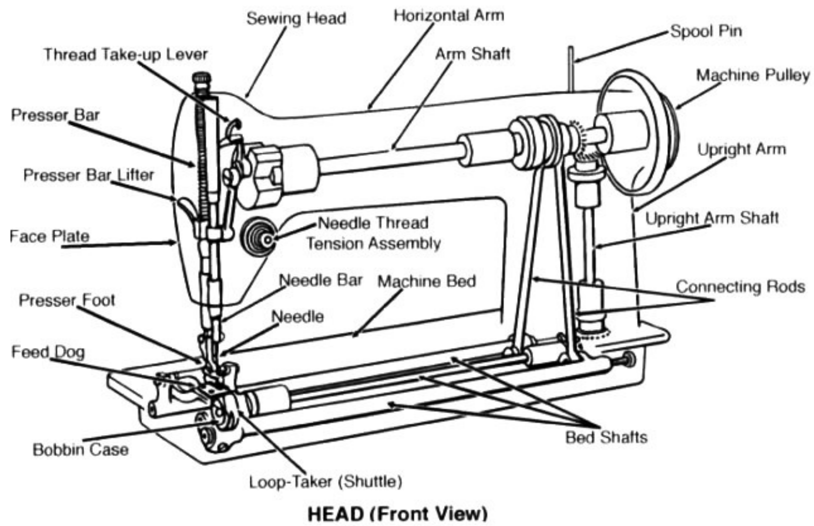

Figure 1 Lock stitch sewing machine [15]

1.1.2 Chain stitch machines mechanism [16]

These stitches can be made with one or multiple threads, the spool thread is goes through the needle and under the sewing bed, the loopers and spreader makes chain or loop for entanglement. This makes chain stitches very common for sewing buttons, swimsuits, underwear etc. The stitches show better elasticity and performance under repeated loadings.

1.2 Sew ability of textiles

It is a generic term used in the field of textile; it shows the ability or possibility of the materials to be connected together with required quality and functionality. Many researchers [17-19] have studies these parameters and came to view that the high quality is not only dependable on the material but majority of the time it is the machine parameters and the expertise of the worker. Many factors like sewing thread, machine parameters, flexibility of the material, and ability of the worker influence the final properties of the 3D garment made from the 2D textile material. Today development of new technologies and the demand of mass production required high production and also high productivity. This requires the understanding of common problems appearing during industrial production of clothing and how to optimise the process and improve production. The sew ability is measured according to the seam strength as compared to the original textile materials used [20], the sew ability is affected by multiple factors like ambient conditions, needle heating, material type, speed of machine, tension type and the efficiency of the worker.

1.3 Seam strength and appearance

Seam appearance and the seam performance are both very important factor for producer and the end user. Seam appearance consists of factors like seam puckering, drape ability, visible faults and uneven stitches. Seam puckering is a term very common in the clothing industry; it is a fault of the seam which causes aesthetic as well as the mechanical losses to the seam [21-24]. This unacceptable problem of puckering is usually evaluated after completion of sewing process. At this time the cost of rework sums up to the garment, and rework is required to make the garment according to demand. Many times, the garments cannot be reworked as re-stitching the seam is also considered as poor quality and loss in the mechanical properties. It is always better to avoid it in the first step and the machine and material parameters should be well understood to obtain good quality seam. The seam puckering is often caused due to following reasons [24].

- Improper pre-tension of the threads
- Feed-jaw mechanism
- Compatible thread to the fabric type

1.3.1 Seam breakage

The easiest measurement of the sewing performance is by the final strength of the seam. There are multiple reasons for the poor mechanical properties of the seam. Few of the most common reasons are listed below [25]

- Machine and material parameters
- Ambient conditions
- Expertise of the worker
- Needle heating
- Lubrication of thread

Most of these factors can be improved with training, investment and experience whereas the **Sewing needle heating** demands more technological improvement, understanding the depth of problem and optimisation of the process.

1.4 Needle heating impact on seam

The loss the strength of seam is either form the mechanical abrasion acted on thread during sewing or the heating of needle. The sewing machines commonly run at 2500-3500/min [26, 27, 29], this speed makes significant impact on the final strength of the seam and can be as low as 40% as compared the original strength of thread [28-30]. When stitching the technical clothing like fire fighter or car seat manufacturing, the sewing speed is intentionally reduced to 1000-15000r/min to obtain better seam performance. The seam strength cannot be judges visually by workers so this problem is often neglected but in case of the technical clothing like fire-fighter or the car seat seam where the airbag pushes out of the seam by breaking the seam, it is important to know the real seam and thread strength.

Needle heating is known for a long time and for traditional textile the only problem was the burnt spots on the fabric [31, 32] but the strength of seam was never considered. Now with more and more technical and smart garment production the highest possible strength and better aesthetic are very important. Consider an example of a car seat air bag, which is deployed through the seam of the car seat and even 20^{th} second delay in the seam breakage can cause fatal injury to the driver. To improve the seam strength at higher sewing speeds, there is only abrasion from machine parts to thread and the heat of the sewing needle. Identifying the needle temperature at different speeds and its impact on the seam can bring useful information for the researcher and industrial partners.

The complications in the experimental technique made many researchers [26, 33-36] to propose theoretical model of needle heating in which researchers used Finite analysis and numerical approach. The results show error of more than 25 % and were never useful for the practical usage in industry. Also, for the comparison the infrared cameras are used which brings significant errors due to the change of the emissivity of metals at different temperatures and smaller size of the needle. Many researchers also worked on the improvement of the machine parts design to improve the sew ability [37-41].

1.4.1 Thermal imaging technique for needle temperature measurement

The contact-less technique of measurement like pyrometers and infrared cameras are commonly used to determine the temperature of object, these devices work on the emissivity principle. The objects like solid wall, human body and non-reflecting bodies are easier to measure the temperature using thermal cameras as their emissivity is high (nearly 1) and does not change for small range of temperature, on the other hand; reflecting objects like metals are harder to measure because of lower emissivity of 0.1-0.3 [41] and if the size is small like sewing needles, then it's almost impossible to focus on the exact measuring part. The technique becomes more flawed when machine is running at higher sewing speed, where a needle size of 1mm need to be focused at speed of 60-80 stitches/second. Secondly the metals need continues calibration of emissivity level as increase in temperature causes significant change in the emissivity levels. Most of the commercial thermal cameras are with fixed emissivity and not possible to change during the measurement period. Anyhow as the technique is quick and low cost, many researchers opt for this methodology to measure the sewing needle temperature.

1.4.2 Thermocouple and heat sensitive paint for needle temperature measurement

Thermocouples is another possibility to measure the needle temperature, in the past these thermocouples were rigid, thick and slow in response but now latest thermocouples of Type C and K can measure extreme temperature with better flexibility, thin diameter and decent accuracy. Thomas Seebeck in 1821 found that two different metallic wires connected together creates a small current with change in temperature. Dorkin and Chamberlain [34] used the thermocouple for measurement of the needle temperature, they run the machine at different speeds and after each stoppage of machine touched the needle with the thermocouple to get estimate value, in the research there were many human errors due to delay of touching the hot needle, also the role of sewing thread was neglected as it caused problems of getting the repeatable results. Researcher [30] also used heat sensitive paints for measuring needle temperature, the researchers claim good results but shows that the coating of paint is removed within few seconds due to friction of thread to the needle eye. The human error and change in the surface property to the adhesion of external material do bring errors.

Another way is to attach the needle and the thermocouple together and perform the sewing process, in the past there were not many thin thermocouples and with poor fatigue it wasn't possible to run the needle attached with the thermocouple. Currently there are multiple high quality, thin and quick response thermocouples available in market. The improvement in this field will be further discussed in the thesis in coming chapters.

1.5 Heating mechanism of sewing needle

Rubbing of two surfaces causes friction and development of heat, in case of sewing process the needle penetrates inside the textile material multiple times a second, secondly the sewing thread passes through the needle eye at a very high speed. The researchers [26,27,32,33,34,42,45,46] have different opinion on this interaction and shows the fabric interaction with the needle as cooling of needle considering the needle is hot and fabric is like an infinite body with ambient conditions. There is an agreement on the heating of needle by the thread, and heat flux generated depends on the thermal conductivity of both surfaces and coefficient of friction. Followed by the heating, simultaneously, the needle cools down by heat conduction the holder, convection with the air and the radiation of hot needle surface.

1.5.1 Boundary conditions

The complexity of the needle temperature analysis is the dependency of heat gain and loss on the time factor. Boundary condition which depends on time with irregular needle shape many researchers have simplified the problem to achieve the maximum needle temperature theoretically. In this kind of thermal system have mainly these boundary conditions, which are that the needle is considered as compact uniform body with homogenous heat flux, needle is attached to the holder with fixed (ambient) temperature.

The illustrative image of thermal mechanism of needle is pointed in figure 2; most of the researchers have neglected the heating by sewing thread and also the cooling by conduction.

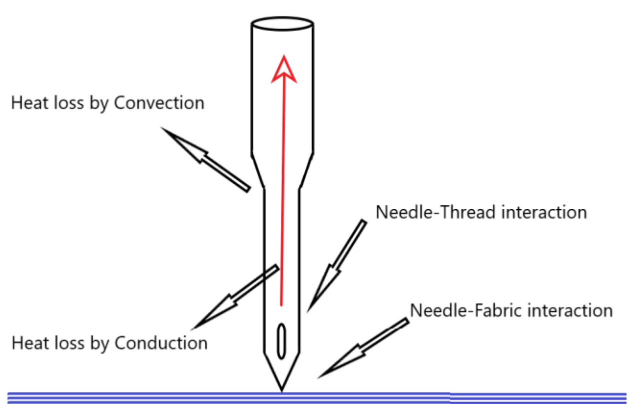

Figure 2 Needle heat balance

The heat flux produced on the needle is by needle to fabric and needle eye surface to thread rubbing, whereas the cooling of needle is conducted either to the needle holder having fixed temperature or to the environment by convection considering a homogenous surface temperature.

The thesis includes 3 latest theoretical models on the problem of needle heating and compared with newly made model, the heating part of the model was made by author in the past but the heat balance equation is newly presented where the heat losses by heat of convection and conduction are theoretical calculated and added to the final heat equation. Adding the heat loss by convection is complicated process and previous researchers have either neglected it or over simplified it by using standard heat transfer coefficient form the literatures. Another issue with the previous researchers is the effect of velocity, it is known fact that the higher speed will bring higher energy and heat to the system but mostly this is opposite used by the previous knows models. The previous models will be discussed first and later a unique theoretical approach is presented, the comparison of new model with the previous models will provide useful information.

1.6 Previous theoretical models

The known fault of the experimental technique was that the researchers measured the needle temperature of 200-230ºC, [28-34], but it was clear from burnt spots on the Polyester fabric that the temperature of needle is definitely above the melting temperature of the needle. This demanded a theoretical approach to predict the needle temperature. Not many models exist in this field as the complex shape of needle, multiple variables and complicated heat exchange phenomena makes it hard have any simplified model. Three of the most well-known models are discussed in this thesis.

Following are latest model published related to the heating of sewing needle.

1.6.1 Sliding Contact Model [26]

When two surfaces are in contact, they produce heat due to friction, the theory is based on idea of Jaegar J [44] where a body rubs on a fixed surface. The theory is applied with little modification according to the requirement as the sewing needle has relatively small diameter as compared the heat flux depth.

Following assumptions were considered for the model

1-Heat is produced at even rate per unit time and unit area.

2- The heat loss is neglected if not in contact to each other.

3- Needle is heated by the fabric (slider).

4- After several cycles the slider also receives the heat from the needle.

5- There will be insignificant heat loss between needle and fabric due to high speed of sliding

With this theory Li[26]made multiple equation showing the heat gain from sliding friction of fabric to needle and loss due to heat of convection.

$$T_n = T_{o1} + (1.06 \cdot \gamma \cdot \frac{q}{K}) \cdot (\alpha \cdot l / v)^{1/2} \quad \text{(eq.1.1)}$$

Where

T_n needle temperature [K]

T_{o1} initial needle temperature [K]

$\gamma \cdot q$ gained needle heat by friction [$W/m^2 \cdot s$]

K needle thermal conductivity [$W/m \cdot K$]

α diffusivity of material [m^2/s]

l needle exchange length with fabric [m]

v velocity (relative) of needle [m/s]

In this model the heat of conduction to the needle holder is neglected by assuming that the needle is infinite long, thread interaction is neglected and the simplified model of needle to the fabric interaction is shown.

Author comments: *The equation 1.1 has interesting parameters but it's strange to have the factor VELOCITY of sewing needle in the denominator; as it is known fact that higher speed create more heat. The model is from Li[26]: The research work is known in the field of sewing heating and claims to predict the needle temperature for lower speeds of sewing.*

Cooling down of needle by force of convection in Sliding model is described by Li [26] as below

$$T_n = T_\infty + (T_i - T_\infty)\, exp\, (-\frac{h_c F}{p \cdot s \cdot V_{ol}}) \qquad \text{(eq.1.2)}$$

Where

T_∞ ambient temperature [K]

T_i initial temperature when cooling begins [K]

h_c convection coefficient [W/(m^2 ·K)]

F area [m^2]

V_{ol} volume of needle to cool down [m^3]

p needle density [kg/m^3]

s specific heat of needle [J/kg·K]

Both the equations are used to heat balance the needle heating, where heating is from the fabric-needle interaction and the cooling ins from heat of convection, the convective coefficients are hard to calculate so the absolute values are taken form literature. The model is predicted from machine speed of 500-2000r/min with the fabric thickness of 2-14mm. Li found out that

- Heat of radiation loss can be neglected due to small needle dimensions
- Linear rise of temperature at different machine speeds
- Fabric-needle friction can be source of heating and cooling, whereas convection heat transfer is major source of needle cooling.

The researcher measures the linear increase of needle temperature with respect the sewing speed and also showed the impact of time factor on the growth of temperature. The model equation has some basic flaws but generally it gives idea of the heating of needle at different time interval and speeds

The results of this model regenerated from raw data are shown in the figure 3.

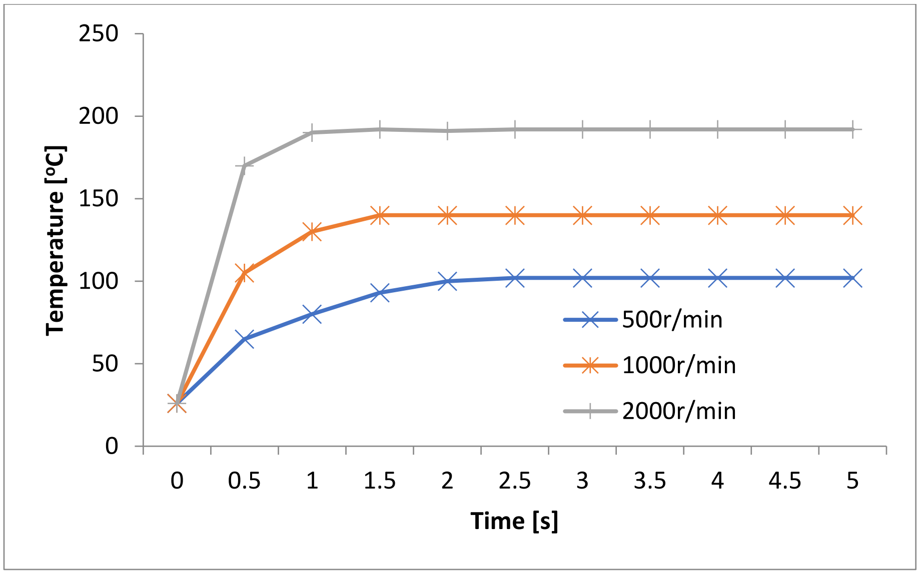

Figure 3 Output result of Sliding contact model [26]

This model can predict the temperature of needle after making multiple adjustments and also avoiding some of the factors like heat conduction through the needle. The results show 25-30% error for lower speed of sewing and errors ranges above 70% when speed is higher than 2000r/min.

1.6.2 Lumped Model [29]

In this approach the motion of the needle with the fabric is simplified considering the touching (contact) of needle as same length as the fabric thickness, the needle passes through each layer by layer of fabrics. The unsteady heat problems are complicated and often require simplification to achieve relatively near results. The lumped variable method is popular when the object has relatively small geometry, or low coefficient of surface heat transfer. In this approach needle is considered as moving heat source which can be modelled. The needle with small diameter slides with the infinite long fabric. The researcher considered 3 processes during the needle cycle and used Matlab to run the simulation. The researcher also considered the rise of the fabric temperature because of the continuous hot needle interaction. The section of interest is drawn in figure 4.

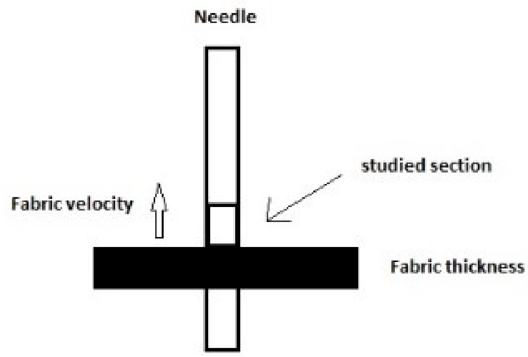

Figure 4 Lumped variable mechanism [29]

The rise of needle temperature due to friction, temperature rise in the fabric and using heat partition ratio to calculate the distribution of heat during each cycle.

1.6.2.1 Rise of needle temperature

Considering a solid shape with volume "V_{ol}", Surface area "A", has uniform initial temperature "T_{ol}", then it will involve constant heat Q(W) from zero time "t" . It is assumed that Q (friction heat) is generated uniformly per unit time and over the contact area. The needle absorbs the friction heat of $\Upsilon \cdot Q$ and the fabric absorbs the $(1 - \Upsilon)Q$.

$$T = T_{\mathrm{ol}} + (\Upsilon \cdot Q/c \cdot \mathrm{p} \cdot V_{\mathrm{ol}}) \cdot t \qquad \text{(eq.1.3)}$$

The time during which friction heat happens between needle and fabric is defined as

$t = \delta/v$, where δ is the studies section and v is velocity [m/s] of needle, so in each stitch cycles there will be multiple of these time periods.

The simulation on Matlab is run to calculate the rise of needle temperature due to friction.

1.6.2.2 Temperature rise in the fabric contact area

First assumption of the model is that heat does not escape the surface of fabric which doesn't contact the hot needle. Rise in the needle temperature is given by following equation

$$T = T_{o2} + ((1 - \Upsilon)Q/2 \cdot \pi \cdot k_2 \cdot b) \cdot t \qquad \text{(eq.1.4)}$$

Where

T_{o2} the initial fabric temperature [K]

$((1 - \Upsilon)Q$ heat conducted to the fabric [W]

k_2 heat conductivity of fabric [W/m·K]

b dimension of needle, calculated experimentally considering the transformation of hemisphere to cylinder [m]

In this model as well the role of thread is neglected and the model predicts the heating of needle based on sewing speed, fabric thickness, time of heating and type of material. The results brought higher error than the previous model; apart from assumptions in the model to simplify it caused the significant error including the role of sewing thread was not considered in the model.

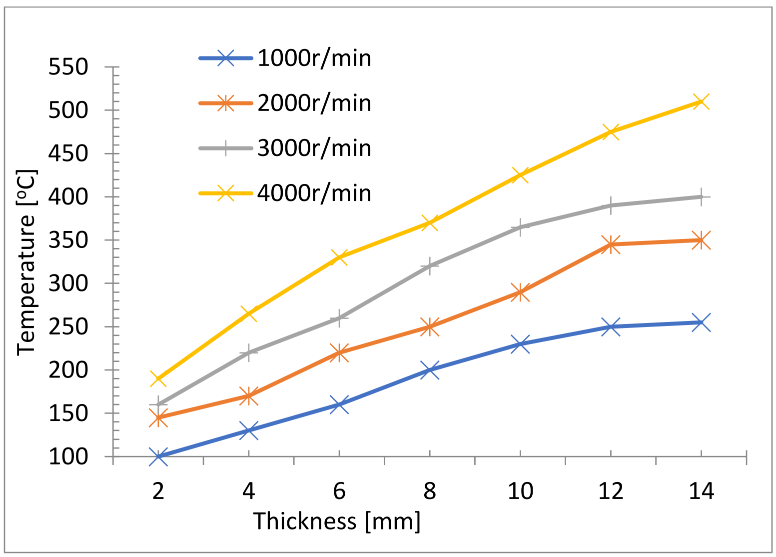

Figure 5 Output result of Lumped model [29]

The model shows somehow linear relationship with thickness of fabric but the results are non-comparable to the experimental results. In some cases, the needle heat was above 500ºC. Overall, the idea is good but the model is based in many assumptions and simplifications.

1.6.3 FEA [33, 35]

Finite Element Analysis are much more complex in terms of meshing of needle and defining the precise the heat transfer coefficients, especially the heat loss by convection. Researchers [33.35] made 2 theoretical models based on the FEA approach which in general are too complex to be used on industrial scale (apparel companies). Also, verification of all these models is performed by the experimental results from the infrared camera, which I have stated earlier that this method brings significant errors of measurement due to technical reasons.

Following assumptions were made for this model.

- The needle speed at penetration and withdrawal from the fabric is same.
- The fabric and needle properties remain unchanged
- The thermal properties of the textile material are uniform and friction heat generated is evenly distributed over the whole area.
- Thermal Radiation can be ignored because of small mass of needle.
- The frictional coefficient is considered constant at different speeds of sewing.
- Convective heat transfer is considered same through each complete cycle of stitch.

The model is initiated with following equations.

The heat produced by the frictional force is show in the below equation [33]

$$q_x = f \cdot v/A \qquad \text{(eq.1.5)}$$

Where

q_x heat produced by friction [W/m^2]

f.v speed of needle and the friction force between needle and fabric [N·m/s]

A contact dimension [m^2]

The needle passing through the fabric, the friction force can be expressed as [33, 35]

$$f = 2\pi \cdot r \cdot th \cdot p \cdot u \qquad \text{(eq.1.6)}$$

Thermal generation (q_{x-s}) when needle passes through fabric, thermal flux can be shown as

$$q_{x-s} = p \cdot u \cdot spd \qquad \text{(eq.1.7)}$$

The fabric act on the needle with normal force p [N/m^2]

r shows needle radius [m]

th shows fabric thickness [m]

u *shows* friction coefficient [-]

spd shows needle force of penetration [N]

Heat produced by needle and sewing thread interaction [35]

$$Q_t = \mu \cdot S \cdot cos\theta \cdot Vt \qquad \text{(eq.1.8)}$$

μ shows frictional coefficient needle/thread [-]

S shows thread stress with the needle [N]

θ shows thread contact angle [º]

Vt shows speed of thread [m/s]

The convective transfer of heat is complicated issue and is considered constant during each stitch cycle. It can be expressed by the convective heat transfer equation.

$$Q = A \cdot h_C \cdot \Delta t \qquad \text{(eq.1.9)}$$

Where,

A is fabric contact area in [m^2]

h_C heat transfer coefficient by convection [$W/m^2 \cdot K$]

Δt is difference of temperature between environment and the surface of needle [K]

Convective heat transfer is complex phenomena and the coefficient used in the model is used form the reference as $80 W/m^2 K$, considering lower machines speed and air turbulence around needle to be less than 3m/s, this may bring significant error to final results.

