KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTYOF MECHANICAL ENGINEERING AND DESIGN

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ANALYSIS OF THREAD FORMING METHODS AND EXPERIMENTAL INVESTIGATION OF TIGHTENING TORQUE IN THIN-WALLED PARTS

Final Master Thesis

Supervisor:
Assoc. Prof. **Povilas KRASAUSKAS**

KAUNAS, 2015

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Industrial Engineering and Management

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ANALYSIS OF THREAD FORMING METHODS ANDEXPERIMENTAL INVESTIGATION OF TIGHTENING TORQUE IN THIN-WALLED PARTS

DECLARATION OF ACADEMIC HONESTY

29 May 20 15

Kaunas

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Gangadharan, S. Analysis of thread forming methods and experimental investigation of tightening torque in thin-walled parts. *Master of industrial engineering and management*final project / supervisor Assoc. Prof. **Povilas Krasauskas**; Kaunas University of Technology, Mechanical Engineering and Design faculty, Industrial Engineering and Management department.

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SUMMARY

This work determines and compares the allowable torque and the maximum torque for tightening the bolt in Friction Drilling process applied for different thin walled materials. Five different thin walled materials were analysed, i.e. S235JR Steel, DC06 Steel, Aluminium alloy, Copper and Titanium thin walled plates, all with a thickness not greater than 1.5mm. since there are no such standard tightening torque to be applied for the bolt in friction Drilling process, the mechanical tests we performed allowed to determine the torque which is to be applied on the bolt for tightening in Friction Drilling process and the same is analysed according to their mechanical properties and also nut factor is also determined. Our experiment is concentrated only M 8.8 bolt and the thin walled material not more than 1.5mm, so its recommended to do more experiments in this field to determine the standards for different bolt dimensions in different thin walled materials which are used in manufacturing sector.

***Keywords**: Friction Drilling, Thin walled joints, Tightening theory, Tightening torque, Nut Factor*

Gangadharan, S. Sriegio formavimo metodų ir sukimo momentų plonasienėse dalyse ekspermintinių bandymų analizė.*Pramonės inžinerijos magistro* baigiamasis projektas / vadovas Assoc. Prof. **Povilas Krasauskas**; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas, Gamybos inžinerijos katedra.

Kaunas, 2015. 65 psl.

SANTRAUKA

Šis darbas nustato ir palygina leistiną sukimo ir didžiausią sukimo momentą veržiant varžtą frikciniame gręžimo procese, taikomam įvairiom plonasienėm medžiagom.Penkios skirtingos plonasienės medžiagos buvo analizuojamos, ty S235JR plienas, DC06 plienas, aliuminio lydiniai, plonasienės vario ir titano lėkštės. Visų storis buvo ne didesnis kaip 1,5 mm. Kadangi nėra tokių standartinių sukimo momentų, kurie galėtų būti taikomi į varžto trinties gręžimo procesą, buvo atlikti mechaniniai bandymai, kurie leido nustatyti sukimo momentą, kuris turi būti taikomas varžto priveržimo frikciniame gręžimo procesese. Tas pats yra išanalizuota ir pagal jų mechaninės savybės, taip pat pagal riešuto veiksnį. Mūsų eksperimentas buvo sutelktas tik į M 8,8 varžtą ir plonasienes medžiagas, ne storesnes nei 1.5mm, todėl rekomenduojama daryti daugiau ekspermentų šioje srityje, nustatant standartus įvairių matmenų varžtams skirtingose plonasienėse medžiagose, kurios naudojamos gamybos sektoriuje.

Raktiniai žodžiai: Gręžimo trintis, plonasienės jungtys, suveržimo teorija, sukimo momentas, riešuto veiksnys

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FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
Head of
Production engineering
Department

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(Signature, date)

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(Name, Surname)

MASTERSTUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme INDUSTRIAL ENGINEERING AND MANAGEMENT

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Analysis of thread forming methods and experimental investigation of tightening torque in thin-walled parts

Approved by the Dean 2015 May 11 Order No. _____________

2. Aim of the project

The aim is to experimentally determine the tightening torque of 5 different materials (Titanium, S235JR Steel, Copper, 5754 Aluminium, and Dc06 Steel) used in the manufacturing industry.

3. Structure of the project

The final work will consist of Introduction part, overview of friction drilling process, theoretical explanation of tightening theory and the experiment to determine the tightening torque for the material using an M6 bolt, where the results are plotted in the graph and analysed. The results are discussed and recommendations are made.