The FEA models gives in depth information of the needle heating, effect of friction and the cooling effect by the thread, the peak temperature observed by the researchers was 180ºC, which is definitely much lower than the actual temperature as this hot needle made burn spots on the synthetic thread made from Polyester, it is estimated that the actual temperature should be at least 260ºC, near to the melting temperature of Polyester.

The theoretical approach provided new information and the surface dimension and properties of the needle, fabric and thread were considered in the model, the results were compared with the experimental work of [27] Hersh, he used the hand-held thermal IR camera to obtain the needle temperature at slow sewing speeds without using sewing thread. The results are greatly questionable but for sure bring new knowledge to the complex field of study.

1.6.4 Regression Analysis (equations) using experimental data of IR camera

The needle temperature measurement is either from heat sensitive colour or thermal cameras. The heat sensitive colour [30] has significant error as the coating is quickly scrapped off due to thread friction, on the other hand thermal cameras are used by multiple researchers [27,45,46], all of them claim error percentage of less than 20% but were only measure the temperature at slow speed of sewing. Muge[32] made the following regression equation using Polyester thread.

$$T = -24.7 + 10.7 \cdot x_1 + 0.62 \cdot x_2 + 0.066 \cdot x_3 \qquad [32] \qquad \text{(eq.1.10)}$$

$r^2 = 93.7\%$

Where T is temperature of needle, [°C]

x_1 is fabric (height) in [mm]

x_2 is Count of thread (fineness), [tex]

x_3 is machine revolutions. [r/min]

Regression analysis models exist in the literature and mostly 3-4 significant factors are considered to simplify the equation and some factors like ambient conditions, needle geometry and frictional coefficient were not included in the model. The flaws of these technique of measurement will be discussed in the coming chapters. The work of the previous researchers brings important information and gives a valid reason to go deeper in to the problem of sewing needle heating. It will be useful to evaluate this problem with newer experimental techniques and explanation by theory.

1.7 Optimisation of the sewing process

The improvement of sewing process is either the final seam strength or better productivity.

Three common advancement/technologies used at the sewing field are

- Cooling needle with forced air/vortex
- Lubrication of thread (Wax/oils)
- Surface finishing of needle or textile materials

Companies try different techniques [37,39,40,47-51] to have better aesthetic look of the seam and highest possible strength, Multiple techniques exist to decrease the needle temperature at the sewing floor but the easiest technique is to use compressed air, where as other methods like surface finish of thread or the fabric is not often accepted by the client. These finishes can change the feel of material and attract unwanted dust particle which has to be removed by another process. On the other hand, compressed air to the hot needle is quick technique but not economical.

1.7.1 Compressed air or Vortex tube

Compressed air or vortex tube are both common at sewing companies especially working with technical textile where the seam strength is very important. The compressed air is pushed through thin nozzle pointed at the sewing needle and similarly for the vortex tube. Only difference is that vortex tube can provide much cooler temperature ranging from 5-10ºC at similar pressure of air. The diagram of vortex tube is illustrated in figure 6.

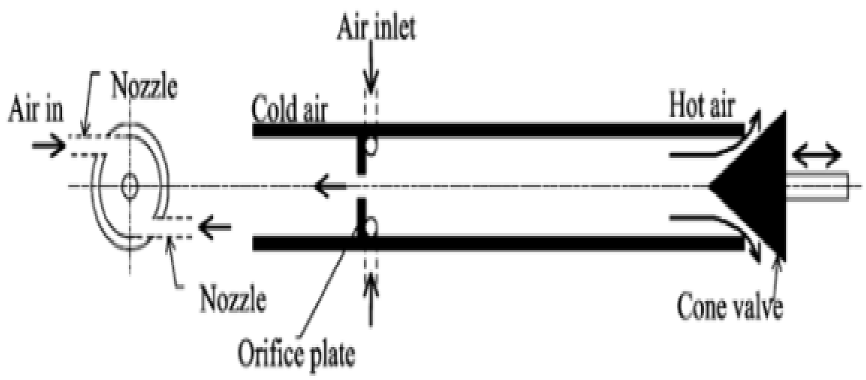

Figure 6 Vortex tube [49, 50]

The compressed gas making is always extra cost for the industry, in this research I have optimised the process to reduce the overall usage of cooling air and use only at specific intervals. These intervals are identified after multiple experiments, the contact time between needle and thread is longest at time of machine stoppage till it fully stops, having a short forceful air flow at this time can bring similar results as compared to the continuous cooling which is much more expensive.

Using compressed air or through vortex tube is still the easiest approach to cool the needle. now a days, it can reduce the needle temperature enough to be lower than the melting temperature of any polymeric textile material. Also, the setup is easier as compared to other cooling technique.

Generally, the workers don't like it as this continuous cooling makes loud noise during sewing process and secondly the cool air makes the worker's hand uncomfortable for the stitching process. The industry uses the cooling only if it required, like stitching of technical or functional clothing where seam strength is very important.

1.7.2 Thread lubrication

In clothing and apparel companies the most common used thread is Polyester core-spun, because it is strong, durable and easily sew able. The thread runs through multiple mechanical parts of the sewing machine including tension devices, guides and the bobbin assembly. It is important to lubricate the thread [52-56], for which silicon lubricants or wax is used. Still there is no guidance or knowledge of how much lubricant to be applied and thread is passed through a bucket of lubricant (attached to the sewing machine) and thread takes the lubricant as it passes. The figure 7 shows how the bucket is attached on sewing machine with thread passing through it. The problem with this system is that it's impossible to control the lubricant intake, as when the machine is running fast then intake is much lower and during machine stoppage or at slow sewing, then relatively higher amount of lubricant is pulled with the thread. Similarly different threads according to their hairiness, density and sorption properties intake different amount of the lubricant. Still this way is cheap and somehow it resolves the issue of thread breakage during high-speed sewing and also the burn dots on the fabric; so, majority of the companies tend to follow this technique of either adding the bucket of Silicon oil to the sewing machine or pass the thread though a wax bar. In this field I have researched the core problems and proposed numerous improvement methods. Figure 7 shows the traditional way of using lubrication bucket.

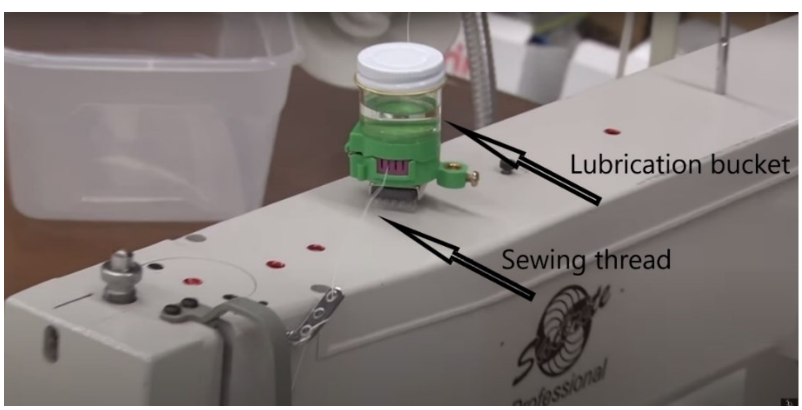

Figure 7 Lubrication setup from company Sailrite®

The lubrication of thread with lubrication bucket setup on the sewing machine with silicon oil is the cheapest technique [53-56] to reduce needle temperature but at higher temperature of needle the wax and silicon turns to greasy structure and attract all the fibers from fabric and which even leads to thread breakage and higher friction. The amount of lubricant required for better sewing needs a lot of research to know how much lubricant decreases the friction and if more amount causes any negative impact. Still the lubrication of threads of company Coats and Amman (largest thread producers) are their company secrets and very less information is available publicly.

1.7.3 Coating and finishing of needle

Hundreds of needle design and shapes are available in the market and two of the most famous needle producers Grozzbeckert® and Schmids® market the needles with multiple low friction surface coatings [57,58] like from Chromium, Ceramic, Titanium Nitride, Teflon and even DLC (Diamond Like Carbon). The design, material and the finishes cause significant impact on the aesthetic and the mechanical performance of the seam. The needle producers are very keen in bringing new product with better frictional properties. In this research some of the known coated needles will be compared.

Coated needles are made for low frictional coefficient, the researchers work on hard-to-find newer coating technique to improve the sewing process. The needles in general last for weeks before the tip of needle is not sharp any more. But when sewing of sewing of leather or technical textiles the needles are changed on daily basis as the not only the tip but the coating inside needle eye and the on the shaft scratched off after multiple cycle of sewing. To keep the seam strength at the maximum possible level, it is advised to change the needle as it its much viable to change needle as compared to have a lower seam strength.

1.8 Sewing process and seam strength

In any sewing operation the aesthetic issues are visible and can be corrected with experience but hidden mechanical damages are either neglected or not considered important for producer as some of the advancement causes extra capital cost or losing production, like running the machine at slower speed causes production loss and using air cooling increase the fixed cost of the producers.

The repeated friction and abrasion during sewing process damages the sewing thread, then the hot needle makes it much worst, the repeated damage negatively impact the strength of thread, generally a thread goes more than 20 times through the needle till it become part of the seam [59-62], the abrasion causes not only mechanical damage to the thread but increases the needle temperature to make it worst for the polymeric materials (fabric, thread).

Multiple researchers have [67-70] studied the effect of sewing speed, machine parameters and thread types on the final seam strength. There is a general trend of 25-30% of less seam strength at higher speeds as compared to lower sewing speeds. The fiber properties and its interaction to obtain a strong yarn/thread is also important factor for thread quality and shows that mechanical properties of fibers, friction coefficient of fiber-fiber and the twist angle makes significant impact to the strength and performance of sewing threads [71-74].

In this research, it shows how the seam strength does not provide the actual condition of the thread, and still the actual seam is much weaker than the experimental results. The sewing thread is tested in sections to know which process of the sewing is actually causing the greatest damage to the sewing thread and causing poor seam strength.

2 Objectives

The objective of the thesis is more in-depth knowledge of the previous research of the author (during dissertation [53]) and advancement in the field of needle heating and improvement of the sewing performance. The field of research is listed below

- **Measurement of the industrial- sewing needle temperature**

The experimental technique to measure needle temperature includes the contact and contact-less approach. It is important to define what are the flaws of these technique and why the results are non-comparable or non-repeatable. The techniques like measurement with thermal cameras is used by multiple researchers and it's important to understand the issue of emissivity for thin shiny needles. The previous work of author on inserted thermocouple approach showed good results but needs a larger set of samples tested for more reliable performance.

Novelty: The measurement by the embedded thermocouple approach provided good results but with the attachment of latest wireless transmission and thin thermocouples, it will be possible to have the temperature of needle in seconds and data can be recorded for longer time. In the previous techniques only the peaks of needle temperature were recorded but by this method it will be possible to have the heating, peak temperature and trend of the needle heat loss.

- **Improvement/optimization of sewing process**

Industrial partners usually go with the easiest or cheapest technique to cool down hot needle, as hot needle decreases the overall production of the company and many techniques like compressed air cooling, lubrication and surface coated needle are used. The amount of lubrication or type of surface finish for process improvement needs a constant growth. The improvement can be either economical like defining the right amount of lubricants for the friction reduction, or optimizing the timing and amount of compressed air cooling for needles. Any advancement in this field needs deeper knowledge of the cause of the heating problem. It will be discussed how the sewing process causes significant impact to the seam strength, what methods are preferred to analyses the true seam strength and finally overall improvement to the technical textile like car seat cover and firefighter clothing will be discussed. As technical garments need not only aesthetically perfect seam but also highest seam strength. Thesis includes how sewing of firefighter clothing and the car seat covers are affected by the adjustment of the sewing parameters. The knowledge of needle heating, thread lubrication and other techniques are used to perform better sewing with high quality seams, especially for the technical clothing like firefighter or the car seats cover materials.

Novelty: As compared to the previous work a larger set of samples at different conditions will be tested for the needle heating and sewing improvement according to the industrial requirements. The compressed air technique is compared with the Vortex tube method to see the improvement in the needle temperature. Also, The DLC (Diamond Like Carbon) coated needles are compared with classical and famous needle (Gabedur) which are commercially available and secondly the performance of new coating after different time cycles are tested.

- **Theoretical analysis of needle heating**

The needle heating is complex phenomena and includes factors like heating by friction of thread and fabric to the needle termed as total heat gain, which was previously theoretically calculated by the author. General approach was to know the peak possible temperature of needle by frictional forces but the overall heat balance includes heat gain and loss by the conduction, convection or radiation.

Novelty: The heat gain of needle was previously calculated and, in this research, the total heat balance will be theoretically analysed, in which heat losses by conduction of needle to the thread, fabric or holder is considered. Followed by the heat convection due to movement of air during sewing motion and the air flow through the needle eye by the sewing thread need to be considered. The last factor is thermal radiation of the hot needle. It is important to have a heat balance equation where heat gain and loss is solved.

3 Sewing needle temperature

It is realized that needle heat is problem for the seam strength [59-61]. To identify the main cause it’s important to know the needle heating either theoretically or experimentally considering multiple factors like sewing speed, time of sewing, ambient conditions and material properties. The thesis discusses the experimental approach followed the proposed analytical model of needle heating.

3.1 Experimental techniques of measurement

A flow chart of the needle heating approach by multiple researchers is shown in figure 8. The collection of techniques is majorly divided in the experimental and theoretical approach. In all the fields multiple researches has been performed in the last decade. The chart gives a general overview what researchers have worked on in the last years and how it will be improved in the author's work. Generally, the contact less techniques of thermal cameras are very famous for experimental techniques on the other side the finite element using simulation software like Ansys is popular to obtain the prediction of needle temperature with respect to time.

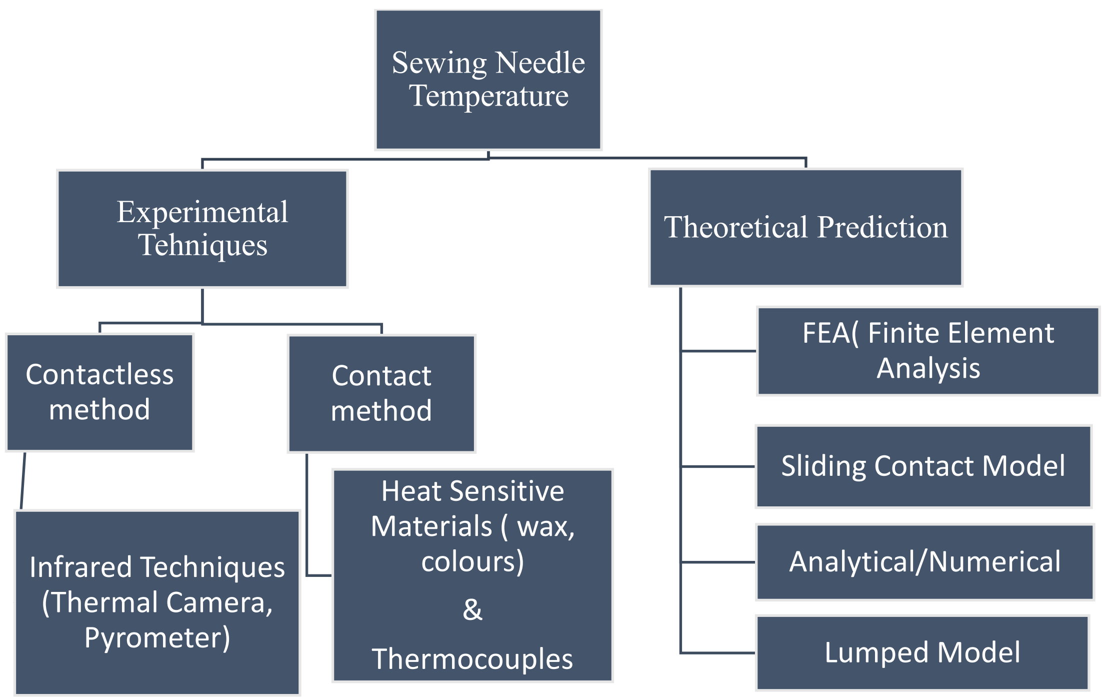

Figure 8 categories of the temperature measurement of sewing needle

It is briefly explained below how the needle temperature is measured and what the problems of measurement are.

3.2 Measurement and reasons of sewing needle heating

3.2.1 Contact method

This technique involves any method of needle temperature in which there is physical contact of the measuring device to the needle, like thermocouple and heat sensitive colours etc. The sewing process goes through enormous roughness between needle, fabric and the sewing thread, and any attachment of colour, waxes and coatings does not last long. Touching the needle with measurement device after finishing the sewing process bring human error and time delay. The needle with small mass and thin size can cool down before the measuring device can be touched.

The scientific idea by prof. Hes is modified to use the K type and C type thermocouple (Company: Omega) which is soldered near the eye of the needle in the groove, the groove is designed for the thread to hide itself during needle insertion time but has enough space of a thin needle to be embedded. In-depth explanation is provided in the published article [53], in which K type thermocouple was used which are relatively slower in measurement and are more rigid with bigger thickness, the thermocouple was replaced with C type with much quick response, size of 0.076mm and connected to fast wireless device for obtaining the temperature each second wirelessly. The thermocouple is selected according to as thin available with measurement range, in thin size the range of K type is less than 300ºC, were as C type can measure till 2300 ºC. The other important property required was the better flexibility to not break the thermocouple during high-speed sewing and also the remote connectivity with the data receiving unit. After multiple tries the whole system form Omega Company was useful for this technique. The tip is soldered in the groove of the needle (the space is enough for the wire to sit inside the groove during the insertion of needle in the fabric) just next to the needle eye, as this is possibly the maximum hot point of the needle. The collector is connected to sewing machine which remotely send the temperature measurement to the computer via Bluetooth. This is accepted that these kind of sensor attachments causes possible change of the thermal disturbance, it was tried to keep this impact as minimum and comparing the results with other techniques, this method shows better accuracy and results were repeatable and reproduceable.

The needle size of 90 or above are most suitable for this kind of measurement (normally size 90-140 are used for Denim or technical apparel) as the groove is big enough for the thermocouple to easily be fixed. The attachment of the thermocouple to the needle eye is shown in the figure 9.

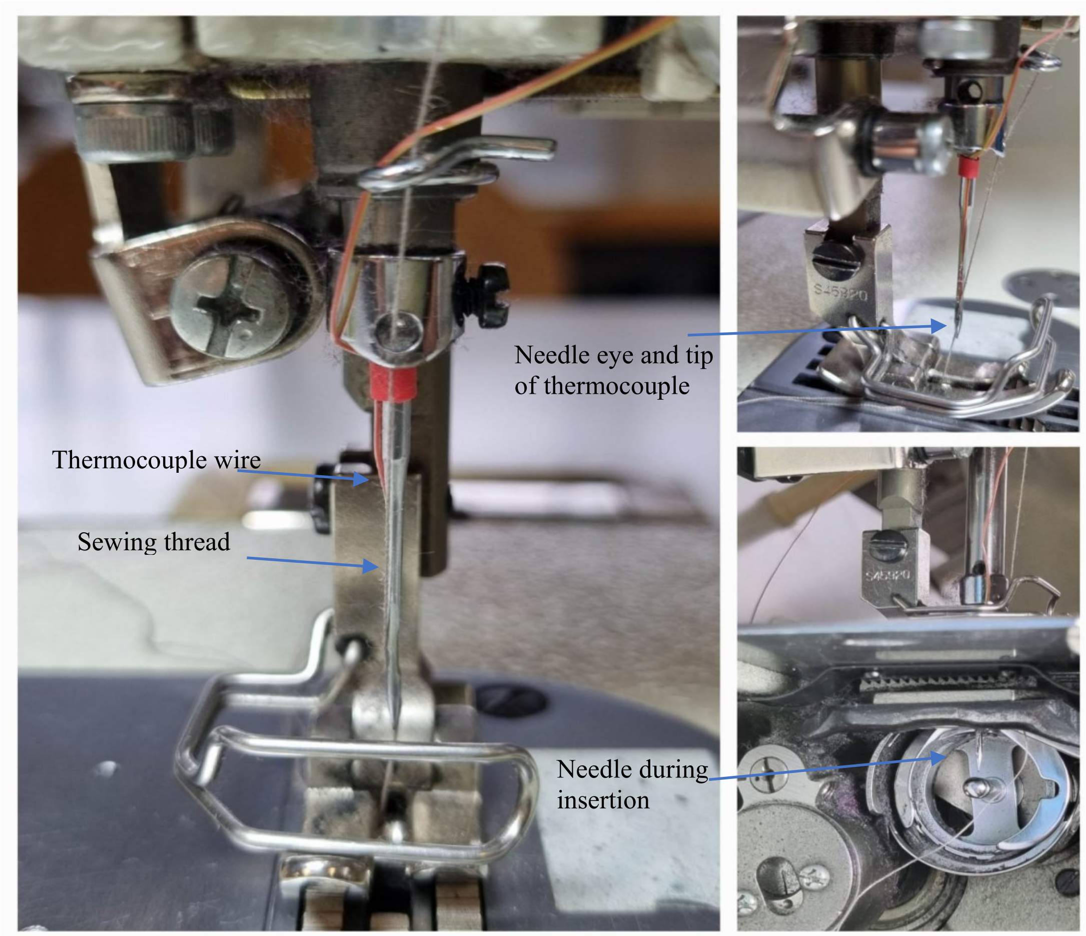

Figure 9 Embedded thermocouple

The classical communication of the thermocouple sensors provided slow response in which it's possible to have the peak temperature but overall gain and loss of needle temperature is very important with respect to short time intervals. As needle gains above 200ºC within first 3 seconds of sewing and similarly the trend of heat loss gives us better knowledge of the heat loss when the machine is decelerating. For this experiment the special wireless connector from the company Omega was ordered. Initially the MWTC wireless device with K type thermocouple(5SC-TT-(K)-36-(36)) is used, these thermocouples are generally good for range below 300ºC, size of thermocouple is 0.1mm, which is thinnest available in the K type for this range of temperature and required flexibility.

Figure 10 Wireless device for K type

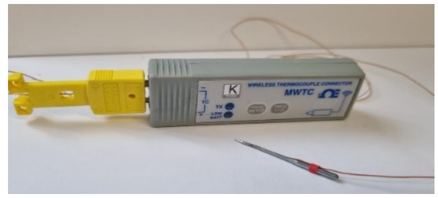

Figure 11 wireless device connected with needle

Figure 12 K type thermocouple embedded in needle

With the improvement in the thermocouple technology the latest device of wireless connectivity UWTC-2 from Omega company can work with thermocouple of type C (W5%Re-W26%Re) which are finer, around 0.076mm and can work till range of 2300ºC, special connector OSTW-C-M-S were used for the connectivity of the thermocouple to the sender device.

Figure 13 Wireless device UWTC for quick response

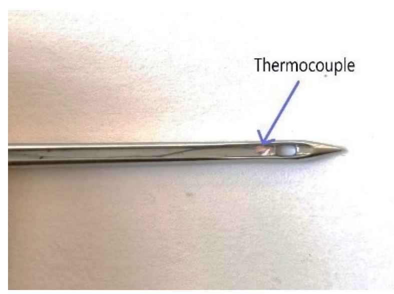

Figure 14 C type thermocouple embedded in needle

With the advancement in the thermocouple thickness, flexibility and the wireless connectivity it was possible to have the peak temperature, gain and cooling of needle heat. Following combination of sewing threads are selected for the research as described in table 1.

Table 1 Threads selected for testing

Trade name	Composition	Thread (density) count [tex]	Coef. of friction μ [-]
(C80) Saba	PET-PET corespun (CS) thread	40	0.13
(C50) Saba	PET-PET corespun (CS) thread	60	0.16
(C35) Saba	PET-PETcorespun (CS) thread	80	0.31
(75) Rasant	PET-COTTON corespun(CS)	40	0.14
(50) Rasant	COTTON-PET corespun(CS)	60	0.17
(35) Rasant	PET-COTTON corespun (CS)	80	0.31
(24/2) Merciful	Mercerised cotton (long staple)	70	0.4
(40) Mercifil	Mercerised cotton (long staple)	50	0.2
(50) Mercifil	Mercerised cotton (long staple)	40	0.13

The testing is performed on industrial Lock stitch machine at difference speed of sewing with 100% Cotton, Denim fabric of 290g/m^2 and two layers of fabric. Each stitch is performed for 20seconds of time. The latest research was performed with new type of thing C type thermocouple and wireless device UWTC from Omega company. The results of the needle temperature are shown in figure 15 with very low standard deviation and repeatable results. At higher speed of sewing from 4000r/min the thermocouple connection was not strong enough for multiple testing and after every 5 tests at higher speed, new needle with attached thermocouple was used.

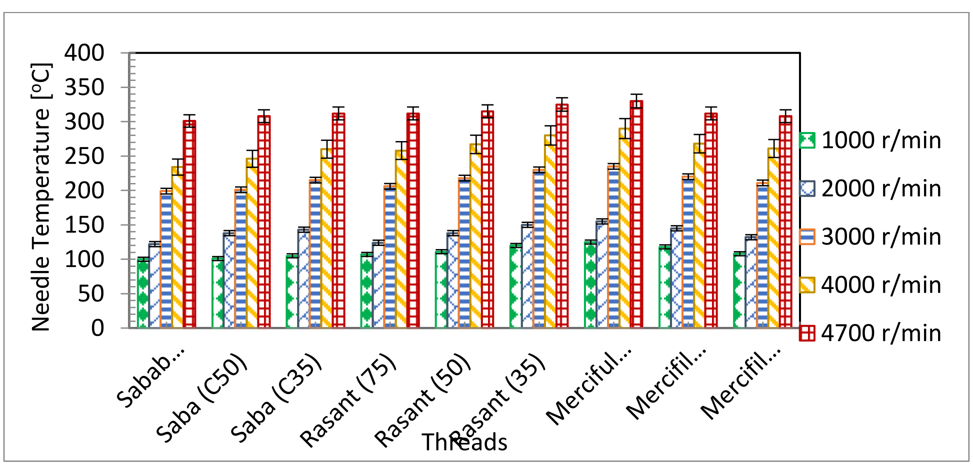

Figure 15 Needle heating with different sewing threads and speed of sewing machine

The gain and loss of the needle heat is shows in the figure below for the speed of 4700r/min, it is obvious that the needle reaches the maximum temperature with in first few seconds of sewing and takes nearly 10seconds to cool down to room temperature.

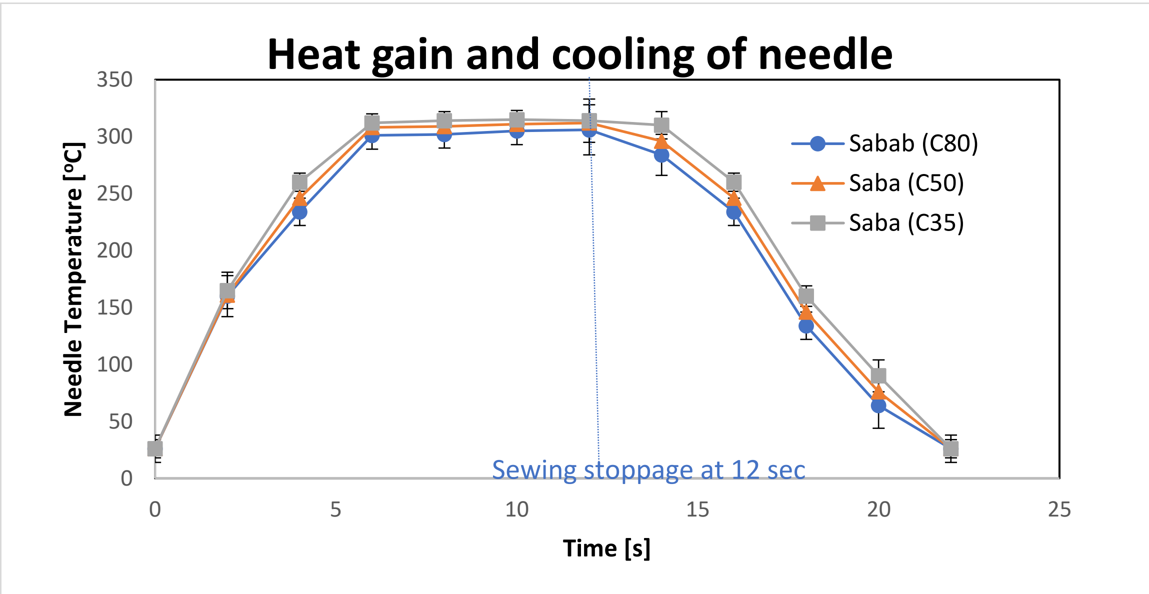

Figure 16 Needle heat gain and loss

The hat gain and loss at very small intervals of time was not possible with K type thermocouple and manual data logging approach, the wireless connectivity and C type thermocouple provided much more reliable results as seen in figure 16.

3.2.2 Contact-less method of needle temperature measurement

These methods include techniques in which the temperature of needle is measured without contact with the needle. Thermal camera, pyrometers and infrared techniques can be used for this approach. Most of the researchers have either used this technique or they have used the results from this method to compare with their theoretical models. In my experiment I used latest thermal camera from Fluke and Flir and observed the temperature of needle from different angles in a dark room, but still it was not possible to observe repeatable results. As revealed in figure 17, that even different position (A, B, C) of camera was tried and with same distance from needle completely and different non repeatable results are obtained. Most of the researchers have used this technique to confirm the needle temperature even though its technically not possible to have the correct results. The technical reason is that the emissivity of needle is very small around 0.1-

0.3[41], which is next to the sewing thread with emissivity of 0.9, the focus on this thin needle at high speed of sewing was not even possible with the latest thermal cameras. Most of researchers have used basic IR camera, with fixed emissivity, the other problem is that the emissivity of the metal changes at higher temperature which no researcher counted.

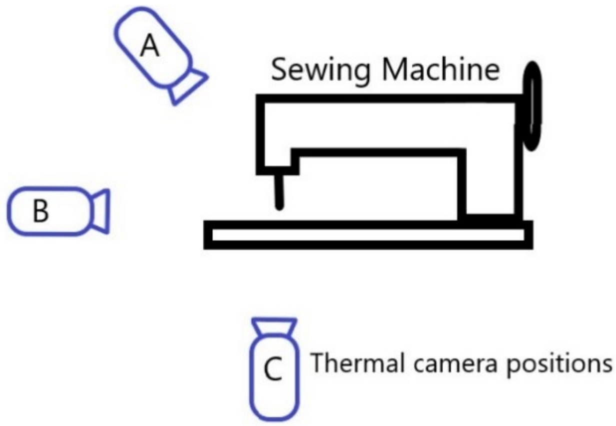

Figure 17 Thermal camera position for measurement

These experiments were formed under black room with controlled climate to avoid any reflection from the surrounding, as working with low emissivity even the radiation reflection from human operator bring false results. From our results it was not possible to measure the correct needle temperature with thermal imaging technique.

3.3 Factors affecting the heating of needle

Multiple factors are tested which potentially can increase the needle temperature, the shortlisted factors are shown in chart 18 as significant and insignificant factors. The measurement is done with the embedded thermocouple approach using huge data set.

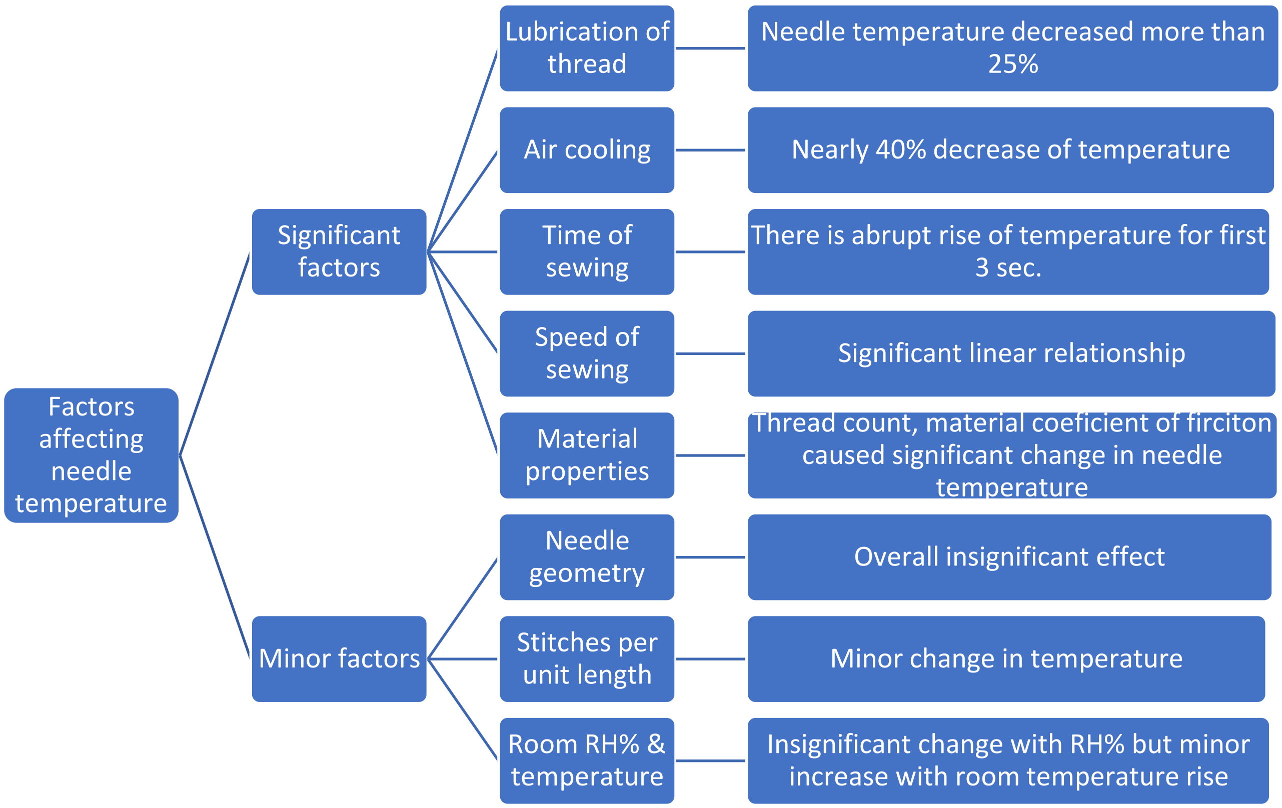

Figure 18 Effect of factors on needle temperature

3.4 Analytical model

The analytical model in this work starts with the heating of needle which was performed by author in the past [53] but the cooling of needle needs more in-depth knowledge of heat of convection, convective coefficient and he loss by conduction, the cooling of needle is the latest advancement by author in this field to finally complete the heat balance equation of the needle. The majority of models available does not consider the thread factor in the calculations or neglected the heat loss by convection. The Finite Element models give useful information but complex meshing and computation makes them almost non practical for any industrial partners. I preferred the analytical model, as they much simpler to analyze and any further improvements can be made according to the theoretical approach. Finally, the industrial partner can utilize at the sewing floor or complex computation can be managed based on the analytic model by researchers. From all theoretical and experimental analysis, it is found that with in first few seconds of the sewing the steady state is achieved which is also very close to the peak temperature of the needle. The heating and cooling are time dependent factor which makes needle measurement much harder and demands much complex computation. The approach is to find the possible peak temperature and later solve the needle cooling equation.

Let's consider initially the temperature increase of the needle by friction of thread-needle and fabric-needle and analytically calculate the maximum needle temperature which needle can attain. The cooling process by heat transfer by convention and radiation takes place at the same time. Normally these all 4 processes as shown in figure 19 operate at the same moment. In the model the assumptions made are listed below Following Boundary conditions are set

1- The needle is considered as solid uniform body with homogenous heat flux attached to the interface between needle and holder with fixed (ambient) temperature.
2- There is constant heat generation by thread friction on the needle eye surface.
3- Constant heat flux generated by the friction of fabric on the surface length of needle.
4- Steady state one-directional heat conduction distribution through the needle to the holder with fixed temperature.
5- Heat transfer from the needle surface to the surrounding by convection with constant temperature.

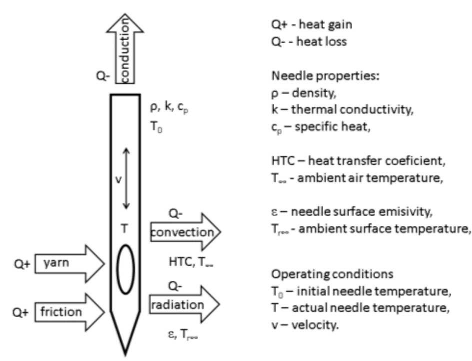

Figure 19 Heat balance of stitch cycle- modified from ref. [26]

Following assumptions are considered for the analytical model. Initial heating part is previous of the author [53], which is used to complete the heat balance equation considering cooling of needle.

1- Start of the sewing process: the fabric, thread and the needle have same ambient temperature.
2- Needle is assumed as cylinder with homogeneous material properties.
3- The fabric, thread and needle material have fixed thermal conductivities and does not change during the process. Whereas λ_N is fixed thermal conductivity of needle, which is considerable higher in comparison to the thread thermal conductivity as λ_y and of fabric material conductivity as λ_F, and are represented by a single value for each respectively.
4- Textile materials (thread, fabric) are considered homogenous throughout length with fixed thermal properties.
5- The small size of needle with small mass and low emissivity is considered negligible for the radiation loss.
6- The peak frictional heat between to surfaces is determined by $Q = f \cdot v$ [33] showing "*f*" as friction force [N] and highest speed between to contact bodies is expressed as "v" [m/s]

7- *"γ"* is Two surfaces in contact shares the frictional heat and this is explained by partition ratio (Charron's relation) [75] as

$$\gamma = \frac{1}{1+\xi_N} \qquad \text{(eq.3.1)}$$

Where $\xi_N = \frac{b_i}{b_N}$, "*N*" represents the needle and *i* expresses the other material interaction, and "*b*" is important factor representing the thermal absorptivity of the materials, it can be expressed as

$b = \sqrt{(\rho \cdot s \cdot \lambda)}$, in which ρ shows density of the material, *s* represents specific-heat of the material and λ is the thermal conductivity of the material.

The needle dimension is simplified as a cylinder to initially measure the heat generation by the friction of thread the needle surface and also the fabric to the needle surface. After getting the peak possible heating, it will be probable to see how the cooling will happen simultaneously.

3.4.1 Speed of sewing thread

The sewing machine running from 500r/min to 5000r/min directly influence the speed of thread; the sewing thread also has a relative speed with the needle movement as well. The sewing thread moved forward, reverse and also remains un moved for 35% of each stitch cycle. To obtain this result high speed camera OLYMPUS is used and thread is marked with dots every 1cm to analyse the speed of thread at complete shaft moved or 1 cycle of the stitch at different speeds of sewing, this information is very important to later use for the heat accumulation in the needle.

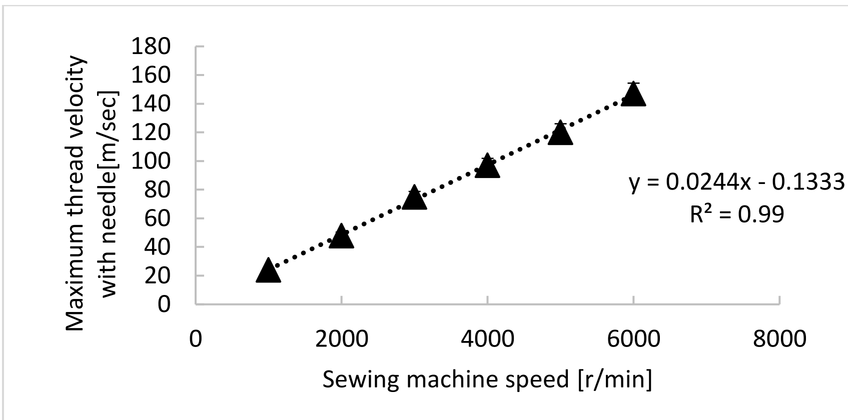

Figure 20 Sewing thread speed

Plotting the obtained results as shown in figure 20, from the high-speed camera shows that there is linear maximum speed of sewing thread at different sewing speeds. In this way a constant can be obtained to be used in the model connected with the machine speed and possible maximum thread speed as shown in table 2.

Table 2 Constant with respect to machine speed

Constant	value
C_F- needle maximum speed	0.0008
C_T -thread speed	0.024

Both factors can be used in the model to obtained the heat generated by frictional force.

3.4.2 Needle penetration force

The normal force acting on the needle will be used in the model, it is possible to obtain these results from literature [103-107] and experimentally is measured using the piezoelectrical sensor behind the shaft of needle, the results of theory and experiment are comparable and can be used in the model where normal force of needle is required. The peak force in Newtons is used for the model.

3.4.3 Friction measurement

Frictional coefficient between needle and thread can be obtained theoretically but in this research the instrument Lawson-Hemphill) is used according to the standard ASTM D-310[91]. For heating of needle by thread and fabric friction, this coefficient will be important.

3.5 Heat gain model [53]

Firstly, it is important to know the maximum heat generated by the needle-fabric and thread friction. Knowing the maximum heat accumulation, it will be much easier to determine the maximum temperature needle can obtain if there was no cooling (Conduction, Convection or Radiation).

3.5.1 Heating of Needle

Initially the heat produced by the friction between fabric and the needle surface can be expressed as

$$Q_{FN} = \gamma_{FN} \cdot \mu_{FN} \cdot F_{FN} \cdot v_{FN} \qquad \text{(eq.3.2)}$$

The second source of heating is the frictional heat production between needle and the thread and can be shown as

$$Q_{TN} = \gamma_{TN} \cdot \mu_{TN} \cdot T_T \cdot \cos\theta \cdot v_{TN} \qquad \text{(eq.3.3)}$$

Where, detail of symbols is listed below and the value/unit is shown in table 3.

γ_{TN} is ratio of heat distribution (needle and thread)
γ_{FN} is ratio of heat distribution (needle and fabric)
μ_{TN} is frictional coefficient between thread and needle

μ_{FN} is frictional coefficient between needle and fabric

T_T is maximum stress on thread in one complete stitch [N]

θ is the thread angle to sewing needle [º]

v_{FN} is maximum needle speed in stitch cycle [m/s]

F_{FN} is needle penetration force with the fabric [N]

v_{TN} is maximum thread speed in stitch cycle [m/s]

Knowing all the sources of heating, the maximum heat absorbed by the needle can be expressed as sum of frictional heat from needle-thread and needle-fabric.

$$Q_N = Q_{FN} + Q_{TN} \quad \text{(eq.3.4)}$$

From the equation of calorimetry in a closed system,

$$Q = m \cdot C_N \cdot (T_M - T_i) \quad \text{(eq.3.5)}$$

Where, detail of symbols is listed below and the value/unit is shown in table 3.

m is needle mass [kg]

c_N is needle's specific heat [J/kg·K]

T_M is final temperature of needle [K]

T_i is needle's ambient temperature [K]

From above mentioned 4 equations, following relation is obtained.

$$m \cdot c_N \cdot (T_M - T_i) = \gamma_{FN} \cdot F_{FN} \cdot \mu_{FN} \cdot v_{FN} + \gamma_{TN} \cdot \mu_{TN} \cdot T_T \cdot \cos\theta \cdot v_{TN} \quad \text{(eq. 3.6)}$$

Many variables shown in equation 3.6 are function of time and to obtain the closest results, the equation must be solved as complex function of time. This type of computation will make the equation time consuming and hard to be used at sewing floor. To make the simplification the maximum absolute values of the variables like F_{FN} and T_T are selected, the core objective is to find the maximum temperature needle can achieve considering steady state.

$$T_M - T_i = Z \cdot v_M \quad \text{(eq.3.7)}$$

Where

$$Z = \frac{1}{m.c_N} \cdot \{\gamma_{FN} \cdot F_{FN} \cdot \mu_{FN} \cdot C_F + \gamma_{YN} \cdot \mu_{TN} \cdot T_T \cdot \cos\theta \cdot C_T\} \qquad \text{(eq.3.8)}$$

Grouping all the known factor it can be seen from equation 3.7 that parameter Z can be derived as shown in equation 3.8.

Initially parameters of this equation can be obtained from literature and this will help to calculate the maximum needle temperature due to recitational heat from fabric and thread towards needle. With this approach it will be possible later to find out the heat losses due to convection, conduction or radiation.

The required data for the equation is listed in the table 3.

Table 3 list of symbol and units

Variables	Symbol	Value	Unit
Heat absorption ratio (fabric/needle) [75]	γ_{FN}	0.97	-
Heat absorption ratio (Yarn/needle) [75]	γ_{TN}	0.96	-
density of sewing thread [93,94]	ρ_y	1350	kg/m^3
Sewing thread Specific heat [92]	S_T	1250	J/(kg·K)
Sewing thread thermal conductivity [92]	λ_T	0.15	W/(m·K)
Fabric density (yarn of fabric) [95]	ρ_F	1540	kg/m^3
Fabric Specific heat (yarn of fabric) [92]	S_F	1450	J/(kg·K)
Fabric thermal conductivity [92]	λ_F	0.06	W/(m·K)
Sewing needle density [96]	ρ_N	7850	kg/m^3
Sewing needle specific heat [96]	C_N	523	J/(kg·K)
Sewing needle thermal conductivity [96]	λ_N	40	W/(m·K)
Needle and thread frictional coefficient [experimental value]	μ_{TN}	0.3	-
Needle and fabric frictional coefficient [experimental value]	μ_{FN}	0.45	-
Sewing thread maximum stress [97,98]	T_T	1.1	N

Sewing needle maximum speed [experimental value]	v_N	$C_F \cdot v_M$	m/s
Sewing revolutions (constant is used in the equation to balance the units)	v_{FN}	1000-4700	r/min
Sewing thread angle to needle [29]	θ	45	o
Penetration force (normal force) [experimental value]	F_{FN}	3.3	N
volume of needle	V_{ol}	2.3×10^{-8}	m^3
Maximum thread velocity	v_{TN}	$C_T \cdot v_M$	m/s
mass of needle	m	0.00018	kg

By this equation it's possible to find out the possible maximum temperature of needle obtained due to friction of needle with thread and needle with the fabric, most of the factors are available theoretically and any other factor can be obtained with a quick experiment. After obtaining the peak temperature of needle, the heat losses of heat by conduction, convection and radiation are shown in the following chapter.