4. Requirements and conditions

The materials selected for the experiment should be the materials used in the manufacturing industry and it should be checked for the preload, allowable torque and the point at which the joint fails. The result should be analysed and discussed and recommendations is to be made for the same.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2015 June 1st.

Given to the student Shejin Gangadharan

Task Assignment received _______________________ ___________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor _______________________ ___________________
(*Position, Name, Surname*) (*Signature, date*)

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1. INTRODUCTION

One of the actual problems in the manufacturing engineering is related to the assembly of the sheet metals, thin-walled tubes or profiles. These tasks could be performed using Friction Drilling technology, which enable to simplify assembly process and to improve reliability of the joint. Friction drilling is also called Thermal Drilling, Flow Drilling, Form Drilling, or Friction Stir Drilling.

Friction drilling is a non-traditional hole-making method that utilizes the heat generated from friction between a rotating conical tool and the work-piece to soften and penetrate the work-material and generate a hole in a thin-walled work-piece. It forms a bushing in-situ from the thin-walled work-piece and is a clean, chip-less process. The purpose of the bushing is to increase thickness for the threading and available clamp load. Thermal drilling is a process that uses friction to produce bushing in metal tubing and flat stock. It is a process of combined rotational and downward force, which creates frictional heat that can reach 900 c for the tool and 700 c for the work-piece.

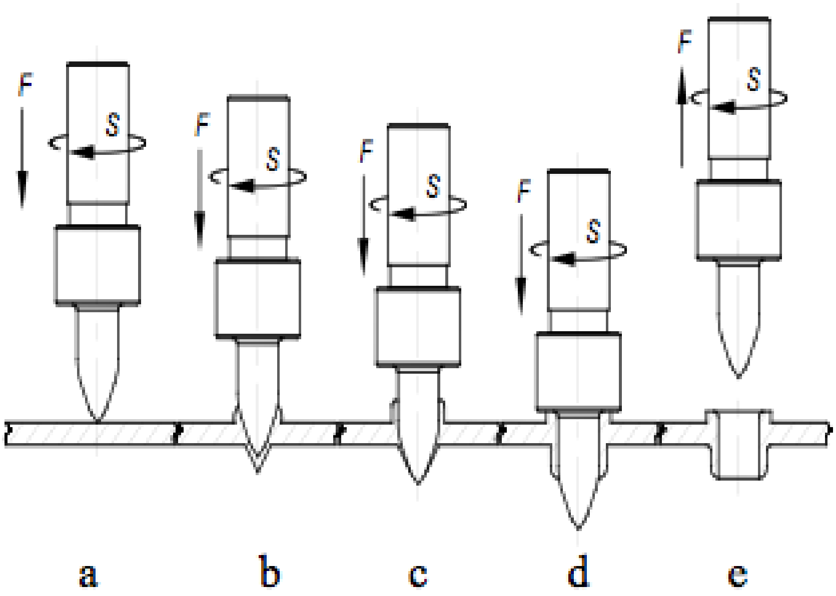


Figure.1.1 Schematic illustration of 5 steps in Thermal Drilling [3]

The above figure shows the process taking in Friction Drilling. The first step is the movement of the conical tool towards the workpiece material as shown in Fig. (a). Figure (b) illustrates the point at which the conical tool touches the surface of the workpiece material. The tool is rotating in a high speed, which results in heating the surface it touches while moving. Thus the work material is heated and subjected to plastic deformation. This deformation helps the tool to move further inwards to the material. This movement is shown in figure (C). The tool reaches to the maximum inward position of the material and the desired hole is created in the material forming a neck on the lower side of the hole and bushing on the upper side of the sheet as shown in figure (d). Then the tool is retracted from the material to form the desire hole in the workpiece material with a bush and neck as shown in figure (e).

Figure1.2 Cross-section of hole and brushing [4]

Hence formed hole is then tapered to form thread which starts from bush to the whole neck providing a no waste to the workpiece material. The cross section of the resulting hole from drilling and the thread formed from tapping is shown in Figure 2. In addition, no cutting fluid or lubricant is necessary, which makes friction drilling a totally clean, environmentally friendly process.