The figure 21 shows the only the peak needle temperature of needle at different speeds of sewing.

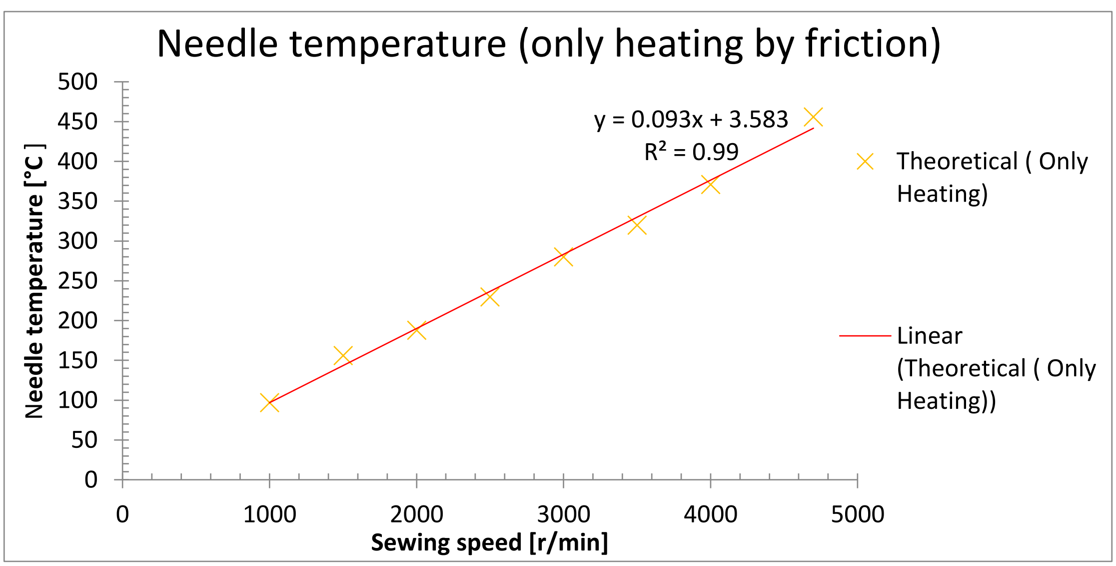

Figure 21 Theoretical prediction of maximum needle heating

3.5.2 Heat Loss from Needle

The predicted temperature is higher than the experimental results, which is obvious as the heat losses are still not measured. The heat loss can be either from conduction, convection or radiation. It is assumed that radiation will have negligible impact on the needle as the small size of needle with emissivity as low as 0.1 will not play any significant role.

Further, the convective heat transfer rate between needle and ambient air (surrounding) and conductive heat transfer through the needle to the holder should be calculated.

3.5.3 Convective heat transfer

The model is initially based on the maximum heat built up in the sewing needle from any source. The factor of radiation can be neglected because of small size of the needle. But the convective heat flow is very dominant factor and cannot be neglected. There are two major complexities for determining the heat loss by convection followed the airflow around the needle.

1- The distribution of the temperature on the needle with respect to time and turbulent non-uniform flow of air around the needle due to penetration and withdrawal process. The illustrative image of needle with flow is shows in figure 22.

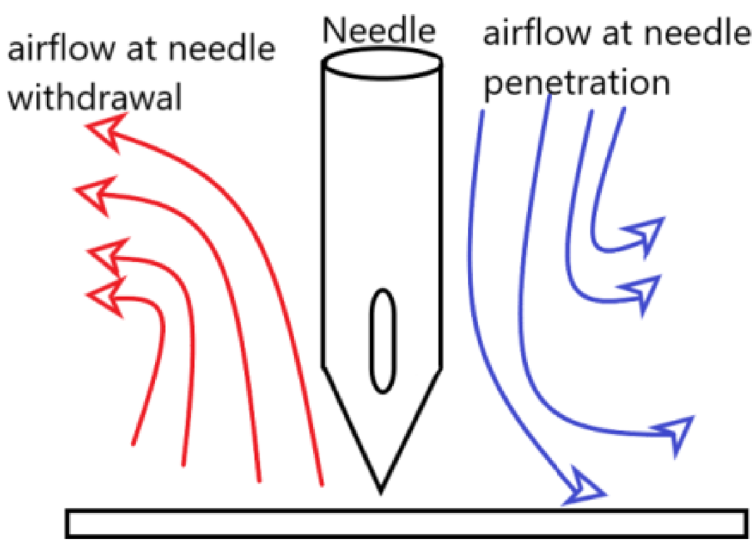

Figure 22 Heat loss by convection with needle penetration and withdrawal

2- The thread contact with the needle is no permanent and the movement of thread through the needle eye bring flow of air specially when not fully in contact with the needle. The illustrative image of needle with flow is shows in figure 23.

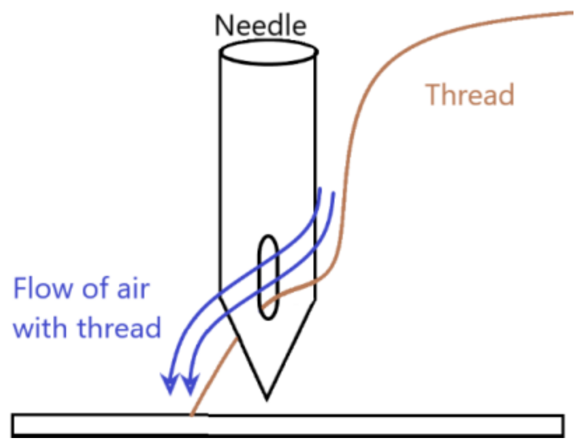

Figure 23 Heat loss by convection due to thread movement

In case of sewing needle its complex as the temperature is distributed on needle with respect to time, the flow of air around is turbulent and penetration and withdrawal of the needle makes huge change in the flow direction, secondly the thread brings flow of air through the needle eye but it can have forwards direction, reverse direction and even stationary with no relative speed of thread (the time when loop of stitch is developing)

To resolve this complex issue, firstly the maximum flow around the needle at different speed of sewing is determined; it was found that there was 2-20m/s (experimental results) flow of air around the needle for machine speed of 1000-4700 r/min. With this result it will be possible to make assumption and determine the representative value of the convective heat transfer coefficient.

According to Perry, [44] for vertical cylinders there is 12W/m^2·K for natural flow and for speed of 3m/s the coefficient is nearly 170W/m^2·K.

From the literature [26, 29] the "h_C" (Convective heat transfer coefficient) for sewing needle for speed of 1000-3000 ranges from 80-120W/m^2·K where the speed flow is 10-15m/s.

The passing of air through needle eye with the thread is complex, knowing the thread moved forward, reverse and also remains constant during each cycle of the stitch. To start with convection analysis, the wired air flow meter from company TESTO (wired Anemometer) was used. As shown in figure 24.

Figure 24 Wire Anemometer

The needle motion of penetration and coming out of fabric makes the air movement in multidirectional and it was better to use the wired anemometer to get the maximum flow of air around needle. Following results shown in table 4 were obtained at different speeds of sewing

Table 4 Air velocity with respect to machine speed

Machine speed [r/min]	Air speed [m/s]
1000	2
2000	7
3000	12
4000	16
4700	20

Knowing the speed of air, temperature of needle and the environment is possible to use the heat of convection equation.

$$Q = A \cdot h_C \cdot \Delta t \qquad \text{(eq.3.9)}$$

Where, A is needle area of surface [m^2]

h_C is convective heat transfer coefficient [$W/m^2 \cdot K$]

Δt is change in temperature of needle [K]

The convective coefficient h_C is composed of factors like properties of fluid, needle geometry, velocity of fluid etc. There are two possibilities considering the air flow either parallel to flat surface or cross flow across a cylindrical body. Both possibilities will be attempted to see the overall difference in temperature.

3.5.4 Cross flow

For parallel flow considering the needle as a cylinder air is actually crossing it, as shown in figure 25. For this configuration the Nusselt number the well-known equation of the turbulent flow can be used [111]:

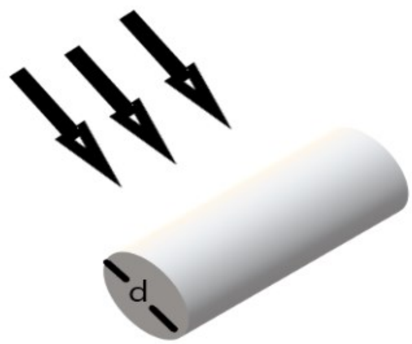

Figure 25 cross-flow on the cylinder

$Nu = 0.59 \cdot Pr^{0.35} \cdot Re^{0.35}$ (eq.3.10)

Where Reynold’s number “Re” can be calculated as below

$Re = U \cdot d/u$ (eq.3.11)

Where "U” is mean velocity of air [m/s]

u is viscosity of air [m^2/s]

d is the characteristic dimension (needle diameter) [m]

And Prandtl number “Pr" can be obtained from literature [110] depending on the properties of air at specific temperature. So convective heat coefficient can be calculated as

$h_c = Nu \cdot \lambda/d$ (eq.3.12)

where

λ is thermal conductivity of air [W/m·K]

d is diameter of needle [m]

This is one assumption that the flow of air is crossing the needle but more realistic assumption should be that the air flow is in the direction of the needle movement, considering this assumption a needle can have parallel flow like air flowing above the flat surface.

3.5.5 Parallel flow

Considering the needle side as flat surface and the penetration and withdrawal process causing a flow of air parallel to the surface of the needle. The literature from Roland [112] was used to match our condition for the equation of Nusselt's number, the illustrative image of air parallel flow on through the surface of plate is shown in figure 26.

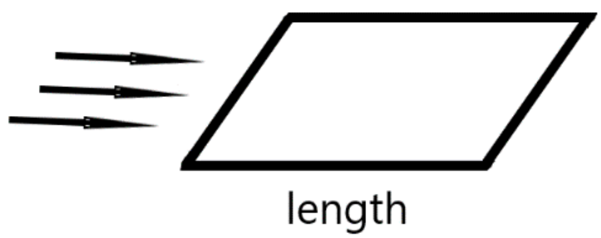

Figure 26 parallel flow on flat surface

This requires calculation using a Nusselt's number as

$Nu = 0.122 \cdot Re^{0.68}$

The Reynolds number can be calculated from equation 3.11 using the length of flat surface as a characteristic dimension.

Both ideas of cross flow and parallel flow are calculated with the given formulas and data depending on temperature are taken from literature respectively. It is good idea to compare the results from both assumption with the experimental results.

In general, the gain of temperature and the heat loss from the needle is illustrated in figure 27, the gain will be from the frictional forces and the loss by convection to the environment can be generalized as below. The picture only depicts how the heating distribution and the cooling by convection are assumed. In which the hottest part of needle is near the eye of needle where the maximum friction al heat from the thread and fabric can accumulate. The gain of heat will further be lost to the environment through convection or to the needle holder by heat of conduction.

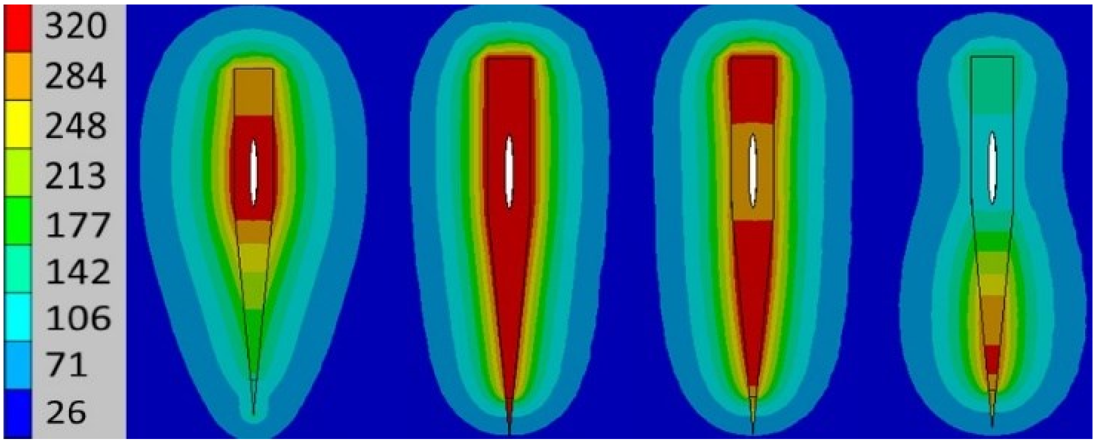

Figure 27 Temperature gain and loss by needle

Considering all the heat gain and later maximum loss by convection or conduction, the convective heat coefficient under cross flow or parallel flow air across needle can be calculated.
The property of air like thermal conductivity, viscosity, density and specific heat at different temperatures are taken from literature [110] to reach more accurate results instead of keeping a fixed average value.
Both the idea of flow of air is solved to see the convective heat coefficient and the total heat loss in terms of temperature form the hot needle. The results are shows in table 5.

Table 5 Heat loss due to parallel and cross flow of air

	Parallel Flow				Cross Flow			
Machine speed [r/min]	Nusselts Number[-]	Convective heat transfer coefficient ($W/m^2 \cdot K$)	Heat loss Q (W)	**Temperature loss [°C]**	Nusselts Number[-]	Convective heat transfer coefficient ($W/m^2 \cdot K$)	Heat loss Q (W)	**Temperature loss [°C]**

1000	6.10	58.54	0.04	**4.40**	4.56	131.21	0.10	**9.90**
1500	9.36	92.62	0.09	**9.40**	6.23	184.99	0.18	**18.70**
2000	11.78	120.60	0.15	**15.30**	7.42	227.88	0.28	**28.90**
2500	13.92	145.73	0.22	**22.30**	8.40	263.77	0.39	**40.30**
3000	16.21	169.68	0.29	**30.30**	9.33	292.93	0.51	**52.30**
3500	19.39	202.93	0.40	**41.50**	10.55	331.38	0.66	**67.70**
4000	23.28	243.67	0.54	**56.10**	11.97	375.91	0.84	**86.50**
4700	26.01	272.23	0.70	**72.50**	12.92	405.75	1.05	**108.10**

It can be seen in the table 5, that the cross flow and the parallel flow brings small difference in the convective heat transfer coefficient and finally the total loss in terms of temperature can be measured. These results will be subtracted from the total heat gain to compare with the experimental results.

3.5.6 Heat loss by Conduction

The second factor for heat loss is heat conduction through needle to the holder. Let's consider a cylinder with temperature of 330^{0}C on one side of it and the flow of heat will be towards the heat sink side (holder)

Using Fourier's Law

$$q = -k \cdot A \ (\Delta T \ / \ \Delta x) \quad \text{(eq.3.13)}$$

Where "k"[W/m · K] shows thermal conductivity of needle, "A" [m^2] is cross-section area of needle and "ΔT"[K]is difference of temperature between the needle tip (maximum temperature) and the holder, "Δx"[m] is the distance of needle hottest part to the holder.

Even at the maximum needle temperature the loss of heat to the holder is negligible (can be solved as $\dot{Q}$ = 0.13 watts) this loss is negligible even at the highest temperature of needle and it is possible to not consider it for the final model.

3.6 Final outcome

To compare the final model the inserted thermocouple approach is used for measuring the needle temperate of PET core spun thread at different speeds of sewing. Identical thread is used for the theoretical model by previous authors, as shown in table 6.

Table 6 Sewing thread used for the experiments

Thread structure	Trade mark	Count (tex)	Twist (t/m)	Direction of twist (ply/single)	Frictional coefficient μ[-]
PET-PET core-spun	Saba C-35 (Amman)	80	490	Z/S	0.30

The theoretical model for sewing needle temperature including parallel flow, cross flow is solved and the results shows that the theoretical solution considering cross flow across needle is much more accurate as compared to the parallel flow. The experimental results are obtained from the inserted thermocouple approach which are close the theoretical results. In general, the results are with lower error than any other model available and it is unique and only existing model where high speed of sewing and sewing thread is considered for determining the needle heating of industrial lock stitch sewing machine.

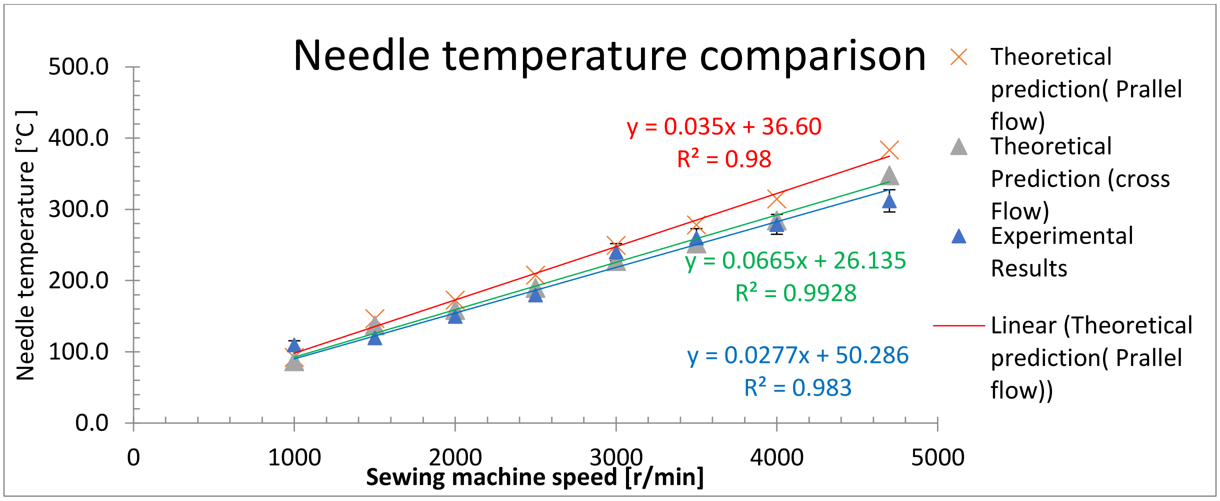

Figure 28 Theoretical and Experimental needle temperature comparison

It can be seen form the figure 28 that there is linear relationship of needle temperature and the sewing speed, also the theoretical analysis using cross flow hypothesis are closer to the experimental results. This analytical technique does not require excessive computation and can be very beneficial for the industrial partners to predict the needle temperature at the sewing floor. The results were also compared with the other models available; the data was taken from the published results of the previous authors [26,29,33,35], Most of the previous models are made without the sewing thread and are over simplified. Whereas the other models which used the complex algorithm uses the thread but the error is even higher than 30% as shown with their own experimental results. Following table 7 shows the comparison of well-known models compared to the present theoretical model.

Table 7 Needle temperature comparison of new model results previous models

Machine speed [r/min]	Experimental Results [°C]	Sliding contact model[26] [°C]	Lumped variable model[29] [°C]	Finite Element Analysis [33] [°C]	**Present Theoretical model [°C]**

500	78(±2.3)	110	110	86	71
1000	118(±3.7)	144	141	126	103
2000	169(±4.4)	192	193	180	162
3000	239(±3.9)	-	-	-	251
4000	273(±4.7)	-	-	-	292

The results from the previous authors were only at lower speed of sewing and majority of these researchers never used the sewing thread during the theoretical analysis. Every model has multiple assumptions and can bring deviation from the final results. The results from the presented model are quite precise and it was also visible in the fabric that machine speed of 4000 r/min or higher there were melted spots on it. Which is clear prediction that the needle temperature is surely above 260^{o} C to cause the melting of the Polyester thread. Which was confirmed form the inserted thermocouple and the theoretical technique. The model can be used for the denim industry which faces biggest issue of thread melting and breakage and causes delay in the production. It is possible to optimize the sewing process to achieve maximum strength of seam without causing damages to the thread or burnt spots on the fabric.

The analytical approach is novel and unique, as in the previous studies the needle temperature by finite element analysis is attempted, which provides useful information but the complexity of the friction heat and time factor makes it almost impossible to be used at any industrial floor. The analytical model on the other hand provides more simplified steps of measurement and can be tested, improved or used by future researchers or industrial partners.

4 Sewing process improvement/optimisation

This chapter involves the advancement in the field of cooling of hot needle by industrial users. There few methods which can be used to decrease the needle temperature

1- Compressed air
2- Thread lubrication
3- Fabric finishes
4- Surface coating of needles

This chapter will include the advancement in the field of all these coating techniques, especially the comparison of needles coatings, optimization of lubrication amount and timing of compressed air cooling.

4.1 DLC coating of sewing needles

To reduce the coefficient of friction of needles, the coated needles are used very common. Two of the largest needle producers Grozzbeckert® and Schmids® produces multiple kinds of coated needles. Diamond Like Carbon (DLC) coated needles are also available in the market but more expensive than other needles [76-79]. The DLC coatings are famous for low frictional coefficient and better hardness properties and that's one of the reasons to be used in the engine pistons etc. [80-90]. The needles are coated with DLC using Plasma assisted vapour magnetron sputtering, these needles are also commercially available but to have different size of coating and final finish, it was self-prepared. The needles turn blacking due to the DLC coating and later the needles are compared with classical and Gabeduer needle from company Goz-Beckert which is the most famous needle in market in terms of low friction and better sew ability. The Atomic force microscopy is used of the surface friction and the later seam thread strength is measured by making 5 samples of 30 second of swing at 4500r/min of industrial lock stitch machine.

The needles are shows in figure 29.

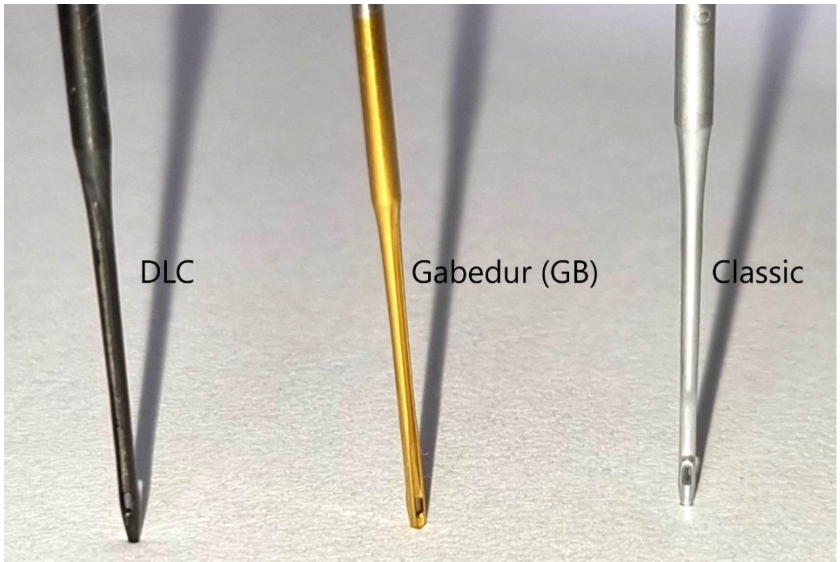

Figure 29 Needles

4.1.1 Needle coating comparison

A classic, Chrome coated, Titanium Nitride coated and DLC coated needles are compared for the surface properties using Atomic Force microscopy and the frictional coefficient of the needle by standards ASTM D-310. These needles are commonly used in the industry and famous for their low frictional performance. The initial results of surface properties are shown in table 8.