2. RESEARCH MOTIVATION

Thread machining is very widely used technique to join the mechanical pats, whether permanent or temporary joints. The traditional joining techniques such as bolt and nut, screwing, nut weld, rivets, press fitting, snap fitting, etc. needs one or more components to join or the material has to be brought to the condition in which it can be joined. Some of the traditional fastening methods are illustrated in figure 3. This all processes either makes wastage of labour expenditure or results in unwanted installation of inventory. We can detail it taking an example from the automobile manufacturing sector. In the automobile manufacturing industries large number of robots are used for different processes to be done which are very much quiet expensive. Now for joining any part in the automobile, say fixing seat to the body, generally the industry uses bolt and nut or welded nuts for the strong fixation. This leads to unnecessary processes as compared to Friction Drilling. For this process to be done in conventional way, the robot has to weld the nut with perfection at first and then the seat has to be bolted through it. Now if this process is done under Friction Drilling process, we can save first and foremost, the inventories. The bolt is not needed and also the robot which does the welding. That robot can be assigned to do just a drilling, tapping and then the seat can be directly bolted. By this we save unwanted labour cost, inventory, and also there will be no waste or else that would be an extra waste of money for the waste removal and disposal.

(a) (b) (c)

Figure 2.1 (a) Bolt and Nut; (b) Rivet; and (c) Weld Nut [1]

Friction Drilling overall makes the process very simple. In the conventional method, to attach thin walled material we use bolt and nut, welded nuts, rivets, etc. which all takes time and labour expense also produces waste which can be completely solved by the Friction Drilling technique. The complicated machinery that does those welding and stamping are all get ridden and it’s replaced by a single robot to drill, tap and fix bolt to the desired location without costing any waste. All the material from the drilling of the thin walled material is transformed to create the thread. This results in simplifying the process and no chip nor cleaning is necessary which in turn saves the disposal cost and ofcorse the time. To make the step simpler, the thread-forming tool can be merged to the drilling tool so as to create hole and thread at a stretch, which in turn saves a process thus saving more time.

The main area of application of this type of thin walled plate fixing can be implemented in automotive industry where there is need of many joints to be attached. Almost most of the elements of automobile body and its working parts are thin walled. So this is the most apt joining method as it saves the inventory, lessen the waste, saves the time which in turn helps in the increase of production of the vehicle. Complicated robots designated to do the complex joining methods can be eliminated and a simpler one can be installed which in turn adds on to a bigger initial savings of money and space. As this is an upcoming process and not widely used, we have no certain known limits of how much torque is permissible for tightening the bolt in different thin walled materials. So in my paper we made a detail study of the allowable torque for tightening and also maximal torque and the point at which the joints fail. Everything is studied experimentally and detailed graph-by-graph and analysed.

3. LITERATURE REVIEW

The principle of the friction Drilling is known from the stone age era itself. At the earlier days stones were rubbed to one another to bring friction in between them and thus producing heat and then fire. The same is used here in Friction Drilling were the friction is created by the contact of two metals, one which is obviously the tool which makes the other, i.e, the workpiece material plastically deformable where easily the desired shape can be given to the particular area. At the earlier time, the drill bit was not so sophisticated as it is now. So much smoke and heat was formed while the friction was done at that time. Then a French named Jan Claude de Valliere working on a little farm, when encountered the same problem he ended up with many experiments that if he could produce a certain amount of heat, that was enough to melt the metals and can be deformed easily. Thus he developed a special drill design to increase friction. But his invention was not at the time practically viable nor commercially affordable.

Till date the studies in the field of Friction Drilling is continuing, as the result, there is no known standards for the Friction Drilling. So studies are performed in different parts of world about the materials which can show good response for the friction, which tools are viable for the process, shape of the tool, material of the tool and so on. The Friction Drilling process in short can be briefed as the process in which the material is brought to the plastically deformable state by bringing friction to the contact point of the tool and the workpiece and then the desired tapping is created in the preferable size where there is no wastage of material nor any external nut is required to fix the bolt to it. The tool consists of a pointed start which broaden at the end as per the required diameter. The tool creates a drilling hole by the friction process turning and protruding into the workpiece. Then the tapping is done with a tapping tool which is easily formable after drilling. The main area of our research is the next part. As said earlier, there are no definite standards for this process and this is where we took our research to determine the allowable torque to the tightening of the bolt in the thread created by Friction Drilling Process for different material.

There are mainly three conventional methods which are taken as standards for the friction drilling process for considering the calculation of torque, co-efficient of friction, etc. These all have their own advantage and disadvantages in the field of joining thin walled materials. This is discussed below taking each joining methods separately.

Bolted and screwed joint are one of the most universally and widely used type of fasteners. The basic principle of a threaded nut is they require a mating thread or use of an extra, internally threaded component. They also belong to the group of detachable joints and can be designed as pierced, pierced and protruding or blind-hole joints. Since our investigation deals with the thin walled materials, that gives Friction Drilling a step ahead of this conventional, universally and widely accepted method. When bolt and nut joining medium is used to join the thin walled plate plates, it need an extra nut, and washers so as to protect the contact surface from deforming.