Table 8 Surface properties needles

	Without coating needle	Chrome needles (Groz Beckert)	Titanium Nitride Needles, Gabedur (Groz Beckert	DLC needle
Frictional coefficient	0.32	0.21	0.14	0.19
Peak to valley roughness R_t	3.95 µm	3.86 µm	3.59 µm	3.72 µm

It can be seen in the table 8 that the coating the needles causes significant improvement to the coefficient of friction. The DLC coated needles are much better than most of the coated needles but still the marketed product of Groz-Beckert with Titanium Nitride coatings is much better in terms of low coefficient of friction. This technique is very unique for coating the sewing needles and in future with better methodology it is possible that these coated needles can be more economical and better than other coatings.

The other problem with the DLC coated needles was quality of coating after multiple sewing processes. The DLC needles were tested at 4500r/min for 45 seconds and it was observed that the coating, especially at the eye of needle were almost removed in just 15 cycles of long sewing. As shown in figure 30.

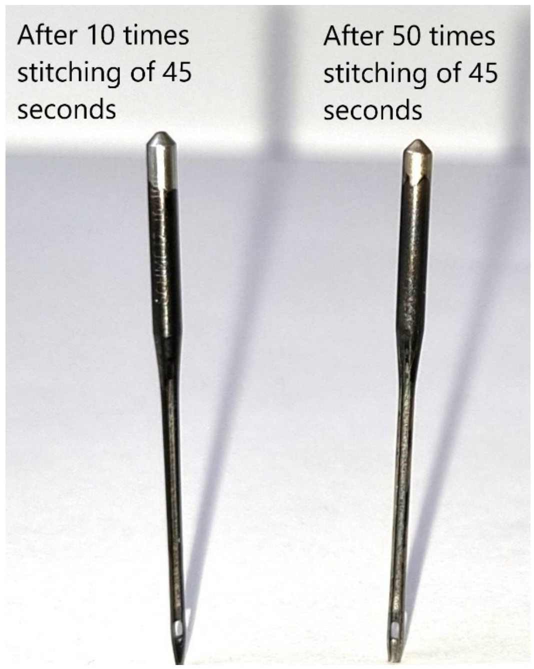

Figure 30 DLC needle after usage

4.2 Improvement of the cooling techniques

The damage of sewing process to the thread and the fabric is well known and many researchers have recommended changes to the process [37-40]. Industrial solution to hot needle is either use compressed air, lubrication to the threads, applying finishes to fabric or coating needle to improve surface friction.

Out of all the compressed air so the easiest solution and many companies do that as it makes the machine run at higher speed with low chances of damage to the garment. Even though the compressed causes a significant cost to the production but as other options are more complicated like using finishing to the fabric is not accepted by the customer and can cause color change or sometimes needs extra work to make the fabric according to the requirement of the client.

Similarly, lubrication of thread is very uncontrolled and difficult to predict the final strength of the seam. It is possible to use a classical nozzle for compressed or also the Vortex tube setup, in the vortex tube it's possible to obtain much cooler air with the same pressure.

4.2.1 Vortex tube or compressed air cooling

The vortex tube (company Festo) is setup to next to the Lockstitch machine to stitch Woven denim fabric of 290g/m^2 with 2 common sewing threads Polyester-Polyester core spun and Polyester-Cotton core spun threads. The machine is run at 4500r/min and the strength of the threads is measured after 30seconds of stitching by using standard D2256.

The ambient conditions were 26°C and 65% RH, the placement of nozzle is shown in Figure 31.

Figure 31 compressed air cooling for hot needle

The sewing process with cooling by compressed air, vortex tube will be compared with the non-cooled sewing process in terms of tensile strength of the seam.

4.2.2 Optimised cooling time

Idea of the controlled cooling is that instead of continuous cooling to the needle, which causes loss of compressed air, noise and discomfort for the worker. It is better to use short cooling time starting only when the operator takes the feet away from the speed paddle and the machine starts to de-accelerate, because the general idea is that the highest damage to the thread is actually done when the machine stops and the thread and longer contact time with the needle. To avoid that if the cooling can be done just few second before and after the machine stoppage then it can provide more economical solution to needle heating. For this experiment a continuous loop of stitching is done at 4000r/min and a total of 10seconds of cooling is performed, starting at 5seconds before the machine stoppage. The results are shown in figure 32.

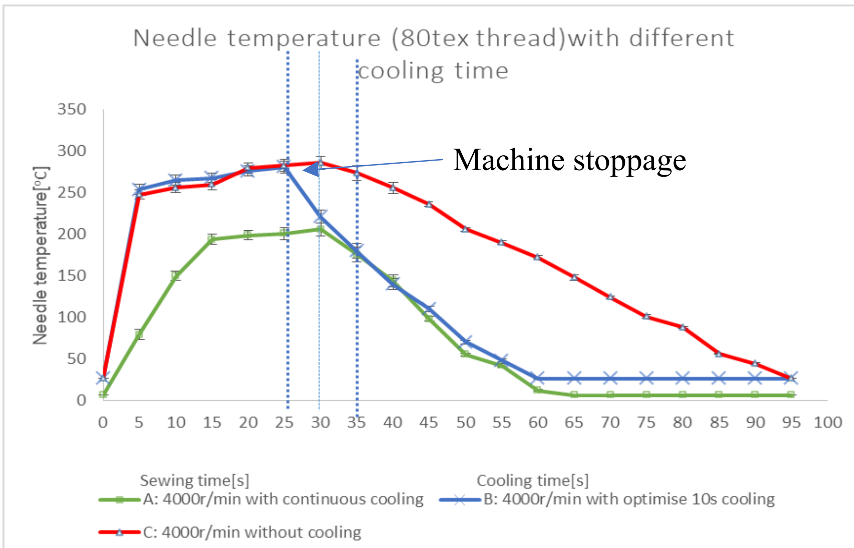

Figure 32 Cooling time and needle temperature

The time of deceleration of the sewing machine till the complete stop was identified as the important time where the needle to thread contact is the highest and the peak of needle temperature can be reduced by using the cooled air. In this figure 32, the 30seconds mark is where machine stops completely and the other two dotted lines shows the optimized time of cooling.

It is seen that within few seconds the need rises above 200°C, this can be avoided by using a continuous cooling but it does not have extreme impact on the tensile properties of the thread, so instead of cooling all the time, the optimized time can be used for cooling needle. all 3 threads from continuous cooling, without cooling and optimized cooling time are tested. The results are shown in figure 33

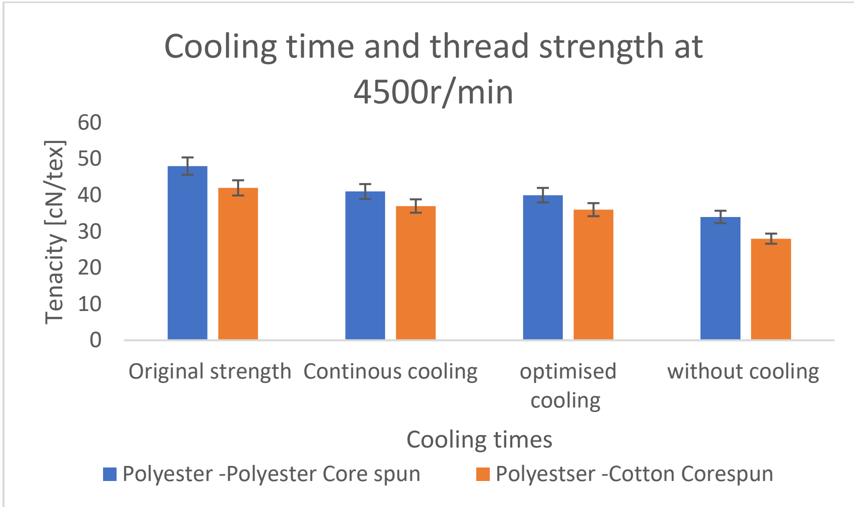

Figure 33 Cooling time impact on the tensile strength of the thread

The graph shows that there is minor difference of tensile strength of the thread when continuous or optimized cooling is used where as there is significant difference when there was no cooling of needle. There is nearly 27% loss of strength if the sewing process at speed is performed without cooling. The results shows that the optimized cooling time can bring similar results as compared to expensive continuous cooling.

4.2.3 Thread lubrication

The thread runs through multiple mechanical parts of the sewing machine including tension devices, guides and the bobbin assembly. It is important to lubricate the thread, for which silicon lubricants or wax is used [89, 90]. Still there is not much research on how much amount of lubricant is enough. Initially denim jeans 2 layers will be stitched using the most common industrial threads of PET core spun and PET Cotton core pun thread. To see the impact of the lubrication amount on the coefficient of friction, PET core spun with different amount of lubrication is used, the thread is obtained from company COATS which are already pre-lubricated at different level of silicon lubricant. Using ASTM D-3108 the coefficient of friction of the thread with different amount of lubrication is shown in figure 34.

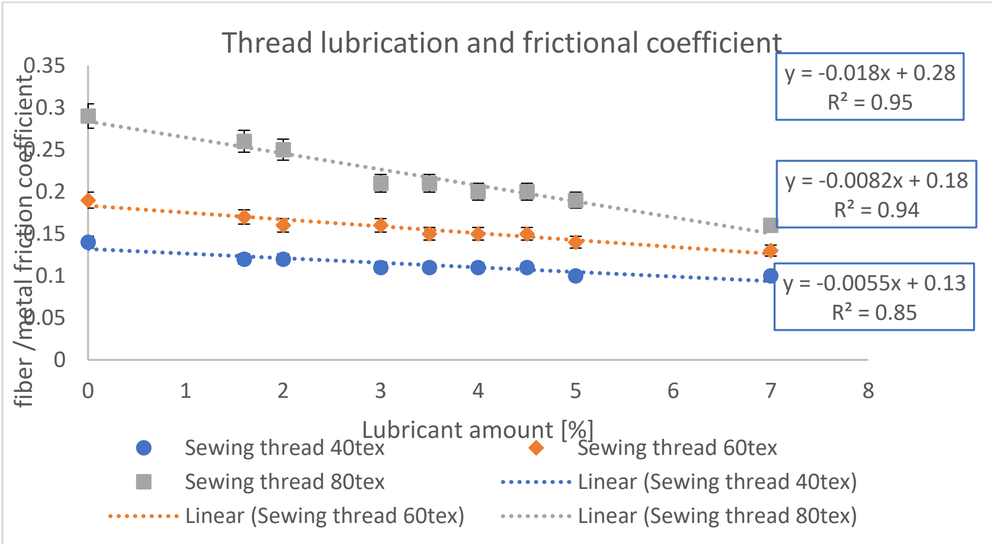

Figure 34 Thread lubrication impact on reduction of frictional coefficient

It was observed that there was 35% decrease in the frictional coefficient with the lubrication of 7%. The lubrication improved the surface finish of the thread and causes less friction which will help in the sewing process but the effect on the tensile property will provide better image to the whole problem. The effect of lubrication on the tensile strength of thread is shown in figure 35.

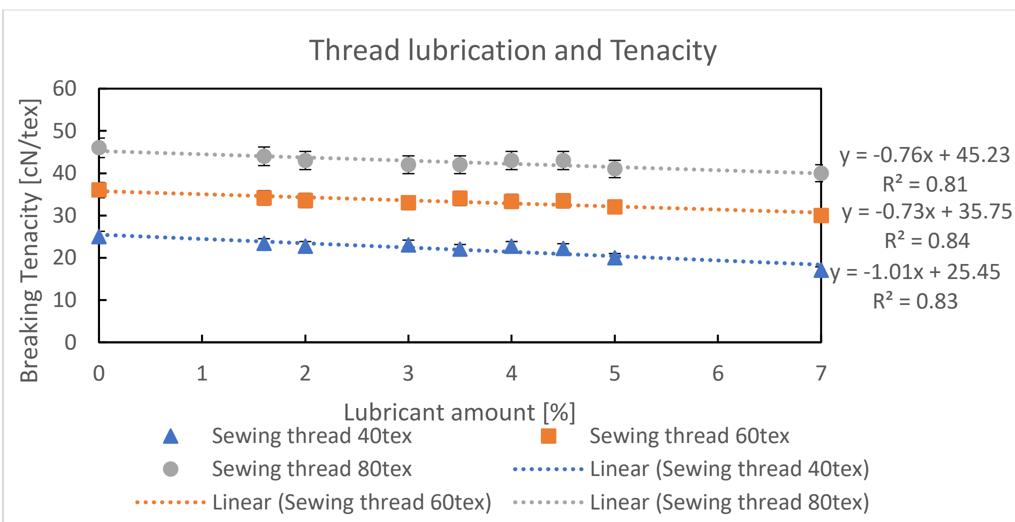

Figure 35 Thread lubrication impact on tenacity

The strength of the sewing threads is also linearly decreasing with the higher amount of lubricant, that might be due to the low fiber to fiber interaction and causing the fibers to slip, nearly 5-7% of the tensile strength was decrease after applying the lubricants.

4.2.4 Optimum condition of lubrication

The effect of lubricant amount on the needle temperature, tensile strength of thread and the elongation at break will provide enough information to conclude the practical advantage of the lubrication on threads. All this data is converted to graphical chart. Plotting these regression contour lines one above each other (superimposing) will bring interesting results as shown in figure 36 and 37.

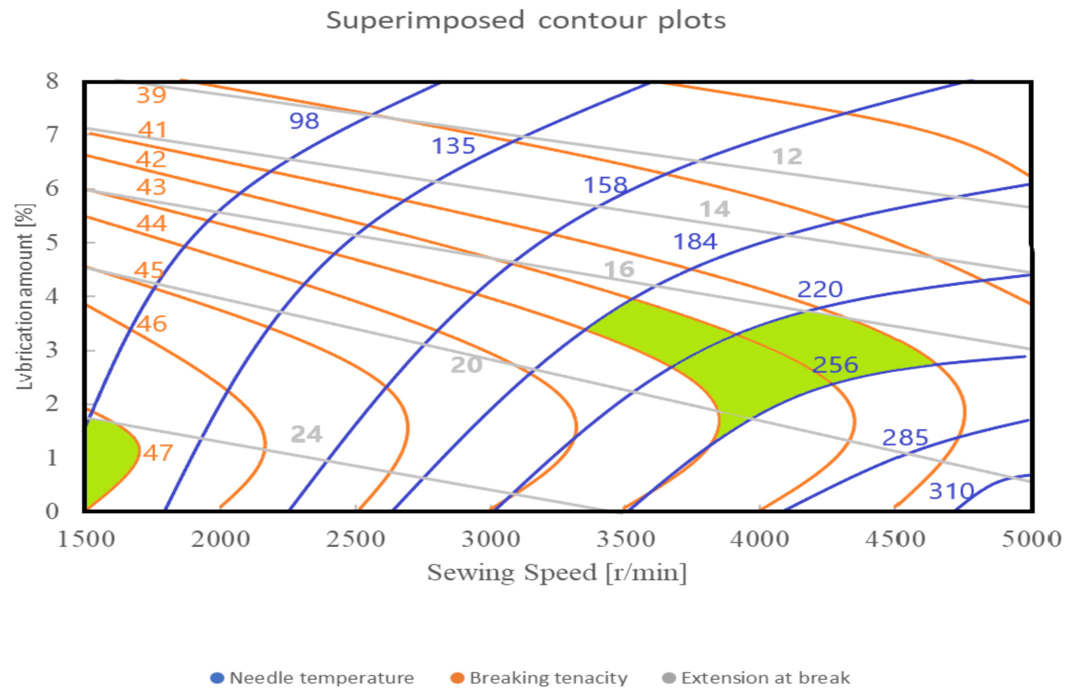

Figure 36 Contour plot of PET core spun thread showing effect of lubricant amount

The green highlighted parts on the graphs are special area of interest. Plots are imposed on top of each to represent temperature of needle, thread tenacity and breaking extension. The contour plots represent the most feasible region of the sewing to achieve maximum seam strength. The interesting part of figure 35-37 is that higher lubrication is causing the tensile strength to decrease, which is commonly neglected factor at the clothing production industry and uncontrolled lubrication provided to thread. The green area is obtained by superimposing the lines of needle heat, elongation at break and the breaking strength. It gives better idea that the most feasible regions of the sewing are with lubrication amount of less than 3.5% and if the speed is slower than 3000r/min then it is unnecessary to use lubricant. This information can save many industrial partners not to use unnecessary the lubricants and know exactly when it is more advantageous for them.

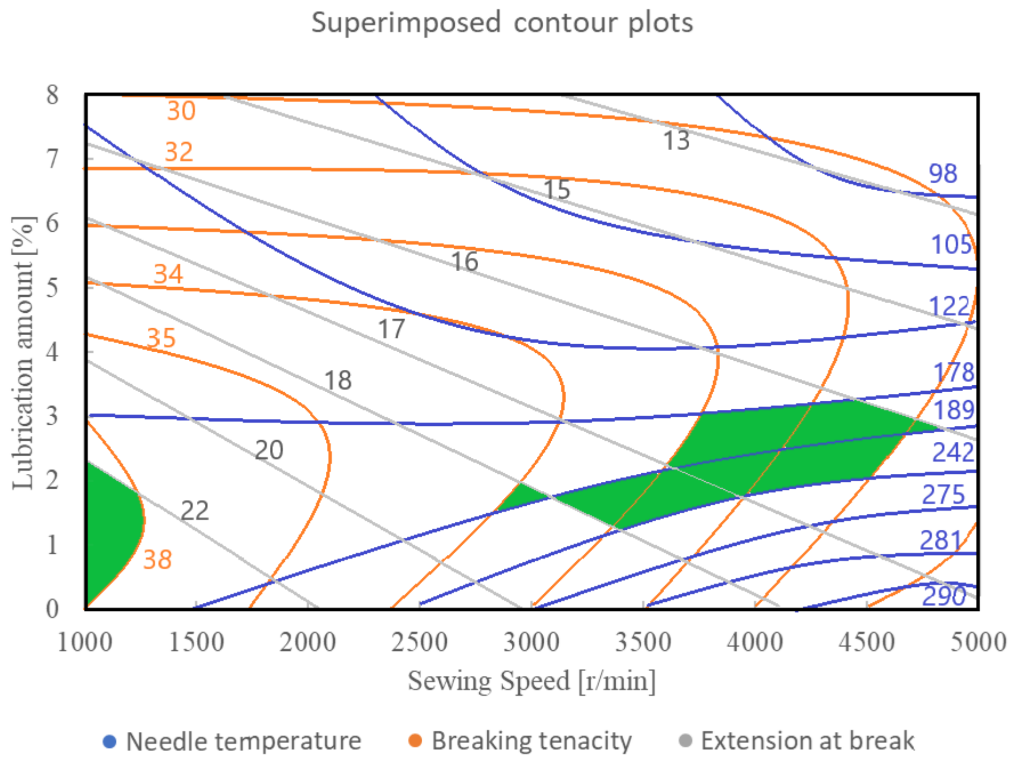

Figure 37 Contour plot of PET-COTTON to show impact of lubricant amount

Figure 37 shows the contour plots of PET-CO core spun thread for sewing denim fabric, results in the green color on graph shows the ideal condition for sewing where best performance of seam is obtained with minimum use of lubricant. The optimum areas to obtain the highest breaking strength will be if the lubricant is used then than 3% and it is not necessary to use the lubricant of the speed of sewing is less than 1000r/min.

The optimized amount of lubricant (green highlighted parts on the graph) is recommended for best performance, durability and minimum lubricant usage.

5 Seam strength of textiles

The most important factor for any clothing especially the technical clothing is the strength of the seam, which is connected to the sewing thread [99-102]. The sewing thread is impacted by mechanical damages during sewing, frictional forces, needle heating or speed of sewing [103-109]. Most of the time the seam strength is predicted by the holding power of all layers of fabric or sometimes calculated according to the strength of the thread. To understand how each section of the sewing process causes the thread damage it is important to identify what factors affect the thread tenacity.

5.1 Sewing thread strength loss in different sections of stitch process

It is important to understand that the thread gets damaged during sewing process either from abrasion or the needle heat. The effect of abrasion or friction is easily predictable in the final seam whereas the needle heat is complicated in terms of the effect is significant when the machine is slowing down till completely stop, the contact time between thread to needle and fabric to needle is maximum, usually this thread which tend to be greatly damaged are either the end of seam, corners of the clothing or sometimes on the start of the seam. This section is removed when doing the seam strength testing. In all standard seam testing methods, the edges are cut and not included in testing, but in the real scenario this weak thread is part of the seam and often the first area which gets the visible damage. In textile the corner seam of car seat cover, the edges of the shoulder seam, arm pit seam are perfect examples of this damaged thread seams.

To analyse which part of the sewing machine actually makes the biggest damage, I divided the sewing thread hypothetically to 4 parts as shown in figure 38, where P1 is parent thread, P2 goes through all the guides, P3 goes through the needle and the P4 is the final thread in the seam. It is often presumed that the P4 will be the weakest thread but from all our experiment it shows that the P3 thread was even weaker than the final thread. Which will be further explained while testing for the stitching of technical clothing. The standard ASTM D2256 is used for the testing of the sewing thread.

Figure 38 Sections of sewing thread damage

Initially two threads, Polyester-Polyester (pp) and Polyester-Cotton (PC) core spun with count of are used to sew the car seat cover (Leather) at 1000 to 5000r/min of sewing speed; the tensile strength of thread at each section (P1-P4) is measured as shown in table 9.

Table 9 Tensile strength of sewing threads at different sections of sewing process

	Property	[r/min]	Tenacity [cN/tex] (±S.D)						
			Original-P1	P2	percentage change with respect to P1[%]	P3	percentage change with respect to P1[%]	P4	percentage change with respect to P1[%]
PP	speed of machine [r/min]	1000	48 (± 1.4)	46(± 0.82)	-4.35	42 (± 0.88)	-14.3	41 (± 1.1)	-17.07
		2000	48 (± 1.4)	46 (± 0.8)	-4.35	41(± 1.22)	-17.1	40 (± 1.86)	-20.00
		3000	48 (± 1.4)	44 (± 0.81)	-9.09	38 (± 1.1)	-26.3	37 (± 2.42)	-29.73
		4000	48 (± 1.4)	43 (± 0.82)	-11.63	32 (± 1.8)	-37.1	36 (± 2.99)	-33.33
		5000	48 (± 1.4)	42(± 0.79)	-14.29	28(± 2.33)	-41.2	35 (± 3.66)	-37.14
PC	speed of machine [r/min]	1000	42 (± 1.6)	39 (± 0.8)	-7.69	37 (± 0.9)	-13.5	36(± 1.3)	-16.67
		2000	42 (± 1.6)	39 (± 0.8)	-7.69	36 (± 1.19)	-16.7	35 (± 2.2)	-20.00
		3000	42 (± 1.6)	37 (± 0.73)	-13.51	35 (± 2.82)	-20.0	33 (± 3.6)	-27.27
		4000	42 (± 1.6)	37 (± 0.77)	-13.51	29 (± 2.95)	-44.8	32 (± 4.1)	-31.25
		5000	42 (± 1.6)	36(± 0.75)	-16.67	28 (± 4.72)	-50.0	31 (± 5.1)	-35.48

Table 9, shows the loss of tensile strength of thread at different stages of sewing process. It is known that there will be loss of strength either form abrasion or the needle heat but the interesting thing is that the part 3 which still didn't go inside the seam has less strength than the final strength of the thread from seam, which looks like to be impossible as it's the same thread that continues to the next part. The reason is that when the machines is running at high speed the contact between hot needle and the thread is very short but as the machine decelerate the contact time is higher and causes more damage to the thread. The classical tensile testing sample making neglects these sections as these parts of the thread comes in the jaws of testing. But in reality, when the machine restarts this frail thread becomes part of the new seam. To avoid this problem its suggested to waste the 10-12cm of the upper thread when starting a new seam particularly for the technical clothing like protective suits.

5.2 Sewing speed, needle temperature and tenacity of sewing thread

The figure 39 shows that there is linear decrease of the tensile strength with respect to the speed of machine, this factor is quite well known but by dividing the sewing threads in different parts, (P2, P3, P4) its clearer which section of the sewing actually makes the strongest impact on the strength of the thread. The loss can be either form the abrasion or from the heat of the needle and nearly 40% of the tensile strength of thread is lost at high-speed sewing.

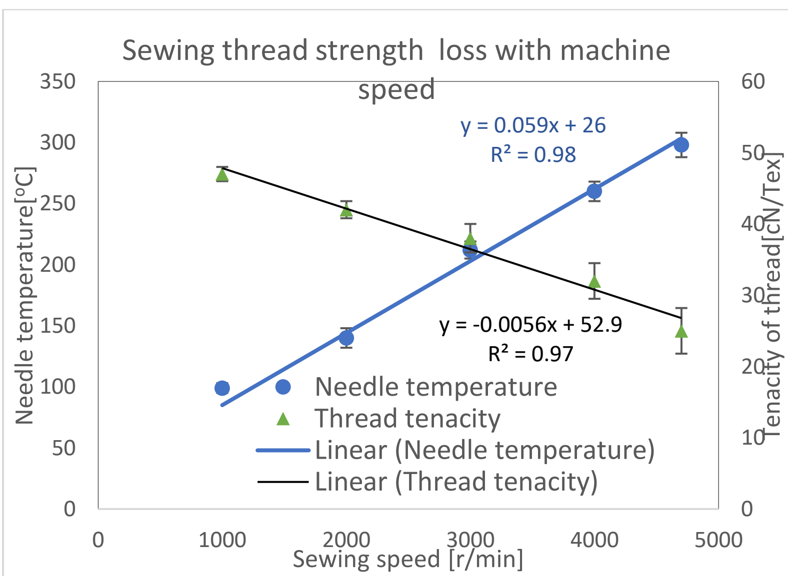

Figure 39 Needle temperature, machine speed and strength of sewing thread

This research illustrates that tensile properties of the thread is significantly reduced due to the sewing process. The damage starts with the abrasion and friction through mechanical parts of the machine and later the needle heat causes the greatest reduction of tensile strength. By diving the sewing thread sin to section, it was determined that after every cycle of stitching the last part of thread around 12cm should be wasted as the machine decelerate and the contact between the thread to hot needle and fabric to needle increases, which eventually causes damage to the textile material. This part of thread is mostly neglected during the seam testing and comes under the jaws of the testing machine. The research shows that due to high speed sewing (50Hz) the thread loses 30-40% of its actual tensile strength.

5.3 Sewing of Firefighter clothing

Fire fighter clothing or any other technical garments demands strong and durable seam. To test the impact of stitching process on the sewing threads used for the fire fighter clothing; six most commonly used threads are tested on fire fighter fabric (3 layers: outer shell as Meta Aramid, middle and third layer are thermal and moisture barrier) the fabric is same for all the tests. The material details are described in table 10.

Table 10 Threads used for firefighter clothing

Samples Number	Material	Melting Temperature [ºC]	Thread fineness [tex]	Twist
1A	Pyrostar- Spun Meta Aramid	371	35	Z/S
1B	Pyrostar- Spun Meta Aramid	371	80	Z/S
2A	Protos- Para Aramid	425	35	Z/S
2B	Protos- Para Aramid	425	80	Z/S

The results of the sample 1A and 1B are both durable and stable thread designed to withstand high temperature as they are used for technical garments like fire fighter suits of gloves for furnace workers, so even high needle temperature above 300ºC might not be the main reason of the overall strength reduction of these technical threads. But surely this high temperature together with the aggressive abrasion of the sewing parts causes drastic decrease of the strength of this thread followed by poor seam strength of technical garments like fire fighter clothing as shown in figure 40.

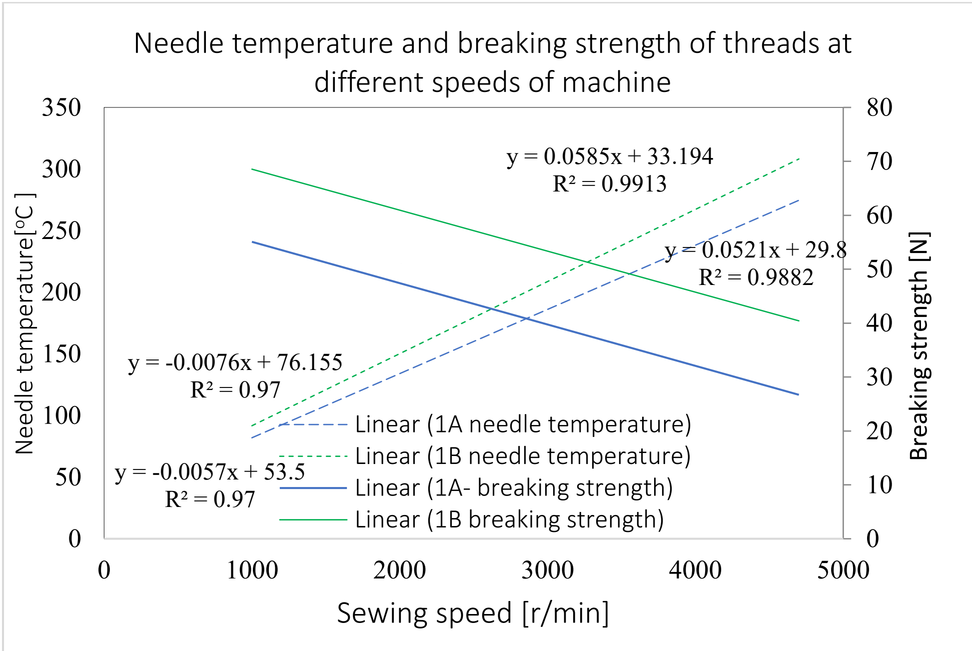

Figure 40 Needle heating and breaking strength of threads

Abrasion of thread with the machine parts, repeated motion through the needle eye and needle heating damages the sewing thread. In case of Para and Meta Aramid the needle heating is below their melting temperature but still above the glass transition temperature and this fatigue at high temperature causes significant decrease of the tensile strength.

5.4 Overall improvement of the sewing performance

For technical seams, it important to keep the sewing speed below 3000r/min. As most of these materials are densely packed or are sandwich structure of multiple layers of functional textile like protective clothing. Higher frictional heat from this thread and the densely packed fabric makes needle extremely hot. Which may not break the strong thread but causes damage to the fabric and mechanical damage to the sewing thread.

5.5 Effect of thread pretension on the seam strength of car seat covers

The pretension of the upper and bobbin thread is considered important for uninterrupted sewing operation but each worker arranges it to acquire just the right stitches or mostly just enough that machine doesn't stop. But is it really the aesthetic or does it change the physical properties of the seam and stitches In this research it shows if the pretension on the thread impact to the seam strength?

Industrial lockstitch machine is used to make the stich type 301 on car seat cover, as car seat covers demands not only aesthetic but excellent seam strength. In the car seat industry, the seam strength is also very important to predict the deployment of the air bag which breaks the seam and pops out from the side of the car seat. The specifications of the material of car seta cover and the threads are shown in table 11 and 12.

Table 11 Material properties for sewing process

Car seat cover material	mass [g/m^2]	Thickness [mm]
Twill woven	430	1.2 (± 0.09)
Leather	640	1.5 (± 0.12)

Table 12 Thread used for the experiment on effect of pretension

Thread	Material [tex]	Material	Twist[m^{-1}]
Upper thread/Bobbin thread	80	PET-PET (Core spun)	260 (Z/S)

Different possible pretension of the top(needle) thread and three different tensions of the bobbin thread are set for the experiment using tension measuring device MODUS. The device determines the maximum stress required to pull the thread. The pretension details are shown in table 13.

Table 13 Thread pretension settings

Upper thread -pretension [cN]	Bobbin thread pretension [cN]

150	80
300	160
600	240
900	
1200	
1800	

All these combinations were tested and from the visual feedback only those combinations in which stitching is formed without thread breakage is selected for the further experiment. To obtain the seam strength of the samples under different tension of upper and lower threads is tested by developing 90 samples, the samples size is huge but provided statistically reliable results of the seam strength measure using ISO13935. It can be concluded that the pretension of thread (which is mostly neglected) impacts the seam strength. In the case of upper thread there was a drop of 20% seam strength with incorrect pretension, whereas the Bobbin thread pretension showed insignificant impact on the seam strength. It should be taken great care in terms of pretension to achieve the highest seam strength. Still the pre-tension of the upper thread works with the expertise of the operator and there is not set standard in the industry.

5.6 Jeans industrial washing impact on the strength of the sewing thread

Denim jeans goes through vigorous washing (dry and wet) during the manufacturing, the impact of washing on the strength of seam and sewing threads is quite unknown, as the jeans are often considered a durable garment which can last for years, so does the washing significantly impact the seam strength can be seen in this research. In this study the 100% Cotton denim with 300g/m^2 was used and stitching is made by the most common commercial threads for denim stitching, details are shown in table14.

Table 14 Thread specification

Number	Material	Thread count (tex)	Number of yarns
A	Polyester-Polyester Corespun	140	3

B	30% Cotton + 70% PES Core spun	135	3

These 2 threads are used to stitch the jeans and each jeans goes through 5 different commercial washing cycles as shown in table 15, a total of 20 jeans are collected after washing (2 jeans for each washing), the seam is enough to provide a total of 15 thread samples from each seam, the effect on the sewing thread due these operations are observed for each samples.

Table 15 Washing operation details

Washing Types	Steps of washing	Time [min]	Temperature [^{o}C]
W1	Washing (Stone + Mesh)	30	26
	Finishing(bleaching)	7	45
	Air dry	35	85
W2	Washing (Stone + Mesh)	35	26
	Finishing(bleaching)	7	45
	Air dry	35	85
W3	Washing (Mesh)	15	26
	Rag bleaching	15	45
	Air dry	35	85
W4	Washing (Stone + Mesh)	15	26
	Air dry	35	85
W5	Washing (Stone + Mesh)	15	26
	Finishing(bleaching)	7	45
	Air dry	35	85

The tensile strength of the threads (seam threads) was measured using standard, each sample is tested for 15 times with jaw distance of 500mm.The seam of the denim jeans (leg part) is tested for all the samples. Upper thread is pulled out of the seam by cutting the bobbin (shuttle) thread. This will give a good idea if the washing as significant damage to the performance of sewing thread, thread properties are shown in the table 16.

Table 16 Tensile properties of the threads (unwashed)

Type of thread	Material	Tensile strength [N](S.D)	Elongation [%]
Thread A	100% PES	59 (±3.1)	37 (±3.2)

Thread B	30% Cotton + 70% PES	55(±2.3)	38(±4.2)

The thread tensile properties after washing are shown in the figure 41

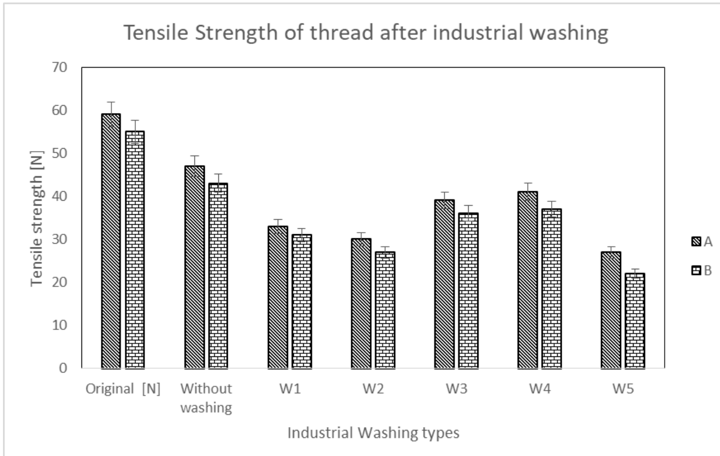

Figure 41 Effect of washing on the tensile strength

It can be seen that there is nearly 12% decrease of the tensile strength for any kind of washing as compared to the unwashed jeans. It is seen that the mechanical properties of the thread having cotton fiber content is much lower as compared to the 100% Polyester threads. That might be due to the staple fibers and higher frictional coefficient of the cotton fibers. During excessive washing and abrasion these fibers have more possibility of getting damaged and causes weaker thread strength finally. The W2- washing impacted the maximum to the tensile properties of both the threads and that might be due to the stone washing and longer wash time causes more abrasion and possibility for the thread-fibres to break. Also, the bleaching caused higher decrease in the tensile properties of the sewing thread. The Thread B experienced more damage and can be because of the bio degradable nature of the Cotton content in the thread. It was concluded that washing play's negative role on the tensile strength of thread and eventually on the seam.

6 Conclusion

Millions of garments being stitched every day demands more improvement of the sewing process and advancement in this field. The research work brings new knowledge in the field of how needle heating impacts the strength of sewing thread, what factors influence the process significantly and optimization of the process itself. This is valuable for the industrial partners; on the other hand, the theoretical explanation of the needle heating and needle cooling bring more in-depth explanation for the researches from academia. The processes like coating of sewing needle and lubrication of sewing thread was studied and further optimisation are shown which significantly provides improvement. Finally, the overall improvement of the sewing process for the technical textiles like fire fighter clothing's and the car seat covers were discussed in this research work. Following can be concluded form the thesis.

Measurement Methodology:

The experimental techniques to measure the needle temperature needs a care full observation as many researchers perform this test using thermal cameras, in this research it was observed that even with the latest instrument it is impossible to focus a thin needle with low emissivity next to the high emissivity thread, secondly the emissivity of metal at high temperatures changes significantly and these cameras are unable to do calibration during the process. The new technique of embedded thermocouple in the needle provided much better results and latest advancement with C type thermocouple and wireless transmitter made it possible to see the rise, decline and the peak of the needle temperature at high-speed sewing. It also made the possibility to short list the significant factors that impact the needle heating, which is important for clothing industry to quickly understand the significant factors affecting needle temperature

Optimisation of cooling techniques:

The cooling of needle involved air cooling, thread lubrication/finishing and coating of needles etc. of the needle. In this research the vortex cooling and the classical compressed air cooling is compared to show how it improves the needle cooling, secondly the optimization of the time of cooling of needle from continuous cooling to only at the time of machine stoppage brings similar results of seam strength and saves unnecessary usage of the compressed air. Also, Thread lubrication method in sewing machine is still uncontrolled and large amount of lubrication penetrates to thread at slow speed swing and vice versa in high speed. It was observed that uncontrolled lubrication causes loss of tensile strength of thread as excessive or very low amount of lubrication is coated/absorbed to the thread, whereas less than 3.5% of lubrication behaved ideally for better strength and lower needle heating, the pre lubricated thread of Polyester and Polyester-Cotton showed similar trend. Similarly, DLC coated needles are tested with classical and commercially coated needles (Gabedur, Groz-Beckert) and results shows that DLC coated needles are better than the classical needles but still lower in performance as compared to the commercially coatings, this might be due to poor coating quality in the eye of the needle.

Finally, the performance of needle under different conditions is tested for special textile, which includes fire fighter clothing and the car seat cover materials. It shows that how small factors like pre-tension of thread on the sewing machine causes substantial impact on the seam of the car seat covers. The pre-tension on the sewing machine is still a manual operation and done only with the operator expertise and no standards values available in the production companies.

Theoretical model

The research work provides unique and novel knowledge of the sewing process in apparel industry, its possible improvement for productive process. The previous work of author in which only the needle heating was calculated in now completed with the heat losses by conduction, convection and radiation. The heat equation is balanced now. The work is also beneficial for the researchers from academia to know the theoretical study of the measurement of the sewing needle temperature, whereas the optimization of the common techniques on the sewing machine can bring economic benefits to the industry.

Short Summary of Thesis

Briefly it can be stated as:

1. Heating of sewing needle is important issue for clothing industry and experimentally its possible to have repeatable results using thermocouple embedded to the needle. The technique is much more reliable than any other method.
2. Multiple factors influence the needle heating and it is possible to short list the significant factors from this research.
3. Optimisation of lubricant amount, compressed air cooling can bring significant advantage to the clothing industry and improve sewing process.
4. The theoretically explanation of needle temperature (heating and cooling) including all major factor is deeply covered in the thesis followed by verification from experimental work and previous model.
5. The overall improvement of the sewing process for the technical textiles like firefighter clothing is also explained.

   The research work is unique and can be very helpful for the researchers as well as the industrial partners

7 Závěr

Miliony oděvů, které se denně šijí, vyžadují další zdokonalování procesu šití a pokrok v této oblasti. Výzkumná práce přináší nové poznatky v oblasti toho, jak ohřev jehly ovlivňuje pevnost šicí nitě, jaké faktory tento proces významně ovlivňují a jak probíhá optimalizace samotného procesu. To je cenné pro průmyslové partnery; na druhé straně teoretické vysvětlení ohřevu jehly a chlazení jehly přináší hlubší vysvětlení pro výzkumné pracovníky z akademické sféry. Byly studovány procesy, jako je potahování šicí jehly a mazání šicí nitě, a ukázána další optimalizace, která významně přináší zlepšení. Nakonec bylo v této výzkumné práci diskutováno celkové zlepšení procesu šití technických textilií, jako jsou hasičské oděvy a potahy automobilových sedadel. Z práce lze vyvodit následující závěry:

Metodika měření

Experimentální techniky měření teploty jehly vyžadují jasné a úplné pozorování, protože mnoho výzkumných pracovníků provádí tento test pomocí termokamer, v tomto výzkumu bylo zjištěno, že ani s nejnovějším přístrojem není možné zaměřit tenkou jehlu s nízkou emisivitou vedle vlákna s vysokou emisivitou, za druhé emisivita kovu se při vysokých teplotách výrazně mění a tyto kamery nejsou schopny provést kalibraci během procesu. Nová technika zabudovaného termočlánku v jehle poskytla mnohem lepší výsledky a nejnovější pokrok s termočlánkem typu C a bezdrátovým vysílačem umožnil sledovat nárůst, pokles a vrchol teploty jehly při vysokorychlostním šití. Umožnilo to také zkrácený seznam významných faktorů, které ovlivňují zahřívání jehly, což je pro průmyslové partnery důležité pro dosažení produktivity a lepší pevnosti švu.

Optimalizace technik chlazení

Chlazení jehly zahrnovalo chlazení vzduchem, mazání/finišování závitu a potahování jehly atd. V tomto výzkumu se porovnává vírové chlazení a klasické chlazení stlačeným vzduchem, aby se ukázalo, jak se zlepšuje chlazení jehly, za druhé optimalizace doby chlazení jehly z nepřetržitého chlazení na chlazení pouze v době zastavení stroje přináší podobné výsledky pevnosti švu a šetří zbytečnou spotřebu stlačeného vzduchu. Také způsob mazání nitě v šicím stroji je stále nekontrolovaný a velké množství maziva proniká do nitě při pomalé rychlosti pohybu jehly, a naopak při vysoké rychlosti. Bylo zjištěno, že nekontrolované mazání způsobuje ztrátu pevnosti nitě v tahu, protože nadměrné nebo velmi malé množství maziva se obalí/absorbuje do nitě, zatímco méně než 3,5 % maziva se chovalo ideálně pro lepší pevnost a nižší zahřívání jehly, podobný trend vykazovala i předem namazaná nit z polyesteru a polyesteru s bavlnou. Podobně se testují jehly s DLC povlakem s klasickými a komerčně potaženými jehlami (Gabedur, Groz-Beckert) a výsledky ukazují, že jehly s DLC povlakem jsou lepší než klasické jehly, ale stále mají nižší výkon ve srovnání s komerčně potaženými jehlami, což může být způsobeno špatnou kvalitou povlaku v očku jehly.

Nakonec byla testována výkonnost jehly v různých podmínkách u speciálních textilií, mezi něž patří hasičské oděvy a potahové materiály autosedaček. Ukazuje se, jak malé faktory, jako je předpětí nitě na šicím stroji, mají podstatný vliv na šev potahů autosedaček. Předpětí nitě na šicím stroji je stále ruční operací a provádí se pouze na základě zkušeností obsluhy a ve výrobních podnicích nejsou k dispozici žádné normované hodnoty.

Teoretický model

Výzkumná práce přináší nové a jedinečné poznatky o procesu šití v oděvním průmyslu a jeho možném zlepšení pro produktivní proces. Předchozí práce autorky, ve které se počítalo pouze s ohřevem jehly, byla nyní doplněna o tepelné ztráty vedením, konvekcí a sáláním. Tepelná rovnice je nyní vyvážená. Práce je přínosná i pro vědecké pracovníky z akademické sféry, kteří se seznámí s teoretickou studií měření teploty šicí jehly, přičemž optimalizace běžných technik na šicím stroji může přinést ekonomický prospěch pro průmysl.

Future Work

My current field of research is related to sewing and assembly process, clothing comfort and performance of high functional textile. In future I would like to keep my focus for the field of assembly process of textile especially for technical application, automatic assembly process and composites stitching. I connected to this field of research for 10 years and I think I can go deeper to the issues related to the sewing in future.

Declaration

I declare with honesty that the results, research and the publication presented in this thesis belongs to me and encase of articles with co-authors, the major share of experiments, research or interpretation belongs to me.

Published articles (Only related to the thesis topic)

The selected articles only related to the **thesis** and published in last 7 years are listed below.