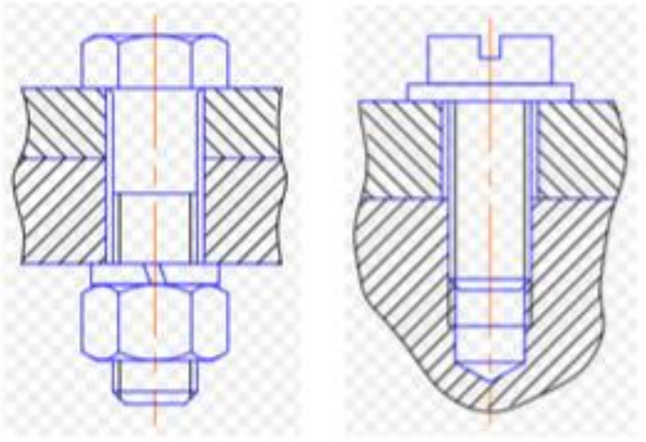


Figure3.1Bolted (left) and Screwed (right) joint [18]

For the thin walled material, this joint is not so advisable as for fixing it need bolt to be aligned according to the hole for fixing which is complicated in the region where it can be impossible to reach out for the alignment of the nut. Also it need much more elements to join the material which in turn is an extra inventory cost, extra labour cost and time consuming as compared to the Friction Drilling process.

Figure 3.2 Weld Nut [22]

The main problem discussed for the bolt and nut joint is the complexity of getting the nut aligned in congested area. This is eradicated in the weld nut technology. Sometimes it difficult or even impossible to reach to position the nut in-order to join components, in such cases nut is pre-set to one of the components to avoid the use of the wrench. To say about the advantage of this method, its much more rigid and stronger than the ordinary or general bolt and nut assembly, ease of connecting any joints by this process and also the simplicity. The main disadvantage of this type of joining process is that, if we apply heat much more than the preferred heat of the material, the material may get deformed and becomes useless, also it makes the assembly complex, thermal distortion and is applicable only for plates. Also it increases the labour cost as a process is added to join the nut to the material in turn effects time, i.e., this process is time consuming than general joining method. Skilled labours are needed to fix the weld to the material that can be also considered as a disadvantage.

The other conventional method other than these two which is widely used is riveted joint. Rivets are relatively low-cost, permanently installed fasteners that are lighter weight than bolts. They are faster to install as compared to other conventional methods and are also are light weighted than bolts, so as a result they are widely used as fasteners in the aerospace manufacturing industry. The general type of rivets are solid, blind, tubular, and metal piercing.

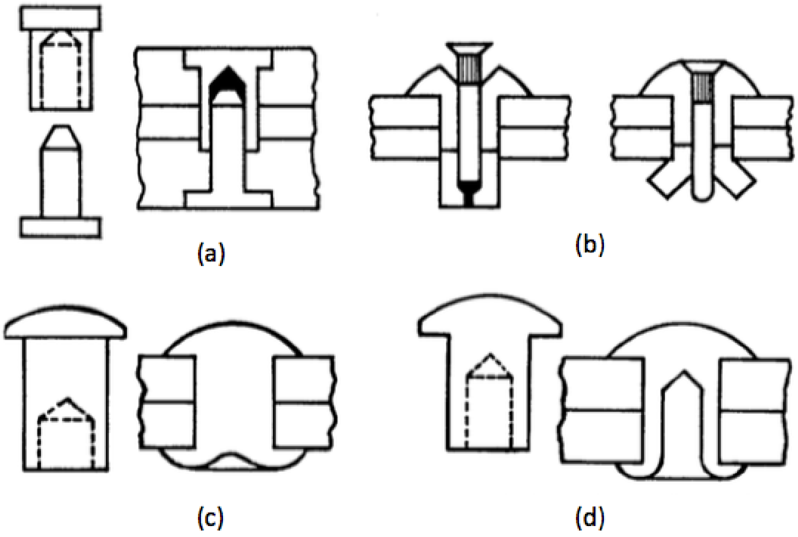


Figure.3.3 Different type of rivet joints (a) Compression tubular rivet (b) Drive-pin rivet (c) Semi-tubular rivet (d) Full-tubular rivet [25]

The main advantages of the rivet joint is that they are light weight and are faster to install than other conventional methods and can be installed very fast thus is time saving process. The main disadvantage of this process is, since they are the joints which are permanently installed, to remove them, it should be drilled out and thus increasing labour cost, jam during assembly, possibility of getting twisted and also has only limited stability. This type of joints cannot be used for the components which need to be disassembled for maintenance or repair which is another negative part of this technique.