Articles in international journals (WOS)

List is arranged according to impact factor

1. Mazari, A. (2021). Effect of Needle Heating on the Sewing of Medical Textiles, Advances in smart Textiles for Health Care and Personal Protection, Polymers 13(24), 4405., 13(24):4405.
2. Mazari, A., Bal, K., & Havelka, A. (2016). Prediction of needle heating in an industrial sewing machine. Textile Research Journal, 86(3), 302-310.
3. Akcagun, E., Öz Ceviz, N., Yılmaz, A., & Mazari, A. (2017). Analyzing the effects of special washing processes on characteristics of sewing threads. The Journal of The Textile Institute, 108(11), 1926-1932.
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6. Mazari, A., Havelka, A., & Kus, Z. (2015). The effects of lubricant amount on sewing needle temperature and tensile properties of Polyester-polyester core-spun thread. Industria Textila, 66(2), 97.
7. Mazari, A., Zhu, G., & Havelka, A. (2014). Sewing needle temperature of an industrial lockstitch machine. Industria Textila, 65(6), 335.
8. Mazari, A., AKÇAGÜN, E., MAZARI, F. B., & Kejzlar, P. (2016). Effect of sewing speed on the physical properties of firefighter sewing threads. Industria Textila, 67 (5), pp. 333-337.
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Appendix [1]

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Article

Effect of Needle Heating on the Sewing of Medical Textiles

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Abstract: Medical textiles, such as gowns, scrubs, and even disposable uniforms, are all stitched by sewing machines. These garments are mostly made from polypropylene (PP) and polyester due to their durability, antibacterial performance, and functionality. Demand for these garments has significantly risen in the last few years, and sewing machines are able to stitch at extremely high speeds. However, higher sewing speeds can cause burnt spots on the fabric, lower seam strength, and a decrease in production due to thread breakage. In this paper, I have deeply discussed how medical textiles lose their strength and functionality due to higher sewing speeds; this problem is often neglected due to high production demands. This research is based on PP medical gowns, stitched with polyester (PET) threads, sewn at different speeds. The experimental work is also followed by a theoretical explanation of needle heating during the stitching of medical textiles.

Keywords: medical textiles; polyester; sewing; thread

1. Introduction

Sewing machines are a necessity for any industry working with clothing, automobiles, footwear, medical textiles, or upholstery. Millions of products, ranging from car seat covers to medical gowns to firefighter clothing, are all stitched using industrial sewing machines. Thomas Saint is considered to have invented the practical sewing machine in 1790 [1]. It was a time of industrial revolution, and machines can greatly improve production capacity. The industrial sewing machine, used in the clothing industry, requires not only high production, but also higher sewing quality (seam strength and appearance). Typically, these machines can complete 70–90 stitches in a second [2], to keep the process as efficient as possible. It's necessary to improve each aspect of the process. Even though sewing machines can run at high speeds, human capability and technical problems during the sewing process forces users to run the machines at the much lower rate at 20–45 stitches per second. There are multiple technical reasons why it is preferable to run machines at less than half capacity, including damage to the thread, burn spots on the fabric, weaker seam strength, and many more [3–5]. The factors that cause these problems range from ambient conditions to the process parameters of sewing.

In the modern clothing production sector, there has been significant technological advancement in the last 10 years. One of the key machines used in these production units is the sewing machine, which has been made more robust, efficient, and durable. High production demand makes users run these machine so as to be as productive as possible. As a result of this high-speed production, abrasion within machine components, frictional forces, and penetration forces cause significant impacts on the overall quality of the final seam [6]. The aesthetic, as well as the functional quality, is very important for clothing, especially technical clothing.

Until now, the production of clothing by sewing machine has been labour intensive work, though sooner or later production will move towards automatic sewing. To achieve this, many aspects of the sewing process need to be closely monitored, to understand and improve them for better care-free performance [7,8]. Semi-automatic sewing machines are already on the market, though they still need constant quality management by workers [9].

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Often, only thread breakage and aesthetic faults can be controlled [10,11], and all other damage, which may significantly reduce the seam strength, is just avoided. One of these semi-automatic sewing machines is used for jeans pockets. In this research, my focus was on the lockstitch machine due to its versatile usage and application in high strength seams, as compared to the chainstitch mechanism.

In the textile industry, the sewing process is a commonly used method to prepare final clothing. In the last few decades, not only the production, but also the quality, of the sewing has become important. Generally, multiple layers are stitched together using a sewing machine (lockstitch machine), and workers are usually paid according to work done. Therefore, it is very important for workers to produce as many garments as possible, to earn more money. Sewing machines which have the capacity to easily run at 60–100 stitches per second are one of the key solutions for workers aiming to produce and earn more. However, this has its own disadvantages. The sewing needle can reach a temperature of ∼150–320 °C [11]. The hot needle damages the sewing thread and leaves undesirable spots on the fabric. The thread usually loses 35–45% of its strength [12,13].

1.1. Medical Gowns

Different varieties of medical apparel are available on the market. Most of them are either stitched by sewing machine or bonded by ultrasonic machine. Generally, all reusable medical gowns and protective gear are stitched with sewing machines for better durability. The material used for making these garments is multiple layers of non-woven spun-bonded PP and PET with functional membranes. In accordance with industry standards, the stitch line is covered with protective tape to avoid leakage of spills or chemicals onto the body. The common standards for medical textiles are EN ISO 13982, EN ISO 13688, EN 13034, EN 14126, and EN 14605.

The effect of sewing speed on these medical textiles is ignored. As medical textiles were often single-use in the past, it was not very important; however, due to industrial waste of medical apparel, the majority of the new gowns are reusable, and are stitched with sewing machines. The current research is focused how sewing speed actually damages the seam strength of medical textiles.

1.2. Basic Thermal Mechanism of Needle Heating

The heating of the sewing needle is complicated process; the temperature abruptly rises in the first 10–13 s to above 130 °C [11,12], after which the rise is minor, until a steady state is attained. In each cycle of stitch formation, there are minor variations in the needle temperature during fabric penetration and withdrawal [12].

Heat is produced mainly due to friction between the needle and the thread, as well as between the needle and the fabric. Some researchers have reservations on this subject, and believe that the fabric is a source of cooling, rather than heating, whereas the other group consider it a heat source, due to the penetration and friction with the needle. Researchers from both schools of thought [12–17] have published numerous articles on this issue.

- Heat flux is generated between the outer surface of the needle and the fabric; this phenomenon depends on the needle-penetration force, withdrawal, and the frictional coefficient.
- Heat conduction between the needle and the thread is another major source of heating, and depends on the friction coefficient of the needle and thread, as well as the material parameters.

Figure 1 shows the configuration of the sewing process that is responsible for the heating mechanism [18].

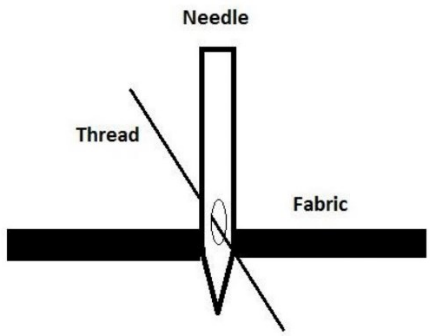

Figure 1. Sewing needle, thread, and fabric diagram [18].

1.3. Contactless Method of Needle Temperature Measurement

The temperature measurement of stationary objects with high emissivity levels, such as clothing, walls, and paints, is comparatively easy, while in the case of sewing needles, with small size (0.1 to 0.2 cm), low emissivity (0.05–0.1) [19], and a high temperature range (100–300 °C) [18], it is almost impossible to obtain accurate results. In addition, the textile material and sewing thread are too close to the needle, with huge difference in emissivity, making it much harder to focus on only the sewing needle. In the past 10 years, the majority of researchers [20] used the following technique to measure the needle temperature during sewing process.

1.4. Sewing Needle Temperature

The temperature measurement of sewing needles is quite complicated due to their small dimension, low emissivity, and high speed during use. There are many methods and techniques used by researchers [4–9] to observe needle temperature, including infrared pyrometer, contact sensors, and sensitive waxes/colors, etc. Moreover, with improved knowledge of sewing needle heating, there are many improvements [21,22] to be made in the design of needle, as well as the use of lubricants and coatings, which can help to decrease needle temperature.

2. Materials and Methods

For this research, the most common medical-textile material and sewing thread was used to determine the effect of sewing processes on seam strength and needle temperature.

The following fabric as described in the Table 1. was used for the experiment.

Table 1. Fabric details.

Material	Manufacturing Technique	Weight [g/m^2]	Thickness [mm] (S.D)	Layers Used
PP	Spun-bonded melt-blown polypropylene	75	1.2 (±0.15)	3

The selection of this material was mainly due to its common usage in the production of medical gowns; as well, this material is preferred for reusable gowns in the medical field. The thread which was used in the sewing of these gowns is listed below in Table 2.

Table 2. Thread details.

Material	Twist	Count [tex]	Producer
PET	Z/S	40	Amman® (Liberec, Czech Republic)

Three layers of fabric were stitched together, for 30 s each time, at different sewing speeds, and properties such as tensile strength of the thread, needle temperature, and aesthetic damage to the textile were recorded before and after the sewing process. The stitch length, needle, and ambient conditions were kept constant for all experiments.

Conditions for all experiments were kept constant at 26 °C and 65% RH. The following machine and accessories were used for the experiment.

- Lockstitch machine (Brother Company, Berlin, Germany DD7100-905).
- Thermocouple by Omega (K type 5SC-TT-(K)-36-(36)).
- Thermocouple by Omega—wireless device and receiver (MWTC-D-K-868).
- Needles (Groz–Beckert, Stuttgart, Germany 100/16) R-type.

Initially, the medical-textile material was stitched at different sewing speeds, and the needle temperature was recorded. The methodology used to measure needle temperature was the inserted thermocouple technique, in which a thermocouple is embedded in the needle to obtain an accurate needle temperature; this technique is explained by the authors of [23].

In this method as shown in Figure 2. for measuring sewing needle temperature, a thermocouple, by Omega (K type 5SC-TT-(K)-36-(36)), was inserted into the groove of the sewing needle and soldered. The thermocouple was located near the eye of the needle, to measure the exact needle temperature, and the temperature was measured at different sewing speeds. This method proved to be very efficient, as it provided continuous changes in needle temperature every second, and it had a low standard deviation.

Figure 2. Thermocouple embedded in the needle.

Subsequently, to measure the strength of the threads, the sewing thread was taken out of the seam and the tensile strength of the final thread, after stitching, was compared with its parent strength. The thread was pulled out of the seam by carefully cutting the bobbin thread, without disturbing the twist.

3. Results and Discussion

A continuous 30 s of sewing was performed, keeping all conditions similar for the duration of the experiment. The results of the needle temperature measurement are shown in Figure 3.

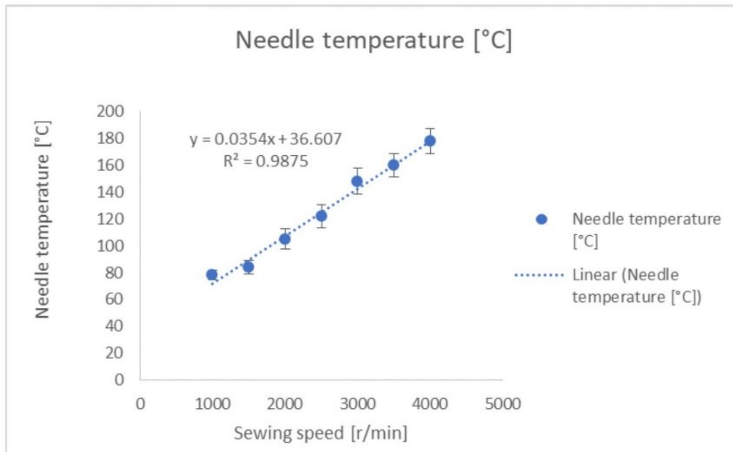

Figure 3. Sewing needle temperature at different sewing speeds.

At a sewing speed of 3000 r/min, the fabric started to show black spots due to the high temperature of the needle. It can be also seen from the Figure 3 that there was a linear increase in sewing needle temperature with respect to machine speed. Polyester thread has a higher melting temperature than PP, and therefore may not melt; nonetheless, this high temperature causes structural changes to the polymer.

The tensile strength of the sewing thread was measured using ASTM 2256 standards. The Figure 4 shows the obtained results.

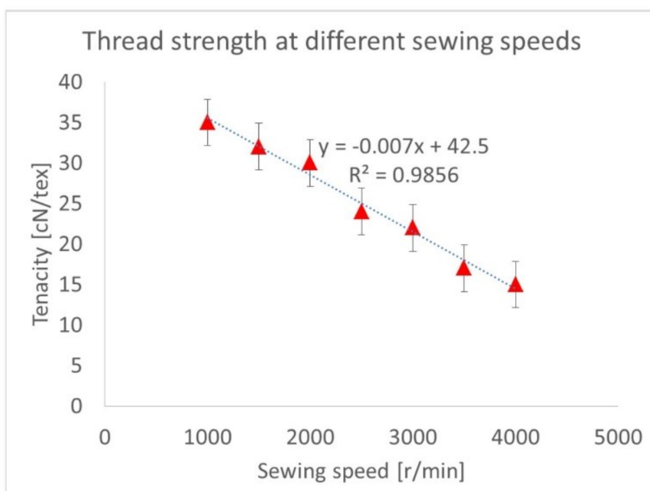

Figure 4. Tensile strength of thread at different sewing speeds.

It can be clearly seen that, at higher sewing machine speeds, there was a significant decrease in thread strength, which may have been due to abrasion, or the high temperature of the needle. There was negative linear relationship between sewing speed and thread strength. It was also alarming that, at speeds of 3000 r/min and higher, the thread lost 50% of its original strength.

Figures 3 and 4 show that, with higher speeds, there is a rise in needle temperature and a decrease in the tensile strength of the thread. The highest temperature, 187 °C, was recorded at a speed of 4000 r/min, during which the sewing thread lost more than 50% of its original strength. To explain this needle heating for sewing thread a theoretical model was developed, which is improved work of the author himself.

Theoretical Analysis

Different methods and approach have been used by researchers in the past, and a major conflict is whether or not the fabric is the source of heating; different schools of thought exist. In my approach, the analytical model is considered, which requires less computation, has higher accuracy, and could be easily used by industrial partners in the future. In this model the assumptions listed below are made:

1- The needle, thread, and fabric are all at room temperature.
2- The needle is a cylinder with the same material composition throughout.
3- λ_N is the thermal conductivity of the needle material, and is significantly higher than that of the sewing thread λ_y and fabric λ_F. Here it is discreetly assumed that both the thread and fabric have lumped thermal properties, i.e., each has unchanging thermal conductivities, represented by single value.
4- The thread and textile fabric are considered homogenous, with constant thermal conductivity value throughout.
5- Radiation heat can be neglected due to the small size of the needle and a smaller contribution compared to other factors.
6- In this model, it is estimated that friction heat is assumed as $Q = F^*v$ [18], where F is friction force and v is the relative velocity of the two surfaces.
7- γ is the ratio determining the amount of heat distribution when two materials rub together. Partition ratio is calculated, using the Charron's relation [24], as:

$$\gamma = \frac{1}{1 + \xi_N} \quad (1)$$

where $\xi_N = \frac{b_i}{b_N}$, N denotes the needle, i denotes the other rubbing material in contact, and b is the thermal absorptivity of the respective materials. The calculated value is given as $b = \sqrt{(\rho * C * \lambda)}$, where ρ is the density of the material, C is the specific heat of the material, and λ is the thermal conductivity.

An analytical approach was used to predict needle temperature, assuming that heat is produced during the sewing process as a result of needle–thread and needle–fabric friction. In this analysis, a steady-state condition is considered, in which the amount of heat generated by friction exactly equals the amount of heat lost by the needle. The complex shape of needle is neglected, and it is treated as a uniform cylinder.

The heat generated due to friction between the needle and the fabric can be expressed as [18]:

$$Q_{FN} = \gamma_{FN} * \mu_{FN} * F_{FN} * v_{FN} \quad (2)$$

The heat generated due to friction between the sewing thread and the surface of needle can be expressed as:

$$Q_{YN} = \gamma_{YN} * \mu_{YN} * T_y * \cos\theta * v_{YN} \quad (3)$$

where the legends are described in Table 3.

Maximum needle speed was found to have a linear function of machine speed with the multiplier constant C_{FN} = 0.0008.

The total heat gain by the needle is finally:

$$Q_N = Q_{FN} + Q_{YN} \quad (4)$$

From the 1st law of thermodynamics in a closed system,

$$Q = m * C_N * (T - T_i) \quad (5)$$

where m is the mass of the needle, C_N is the specific heat of needle, T is the final temperature of needle, and T_i is the initial temperature of needle

From Equations (1)–(5), following relation is obtained:

$$m * c_N * (T - T_N) = \gamma_{FN} * \mu_{FN} * F_{FN} * v_{FN} + \gamma_{YN} * \mu_{YN} * T_y * \cos\theta * v_{YN} \quad (6)$$

Equation (6), for a more precise result, should be solved by calculating it numerically over time, as many of the variables present in Equation (6) are complex functions of time. However, in order to simplify the calculations, the maximum value of F_{FN} and T are considered here for the prediction of maximum needle temperature. Similarly, the maximum relative speed between the needle and sewing thread is used as v_{YN}. As an additional approximation, both v_{FN} and v_{YN} are stated as proportional to the machine speed v_M. If C_{FN} and C_{YN} are the two coefficients of these proportionalities, respectively, then it can be obtained from Equation (6) that:

$$T - T_i = B * v_M \quad (7)$$

where "B" is:

$$B = \frac{1}{m \times c_N} * \{\gamma_{FN} * \mu_{FN} * F_{FN} * C_{FN} + \gamma_{YN} * \mu_{YN} * T * \cos\theta * C_{YN}\} \quad (8)$$

Thus, Equation (8) shows that the highest needle temperature is a linear function of machine speed. An estimate of maximum needle temperature, from machine speed, is possible if the parameter B can be calculated using Equation (8). The value of the symbols are described in Table 4.

It can be seen from Figure 5 that the theoretical and experimental results both show a linear trend of increasing needle temperature. A difference in absolute values is possible, as in all theoretical models many assumptions are made to simplify the model. The analytical approach can be solved without complex simulation.

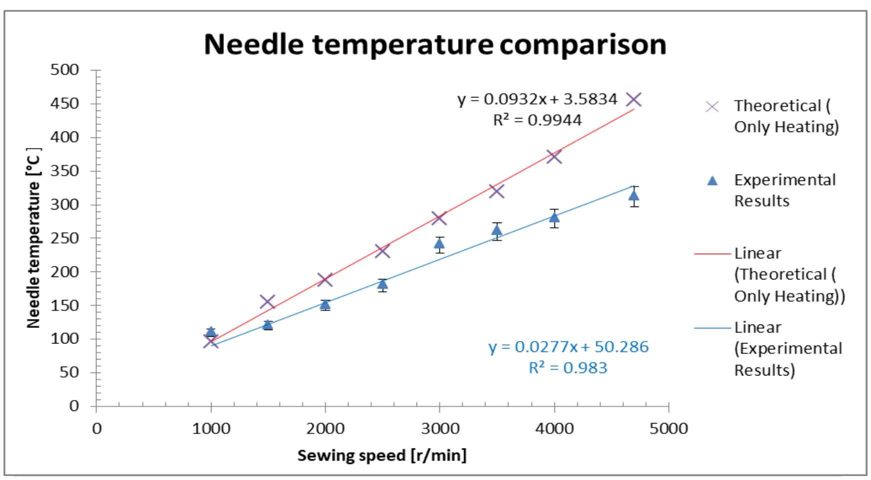

Figure 5. Comparison of experimental and theoretical results.

Table 3. Legend of equations.

γ_{NY}	Partition ratio of heat gain between needle and thread using Charron's relation.
γ_{FN}	Partition ratio of heat gain between needle and fabric using Charron's relation.
μ_{YN}	Coefficient of friction between needle and sewing thread.
μ_{FN}	Coefficient of friction between fabric and sewing thread.
T_y	Maximum tension of sewing thread during sewing cycle.
θ	Angle of sewing thread with respect to the needle.
v_{FN}	Velocity of needle with respect to the fabric.
F_{FN}	Needle penetration force with respect to the fabric.
v_{YN}	Velocity of thread with respect to the needle.

Table 4. List of symbol and units.

Property	Symbol	Value	Unit
Heat partition ratio (fabric & needle) [24].	γ_{NF}	0.945	-
Heat partition ratio (thread & needle) [24].	γ_{NY}	0.958	-
Density thread [25].	ρ_y	1400	kg/m^3
Specific heat of thread [26].	C_y	750	J/kgK
Thermal conductivity of thread [26].	λ_y	0.15	W/mK
Density of fabric [27].	ρ_f	920	kg/m^3
Specific heat of fabric [26].	C_f	1700	J/kgK
Thermal conductivity of fabric [experimental].	λ_f	0.04	W/mK
Density of needle [28].	ρ_n	7850	kg/m^3
Specific heat of needle [28].	C_n	523	J/kgK
Thermal conductivity of needle [28].	λ_n	40	W/mK
Friction coefficient of needle and thread [experimental value].	μ_t	0.3	-
Friction coefficient of needle and fabric [experimental value].	μ_{fy}	0.21	-
Tension thread maximum [29,30].	T_y	1.05	N
Needle velocity [experimental value].	v_N	2.3	m/s
Machine speed (to be used with constant to balance the equation).	V_m	1000–4500	r/min
Needle and thread angle of contact [31].	θ	60	o
Frictional normal penetration force to needle from fabric [experimental value].	F_{FN}	2.5	N

4. Conclusions

The process of sewing is very important for any clothing or wearable textile company. Any improvement in the process can provide huge economic benefits, including higher productivity. Generally, the strength of the seam, or sewing thread, used in the stitching of medical textiles is neglected. As the demand for reusable medical textiles, such as gowns, is increasing, it is important to understand the performance parameters of the seams and sewing threads used in the stitching of medical textiles. The focus of this research was the theoretical and experimental explanation of how needle heating due to machine speed can impact the strength of medical textiles. This work provides in-depth knowledge of the sewing process, including possible limitations and improvements to be made in the textile industry. This work is also beneficial for researchers, as it provides a theoretical analysis of sewing needle temperature measurement. If cooling accessories are not used, it is advisable to run the sewing machine at a speed of 2000 r/min or lower.

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Appendix [2]

Akcagun, E., Öz Ceviz, N., Yılmaz, A., **Mazari, A.** Analyzing the effects of special washing processes on characteristics of sewing threads (2017), Journal of the Textile Institute, 108 (11), pp. 1926-1932.