The Friction Drilling process stands ahead of all these conventional methods in the case of thin walled material. For the thin walled material, all the conventional methods like bolt and nut, rivet joint and weld nut joint has much disadvantage in one or the other way. Friction Drill is a process in which thread is formed by piercing the same material by friction creating a thin walled material without any chips and a bushing is formed underneath the workpiece from the existing material. The thickness is formed not with any additional material nor inserts, it forms from the projected material thus giving no wastage in the form of chip.

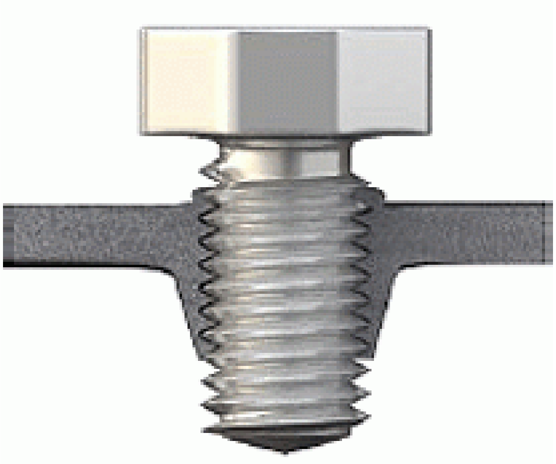


Figure 3.4 Cross-sectional view of bolt tightened by Friction Drilling process [5]

The Friction Drilling process provides a secure hold within the materials together with no twist and also it's a quick mounting process. No additional attachments are require for the joining of material which give it an extra edge for the attachments done in round tubes. The process speed up the production by saving the time as the process takes only half the time that a rivet nut takes. Considering the cost, it would save about 70% of the cost as compared to riveted joint.

This research paper mainly deals with the tightening theory of the friction drilling. As this process is not widely use, so still many of its parameters is unknown and still studies are going on in this field to make the process more effective. In this paper, we detail about the experiments done in different thin walled materials for the allowable torque and checked the torque at which the material fails, thus to determine the allowable torque for S235JR Steel, DC06 Steel, Aluminium alloy, Copper and Titanium. Still more studies are required in this process considering other thin walled materials and not only check only for tightening, but for other parameters too.

4. THEORETICAL ANALYSIS OF TIGHTENING PROCESS

The tightening process begins when the screw head makes contact with the near plate material. At this point, all of the applied torque, or rotational force, goes into overcoming the internal stress of the materials as well as friction forces. As the screw is tightened, the internal stresses increase. When the torque is released, it is these stresses that fasten together the screw and materials. However, certain stresses may cause failure if the torque is too high. These stresses are presented in section 6.1.the model presented in and calculated the torque required to advance a screw during the tightening process, but did not look into failure that may occur during tightening. Screw tightening is carried out in order to stop objects from moving (to fix them).

Followings are major objectives of the screw tightening.

- For fixing and jointing objects
- For transmitting driving force and braking force
- For sealing drain bolts, gas and liquid

The fixing force at this time is called the axial tension (tightening force), and the target of screw tightening is to “apply an appropriate axial tension.”

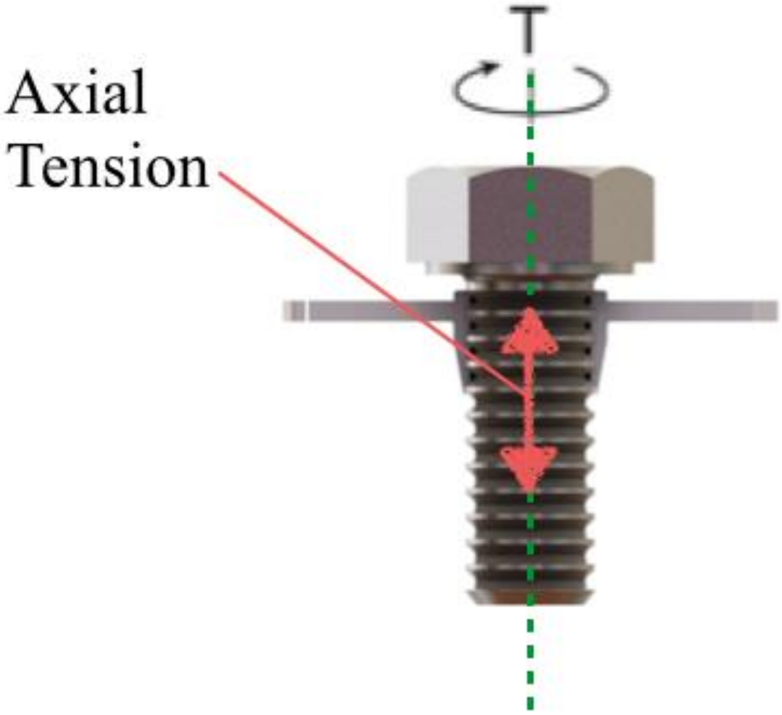


Figure 4.1 Schematic diagram of screw tightening [8]

Although axial tension control should normally be carried out, because axial tension is difficult to measure, torque control is used for its substitute characteristics that allow tightening administration and operations to be carried out easily.