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Analyzing the effects of special washing processes on characteristics of sewing threads

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ABSTRACT

In recent years, wet (washing, bleaching, etc.) and dry (abrasive, laser shaping, rodeo, etc.) operations applied on fashion denim products have become an important factor to increase the added value. However, these wet and dry processes applied to the denim products may have adverse effects on the strength of the fabric and other supplementary materials of denim products. For example, thread breakages affect the repair ratios and quality of products, which causes time and profitability losses in companies. The main objective of this study is to analyse how the types of washing affect the strength of the sewing threads that are commonly used in the production of denim trousers. In this study, 100% cotton denim fabric with a weight of 11.5 ounces and two different sewing threads were used. The fabrics are sewn as trouser legs with chain and lock stitch. Five different washes were applied to the trouser legs. The obtained data were evaluated in the R statistical program. As a result of the analyses made it is proven that the washing techniques used have an effect on the sewing threads' tensile strength and elongation at break. The tensile strengths of lock stitch and chain stitch decrease averagely 35% and elongation at break of lock stitch decreases %22 and chain stitch decreases 29.8%.

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Sewing; sewing threads; denim washing; stone washing; bleaching

Introduction

Clothing manufacturing can be described as transforming the two-dimensional fabric surfaces into three dimensions through sewing. Sewing forms the main operation in this transformation (Khanna, Kaur, & Chaterjee, 2015).

Sewing is embedding the sewing thread into the fabric by pushing the needle in and out of the fabric. The sewing threads that hold the parts of the fabric together are identified by their fibre types, composition and numbers. Sewing threads can be produced from a single fibre type such as cotton, nylon or polyester or from a combination of cotton/polyester (Nashwa & Nesreen, 2010).

Sewing threads are made from natural or synthetic fibres twisted into plies, subjected to different operations such as gazing, mercerizing, bleaching, dying, polishing or glazing (finishing), then rolled onto a spool, roller, coil or a skein and used in machine or hand sewing (Gürarda, Kaplangiray, & Kanık, 2011). The quality of the sewing threads is determined by the mechanic and physical characteristics of the threads as established by the sewing quality and sewing strength (Lojen & Gersak, 2003).

During high-speed sewing, the sewing thread is repeatedly subjected to a number of effects such as tensile stress, spinning, pressure-twisting, fraying and heating. These forces are exerted onto the sewing thread repetitively and before a sewing thread becomes part of the stitch, it has to pass through the needle eye, fabric and coil mechanism 50–80 times (Winkler, 1971). The friction in the needle eye can cause local wearing and breaking (Mazari, Havelka, & Kus, 2015). Initial studies conducted on the subject revealed that after sewing, there is a 60% reduction in the strength of the sewing thread. Further studies concluded that in cotton sewing threads, 30–40% fall in the strength of the sewing thread is observed following the sewing operation (Mazari, Havelka, Wiener, & Zbigniew, 2015).

Denim is one of the most fashionable and widely used products in the clothing industry. Various washing methods are used to give a worn-out look, to modify the appearance and to improve comfortability of denim products (Khalil, 2015). Some of them are stone washing, bleaching, mesh washing and random washing.

In stone washing, denim products are washed together with pumice stones in industrial washing machines and lighter the colour of the product and worn out effect is given (Khan & Mondal, 2012). Denim products are placed in a large industrial washing machine that is also filled with stones. As the wash cylinder rotates, the denim product fibres are repeatedly pounded and beaten as the tumbling stones ride up the paddles inside the drum and fail back down onto the fabric (Mezarciöz & Toksöz, 2014).

Bleaching is an essential washing process leading to a significant colour shade for the blue dark denim fabric. There are

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Table 1. Characteristics of the sewing threads.

Type of thread	Material	Thread ticket number	Thread number (tex)	Number of plies
Thread A	100% PES	18	150	3
Thread B	30% Cotton + 70% PES	20	150	3

Table 2. Descriptions of industrial washing cycles.

Operation code	Operation step	Duration (Min.)	Degree (°C)
W1	Mesh washing (bad washing)	20	30
	Stone washing	20	30
	Bleaching	5–10	50
	Drying	45	80
W2	Stone washing + mesh washing	20	30
	Bleaching	5–10	50
	Drying	45	80
W3	Mesh washing	20	30
	Stone washing	20	30
	Random washing (rag bleaching)	20	30
	Drying	45	80
W4	Stone washing + mesh washing	20	30
	Drying	45	80
W5	Mesh washing + stone washing	20	30
	Stone washing	20	30
	Bleaching	5–10	50
	Drying	45	80

three ways about bleaching according to the classification for bleaching agent. These are chlorine bleaching, the hydrogen peroxide bleaching and the potassium permanganate bleaching. Bleaching process is also applied to obtain light shades that cannot be obtained by other washing techniques. It is well received by the market because of its rough fade effect (Shi, Zuo, Chen, & Yi, 2015).

Special washing techniques used in this study are random washing (rag bleaching) and mesh washing (bad washing).

Random washing is a regional bleaching. Process has a high range of controllability. The method is based on the impregnation of some special towels or rags with permanganate or hypochlorite, and the denim products are turned waterless on the machine with these towels or rags. Bleach impregnated special towels randomly strike the denim products, while the tumbler is rotating and provide regional bleaching at the points of impact. Once the process is complete, it is necessary to neutralize it (Bağıran, 2011).

Mesh washing is a washing method that has been found in most denim products and washing wrinkle effect has been obtained after the result of bad and wrong washing. The method is based on the fact that the denim products are placed in a special mesh and applied stone washing process or pre-washing process. After obtaining the desired wrinkle effect, the products are removed from the mesh and other washing processes are carried out (Bağıran, 2011).

Denim products are exposed to various washing techniques after sewing. Long and intense washing cycles not only adversely affect the tensile strength value of denim fabrics but also the sewing thread used in sewing the denim fabric (Çetinaslan, Mezarcıöz, & Çetiner, 2013).

In this study, the effects of different washing techniques on the strength of sewing threads were analysed. For this purpose, two different sewing threads were sewn to the trouser legs using lock stitch and chain stitch. After this process, the trouser legs were subjected to five different washing processes. Strength characteristics of sewing threads before and after washing were examined statistically.

Experimental

Materials and methods

In this study, 100% cotton denim fabric with a weight of 11.5 ounces was used. Firstly, six pieces of 1-m length fabric (trouser leg) are sewn with lock stitch and chain stitch. Following the sewing, one piece of trouser leg was taken to measure the tensile strength of sewing thread after sewing before washing. The strength of upper thread was measured after cutting the bobbin thread. The other five trouser legs were subjected to different special washing processes. After washing, the strength of the upper thread is measured after the bobbin thread has been carefully cut.

Thread A is composed of 70% polyester filament fibre (in the centre) and 30% polyester staple fibre wrapped around the core. Thread B is a premium quality core spun sewing thread with natural cotton-coated (30%) structure over a high-strength filament (70%). This thread has superior washing properties and therefore ideal for use in denim products. Table 1 shows the characteristics of the threads.

Washing of sewing trouser legs was carried out in sample washing machines. Table 2 shows the descriptions of industrial washing cycles.

The tests are performed with Instron Strength Testing Machine according to TS 245 EN ISO 2062 standard was conducted with 500-mm jaw distance and a test speed of 500 mm/min under the standard atmosphere conditions (20 ± 2 °C and 65 ± 4% RH). Each measurement was repeated five times. The effects of various washing types on the thread strength were examined statistically. The R programming language was used in the statistical analysis and graph creation process. R was selected because of its

Table 3. *T* Test table for comparing thread A's lockstitch tensile strength values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	σ (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.1	6	3.677	0.203	12.147	4	0.00026
W2.1	6	3.817	0.384	6.8002	4	0.00244
W3.1	6	3.500	0.323	10.87	4	0.00040
W4.1	6	4.884	0.194	3.8576	4	0.01818
W5.1	6	3.618	0.383	7.4617	4	0.00172

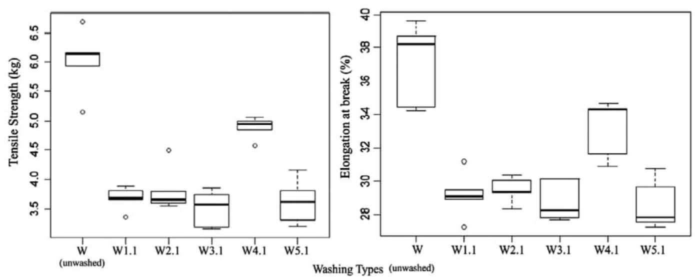

Figure 1. Box plot for thread A's lockstitch tensile strength and elongation at break.

Table 4. *T* Test table for comparing thread A's lockstitch elongation at break values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	*σ* (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.1	6	29.166	1.408	5.128	4	0.00684
W2.1	6	29.472	0.780	8.4022	4	0.00109
W3.1	6	28.796	1.241	4.9242	4	0.00790
W4.1	6	33.142	1.749	2.7629	4	0.05070
W5.1	6	28.600	1.540	8.5011	4	0.00105

Table 5. *T* Test table for comparing thread A's chain stitch tensile strength values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	*σ* (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.2	6	4.290	0.164	6.044	4	0.00378
W2.2	6	4.200	0.236	11.452	4	0.00033
W3.2	6	4.140	0.255	6.0797	4	0.00369
W4.2	6	5.030	0.347	2.7376	4	0.05203
W5.2	6	5.010	2.749	0.69891	4	0.52310

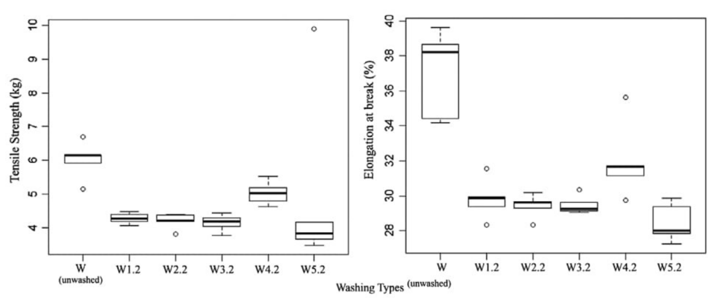

Figure 2. Box plot for thread A's chain stitch tensile strength and elongation at break.

strong programming language in addition to its detailed features in quantitative analysis calculations that are prone to constant improvement (R team, 2004).

Results and discussion

In the data-sets obtained by measuring the tensile strength and elongation values of two separate fabrics in five different washing types, box plots were used to show the frequency distribution of each variable. The box plots are beneficial in their ability to show the profile of the distribution, central tendency and the level of dispersion of the variables. For box plotting, five separate values were observed for each variable (fabric and washing types), i.e. the smallest value, lower quarter (Q1), median value, upper quarter (Q3) and the largest value. This made comparison of variables for each value possible.

For comparing thread A's lock stitch tensile strength values, the unwashed thread was compared separately for each washing type, and the *t* test table obtained as a result indicates that different washing methods give different outcomes for unwashed thread as seen in Table 3. According to this, while the tensile strength of W1.1 (p = 0.00026) is higher than other washing

Table 6. *T* Test table for comparing thread A's chain stitch elongation at break values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	*σ* (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.2	6	29.818	1.159	9.7256	4	0.00062
W2.2	6	29.422	0.681	6.5035	4	0.00288
W3.2	6	29.478	0.519	6.4132	4	0.00303
W4.2	6	31.980	2.179	4.286	4	0.01279
W5.2	6	28.460	1.108	6.1693	4	0.00350

Table 7. *T* Test table for comparing thread B's lockstitch tensile strength values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	*σ* (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.3	6	3.460	0.168	20.679	4	3.231e-05
W2.3	6	3.330	0.259	13.057	4	0.000198
W3.3	6	2.870	0.489	11.188	4	0.000363
W4.3	6	4.720	0.137	6.7998	4	0.002443
W5.3	6	2.960	0.496	12.258	4	0.000254

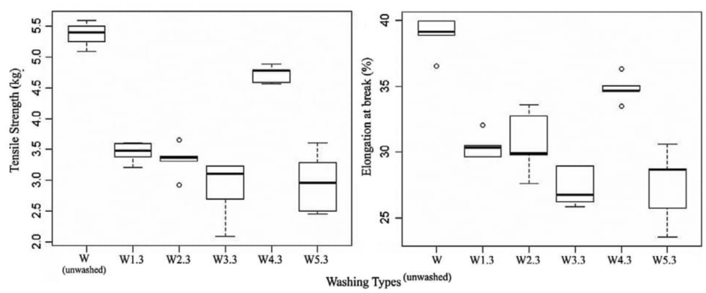

Figure 3. Box plot for thread B's lockstitch tensile strength and elongation at break.

Table 8. *T* Test table for comparing thread B's lockstitch elongation at break values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	*σ* (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.3	6	30.428	0.966	12.259	4	0.000254
W2.3	6	30.716	2.432	5.1583	4	0.006706
W3.3	6	27.354	1.507	9.8514	4	0.000595
W4.3	6	34.830	1.008	4.953	4	0.007745
W5.3	6	27.458	2.802	12.349	4	0.000247

types, all washing methods ($p < 0.05$) actually exhibited a good tensile strength in unwashed thread.

The Figure 1 box plot given above shows the data distribution of unwashed thread and five separate washing types including thread A's lock stitch tensile strength and elongation at break. The tensile strength graphic shows that the distribution of W3.1 and W5.1 assume wider ranged values compared to other washing methods. Apart from W4.1, the averages of other types of washing are almost identical whereas W4.1 has a much higher average value. The high value of W4.1 shows that the washing type used frays the thread less and hence approximates the tensile characteristics to the unwashed thread. The reason might be the chemicals used in type W4.1.

Table 4 for elongation at break shows that W3.1, W4.1 and W5.1 values extend to wider ranges. In this table, W4.1's elongation at break percentage exhibits dissimilarity from other washing types. This indicates that W4.1 approaches to unwashed (W) fabric, and the reason is the washing method used. While the fabric is less frayed, it maintains its resistance with W4.1.

For comparing thread A's chain stitch tensile strength values, the unwashed thread was compared separately for each washing type, and the t test table obtained as a result indicates that different washing methods display different outcomes for unwashed thread as seen at Table 5. According to this, while the tensile strength of W2.2 ($p = 0.00033$) is higher than other washing types, W1.2 and W3.2 methods ($p < 0.05$) also have a good tensile strength for unwashed thread. W5.2 on the other hand has quite a low tensile strength value.

The Figure 2 box plot given above shows the data distribution of unwashed thread and five separate washing types including thread A's chain stitch tensile strength and elongation at break. The tensile strength graphic shows that the distribution of W4.2

Table 9. *T* Test table for comparing thread B's chain stitch tensile strength values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	σ (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.4	6	3.160	0.165	17.247	4	6.631e-05
W2.4	6	3.500	0.279	19.615	4	3.984e-05
W3.4	6	3.450	0.350	8.7488	4	0.000940
W4.4	6	4.310	0.208	16.259	4	8.374e-05
W5.4	6	2.920	0.453	9.2732	4	0.000752

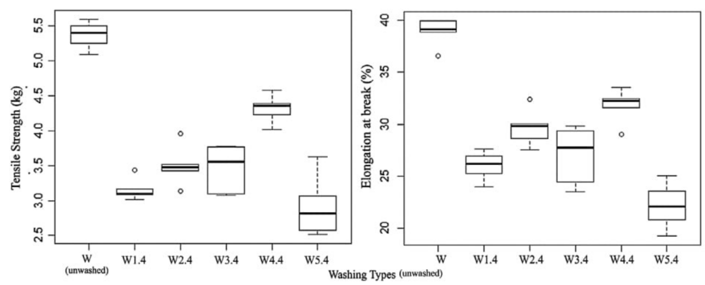

Figure 4. Box plot for thread B's chain stitch tensile strength and elongation at break.

Table 10. *T* Test table for comparing thread B's chain stitch elongation at break values with unwashed thread according to different washing types.

Group	*N* (Number of samples)	Average	σ (Std. deviation)	*T* (*T*-score)	df (Degree of freedom)	*p* (Significance value)
W1.4	6	25.996	1.436	17.349	4	6.479e-05
W2.4	6	29.694	1.801	19.14	4	4.391e-05
W3.4	6	26.988	2.875	7.0904	4	0.002089
W4.4	6	31.770	1.678	19.093	4	4.434e-05
W5.4	6	22.152	2.276	11.37	4	0.0003413

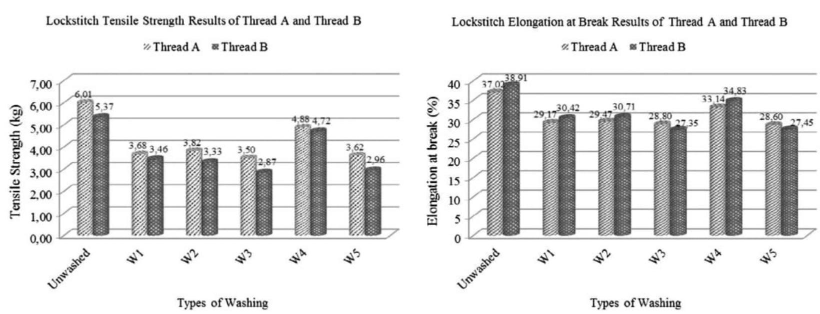

Figure 5. Lockstitch tensile strength and elongation at break results of Thread A and Thread B.

and W5.2 assume wider ranged values compared to other washing methods. In W1.2, W2.2 and W3.2, the averages of washing types are almost identical, whereas W4.2 has a much higher average value. The high value of W4.2 shows that the washing type used frays the thread less and approximates it to the unwashed thread in terms of strength, while the washing type in W5.2 wears the thread less.

Table 6, the elongation at break table, shows that W5.2 values extend to wider ranges. In this context, W5.2's elongation at break percentage exhibits dissimilarity from other washing types. Even though this thread exhibits a wider dispersion, with its lower breaking percentage it proves that it is affected by the type of washing and stitching.

For comparing thread B's lock stitch tensile strength values, the unwashed thread was compared separately for each washing type, and the t test table obtained as a result indicates that different washing methods give different outcomes for unwashed thread as seen in Table 7. According to this, while the tensile strength of W1.3 (p = 3.231e-05) is higher than other washing types, the thread exhibits a well tensile strength against unwashed thread in all washing methods ($p < 0.05$).

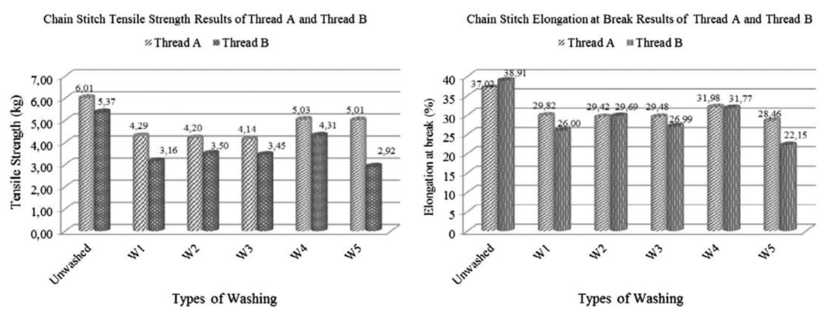

Figure 6. Chainstitch tensile strength and elongation at break results of Thread A and Thread B.

The Figure 3 box plot given above shows the data distribution of unwashed thread and five separate washing types including thread B's lock stitch tensile strength and elongation at break. The tensile strength graphic shows that the distribution of W3.3 and W5.3 assume wider ranged values compared to other washing methods. In W1.3 and W2.3, the averages of washing types are almost identical, whereas W4.3 has a much higher average value. The high value of W4.3 shows that the washing type used frays the thread less and hence approximates the tensile characteristics to the unwashed thread.

Table 8 for elongation at break shows that values in W2.3, W3.3 and W5.3 extend to wider ranges. However, W4.3 has very similar elongation at break properties compared to the unwashed thread and exhibits an almost identical dispersion.

For comparing thread B's chain stitch tensile strength values, the unwashed thread was compared separately for each washing type, and the t test table obtained as a result indicates that different washing methods display different and very good outcomes for unwashed thread as seen in Table 9. Among these five washing types, W4.4 has the best outcome. Even though W4.4's tensile strength (p = 8.374e-05) is much higher than other washing methods W1.4 and W2.4 too exhibit better outcomes. In fact, the thread exhibits a better tensile strength against unwashed thread in all washing methods ($p < 0.05$).

The Figure 4 box plot given above shows the data distribution of unwashed thread and five separate washing types including thread B's chain stitch tensile strength and elongation at break. The tensile strength graphic shows that the distribution of W3.4 and W5.4 is wider ranged compared to other washing methods. The washing methods approximate the dual thread sewed with chain stitch to unwashed thread in W4.4. The high value of W4.4 shows that the washing type used frays the thread less and hence approximates the tensile characteristics to the unwashed thread.

Table 10 for elongation at break shows that the value of W3.4 extends to wider ranges. In this context, W3.4's elongation at break percentage exhibits dissimilarity from other washing types. W4.4 on the other hand has more similar values to unwashed thread in terms of elongation at break percentage.

In Figure 5, as a result of tensile strength and elongation at break tests conducted on threads taken from cuffs sewed by lock stitch with Thread A and Thread B, Thread A exhibited higher tensile strength, while Thread B gave better outcomes in elongation at break with W1, W2 and W4. On the other hand, in W3 (28.80) and W5 (28.60), Thread A is slightly better in terms of elongation. This might be due to natural cotton thread around thread B. Because of lock stitch being the strongest stitch as well as its cotton composition, elongation at break figures were better in thread B.

When the results of tensile strength test conducted on threads from chain stitched cuffs with Thread A and Thread B are analysed, we can see that Thread A shows higher figures than Thread B in tensile strength measurements in Figure 6. Particularly after W5, better outcomes can be observed in Thread A (5.01 kg) than Thread B (2.92 kg). When the results for elongation at break is examined, even though similar outcomes can be observed after W2, W3 and W4; Thread A, following W5, displays better outcomes than Thread B (28.46 and 22.15%, respectively).

Conclusion

In this research, two types of threads are used for sewing of denim fabric which undergoes five different kinds of washing. Classical technique of lock stitch and chain stitch is used for sewing and effect of washing on performance of thread is concluded as below.

It is observed that that all type of washings significantly impacts the tensile properties of the sewing thread. The minimum damage of thread is achieved when bleaching is not performed, as shown in graphs as column W4.

Thread 'A' made from polyester fibres show 30% better performance than Thread 'B' made from cotton fibres, which might be due to the biodegradable nature of cotton fibre. The polyester in the filament structure, both in the centre and around thread, is thought to increase the strength of thread. When the elongation at break values is compared, it is observed that both the lock stitches and the chain stitches results are close to each other.

As a result of the analyses made it is proven that the washing techniques used have an effect on the sewing threads' tensile strength and elongation at break. The tensile strengths of lock stitch and chain stitch decrease averagely 35% and elongation at break of lock stitch decreases 22% and chain stitch decreases 29.8%.

It is believed that the tensile strength values of the thread containing 30% cotton fibres in the structure are lower than 100% PES fibre thread due to the staple structure of the cotton. Therefore, it can be said that the staple structure of the thread affects the tensile strength value more adversely than the filament structure of the thread. As long as intensive washing processes affect the tensile strength of the denim fabric in the negative direction, it also affects the sewing thread used in the denim fabric sewing process.

Disclosure statement

No potential conflict of interest was reported by the authors.

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