Table 4.1 Various Tightening Methods

Tightening method	**Description**	**Advantages and disadvantages**
Torque control method	Bolt tightening is controlled by the torque value. This is the most widely used method.	Tightening control and operation is easy. Since the torque value does not change because of the bolt length, standardization is easy. The dispersion band of the axial tension is wide and bolt efficiency is low.
Rotation angle method	Bolt tightening is controlled by the angle. The bolt is tightened to a defined angle from the snug torque.	When bolts are tightened within the plastic zone, dispersion of axial tension is small and operation is easy. Since tightening will go beyond the yield point, there is a limitation on the threaded joint with additive load or retightening. It is difficult to define the tightening angle.
Torque gradient method	The bolt is tightened from the proportional point until the yield point is reached. An electronic circuit carries out arithmetic processing of the angle, torque, etc.	Since the dispersion width of the axial tension is small, the efficiency of the bolted joint is large. Inspection of the bolt itself is possible. Tightening will go beyond the yield point. The tightening device is expensive. In the service field, the tightening method is not available.
Elongation measurement method	The elongation of the bolt, generated by bolt tightening, controls bolt tightening. Elongation is measured by micrometer, ultrasonically, or with a mandrel.	The dispersion of the bolt is very small. Tightening within the elastic zone is available. The efficiency of the bolted joint is large. Additive loading and second-time tightening are possible. End face finishing of the bolt is required. The tightening cost is high.
Loading method	While the defined tensile load is applied to the bolt, the load given to the bolt controls tightening.	Axial tension can be directly controlled. Torsion stress of the bolt is not generated. The tightening device and bolts are specially made. High cost.
Heating method	The bolt is heated to generate elongation. Tightening is controlled by the temperature.	Space and force are not required for tightening. There is no clear relation between the heat and axial tension. Temperature setting control is difficult.

4.1. Friction Drilling Vs Traditional Methods

Friction drilling is a non-traditional hole-making process. A rotating conical tool is applied to penetrate a hole and create a bushing in a single step without generating chips. Friction drilling relies on the heat generated from the frictional force between the tool and sheet metal work piece to soften, penetrate, and deform the work-material into a bushing shape.

Traditional drilling types are bow drill , brace and bit, Gimlet, hand drill, breast drill, push drill, pin chunk.

Table 4.2 Friction drilling Vs Traditional methods

CRITERIA	TRADITIONAL METHODS			FRICTION DRILL
	PRESS NUT	WELD NUT	RIVET NUT	
RELIABILITY	Given only conditionally	As rule high	Given only conditionally	Particularly high
SCREWING	If applicable in exact pressing, slant position	If applicable distortion	If applicable distortion of thread and risk of slipping	Homogenous moulding in direction of drilling axis
MULTIPLE SHIFT USAGE	Conditionally possible	Yes	Conditionally possible	Yes
TORQUE LOADING	Low	High	Low	High
TYPE OF CONNECTION	Mechanical keyed press connection	Partly joining of microstructure due to spot welding	Mechanical, keyed press, connection	Homogeneously closed joining of microstructure
JOINING PARTNER	Work piece press nut	Work piece, weld nut (normally well deposit)		Parent material only

4.2. Traditional tightening methods

There are several methods of tightening bolts. The corresponding principles are quite different, as are the quality and accuracy levels accomplished. Most commonly used methods are briefly described below.

4.2.1. The torque wrench

Tightening by torque wrench is the most common tightening method upto a bolt diameter of 30 mm. this makes this method a very simple and quick to use method. But from the theoretical developments and experimentations, this method also lacks perfection in some cases which leads for the invention, experimentation and adoption of new methods.

1. High amount of uncertainty as to the final bolt tension load

The factors that influence the final tightening loads are the coefficient of friction on the threads of the nut and the bolt, and on the contact surfaces between the flange and the nut. The reliable and accurate values of these coefficients are impossible to know practically, so for a given nominal torque value, the deviation of the final tightening load of the bolt can vary between +/- 20% when conditions are good, and +/- 60% when conditions are bad.

This wide range is due to the combination of the following three phenomenon:

- The tolerance in the applied torque, which can vary from +/- 5% to +/- 50%, depending on the tool;
- Geometric defects and surface roughness on the threads and the bearing surfaces of the fastened components;
- Degree of lubrication of bearing surfaces.

Table 4.3: Accuracy of the tightening load for various tightening methods using torque

Tightening method	**Accuracy on pre-load**	$\boldsymbol{\gamma}$
Caliberated torque wrenches Power tightening tools with regular caliberatin on application	±20%	1.5
Impact wrenches with stiffness adjustment and periodic calibrationon application	±40%	2.5
Hand wrenches Shock wrench	±60%	4

$\gamma = \frac{F_{\circ}max}{F_{\circ}min}$: Uncertainity factor on tightening load

2. Incorporation of additional “parasite” torsion stress

A parasite torsion stress is induced in addition to the desired axial tension stress in the bolt which can reach over 30% of the tension stress. The resulting equivalent stress in the bolt (Von Mises or Tresca criteria) is greatly increased and can exceed the yield point of the material, whereas the torsion stress itself remains within admissible limits. Furthermore, the residual torsion stress increases the risk of spontaneous loosening at a later stage and also since the torque is most often applied in a non-symmetrical manner, bending stress is induced which is comparatively a very small value, hence ignored. In cases where the working conditions are near to the limit, his bending stress is taken in account

Table 4.4 Deviation of torque in industrial applications

Accuracy range of torque tightening method	Equipment type			Usage limits
	Manual hand tool	Portable power tool	Non-portable power tool	
D ± 20% to ± 50%		Simple shock wrenches		≥ 50 Nm
		Power tightening tools with positive clutch		≤ 50 Nm
C ± 10% to ± 20%		Power tightening tools with pneumatic adjustment		≤10 Nm
		Power tightening tools with electric adjustment		≤10 Nm
		Impact wrenches with stored energy (torsion bar or other means)		≥ 10 Nm
		Adjustable wrenches with angle drive		≤ 20 Nm
	Calibrated wrenches with simple device			≤ 400 Nm
			Simple air-driven tools	No limits
B ± 5% to ± 10%			Hydraulic screwing tools	-
	Calibrated wrenches with release device and automatic resetting			≤ 800 Nm
	Calibrated wrenches with dial gauge			≤ 2000 Nm
		Wrenches with angles drive and release device		≤ 80 Nm
			Air-driven tools with controlled torque	No limits
			Air pulsed tools	No limits
A < ± 5%			Electric power tightening tools	No limits
	Electronic calibrated wrenches			≤400 Nm
			Dual-speed motors	No limits
			Servo controlled motors	No limits

4.2.2. Tightening with heater rod

This is a tightening process in which the bolt is elongated by heating with the help of inserting a heater rod down the bolt centre. It then serves to turn the bolt with a minimal torque force till the bolt contacts with the flange. Then the bolt is cooled, which inturn contract the bolt lengthwise, hence tightening the nut. Simultaneous tightening of several nut is possible. The method is theoretically accurate but in fact has several disadvantages:

- A hole must be drilled down the centre of the bolt to receive the heating rod.
- Heating systems, electrical connections, temperature control devices and handling means are required, especially in the event of simultaneous tightening.
- The method is exceedingly slow, due to the time required to heat the bolts, and the final tightening load can only be checked after the bolts have cooled down, which takes even longer.

The process cycle includes: heating the bolt, advancing the nut, cooling down the parts, and measuring the parts. This cycle must be repeated several times in order to adjust tightening. The temperature required to get appropriate elongation is often so high that it could modify the mechanical properties of the equipment. As a result, when thermal elongation is lacking, additional torque tightening must be executed and verified by measuring the nut angle. This thermal elongation technique is fairly rarely used and is generally only applied to large sized bolts (diameter > 100mm).

4.2.3. Tightening by mechanical elongation

With this method, the tension load is directly applied to the bolt. In general, the body of the nut is provided with a set of small thrust screws located symmetrically around the main threaded hole. These screws apply - either directly or through a washer - a bearing pressure on the contact surface of the flange. They are turned one by one and step by step using a low torque load until a suitable tension load for the bolt is reached.

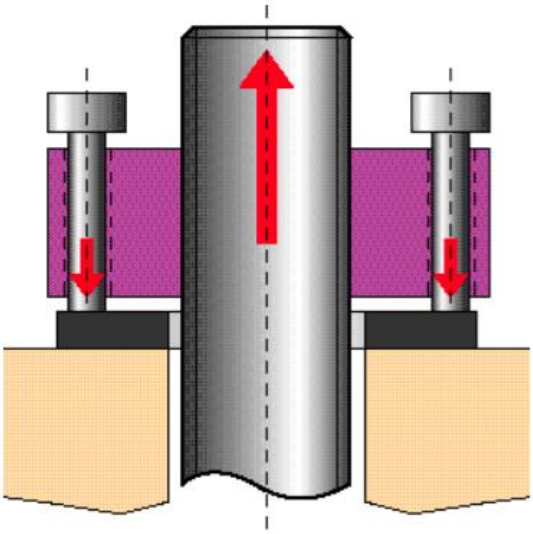


Figure 4.2 Tightening by mechanical elongation [18]

The bolt elongation is most often measured using one of the previously mentioned methods. In spite of the fact that this method eliminates torsion stress in the bolt, it has several drawbacks:

- Simultaneous tightening is not easy to carry out: only a step-by-step tightening process is reasonably possible, from one bolt to the next. This is both tedious and time-consuming, and the result is pseudo-simultaneous tightening.
- To precisely determine whether tightening was carried out correctly, an additional measurement means must be provided, such as elongation method or the use of load-measuring washers.
- The nuts are generally expensive, since they are bigger and require several small thrust screws and machining of several threaded holes
- When professionally applied, this method is the best way to achieve the quality criteria of proper tightening as described in the introduction.
- The process is very slow because the small screws have to be hand-tightened several times.

For all of these reasons, the mechanical elongation method is not used frequently.

4.2.4. Tightening with hydraulic bolt tensioners

The bolt must have an end that protrudes above the tightening nut. Cold extension is applied to the bolt by means of an annular hydraulic cylinder placed around it. The bolt undergoes an axial traction load only. The stress-free nut is then turned down with very little effort and does not transmit any torque to the bolt. When the fluid pressure is released in the tensioner, the major part of the hydraulic load on the tensioner is transferred into the nut, and tightening is completed. For optimum accuracy, it is recommended to perform traction of the bolt and turning-down of the nut twice.

In effect, the first turning-down operation compensates for clearances, compresses the roughness of the surfaces and sets the load balance, while the second operation serves primarily to obtain the required accuracy of residual load in the bolt.

Advantages of hydraulic bolt-tensioning

1. No torsion stress
2. Good accuracy
3. Easy implementation
4. Material variety
5. Suits a wide range of bolt diameters
6. No damage to components
7. Easy untightening
8. Simultaneous tightening is possible
9. Process automation is possible

4.3. Tools using for Drilling Process

Thermal friction drilling tools

Mainly:

1. FLAT
2. CUSTOM

Machine Tapping Tool

Figure4.3 Tapping process

Figure 4.4 Tapping tool [6]

Thread forming taps is an important step of friction drilling process. These taps form the threads by displacing the metal rather than cutting it. The resulting threads are smoother and stronger than cut threads. The taps are a lot stronger because they do not have flutes. The can be run faster and don’t bind up with chips. It looks like the combination of thermal drilling and thread form taps creates a very clean operation.

The tool comes into contact with the material using relatively high axial pressure and rotational speed. The generated heat makes the material soft and malleable enough to be formed. As the tool pushes into the material, some of the displaced material forms a collar around the upper surface of the work piece. A bushing in the lower surface of the work piece is formed the rest of the material. All this happens in a matter of seconds. The resulting collar and bushing can be up to 3 times the original material thickness accurately by the cylindrical part of the tool determines the diameter of the bush.

4.4. Different steps of Friction Drilling Process

Step 1

Position the drilling tool to just touch the material.The friction drill is running at the speed,best for the material and drill size.

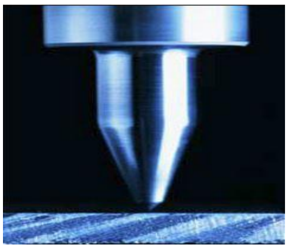


Figure 4.5 Tool bringing to contact [7]

Step 2

The drilling tool tip is pushed against the material, creating friction heat, and raising the temperature in the surrounding material to about 600 degrees Celsius.

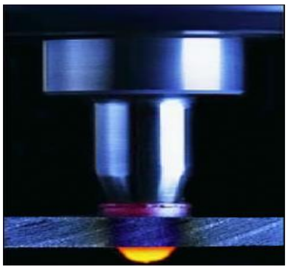


Figure 4.6 Starting of the Friction process [7]

Step 3

By feeding the friction drill into the material, the desired hole is formed. Within seconds, the excess material creating a bushing , and is added to the surrounding metal as in friction welding. No chips are generated.

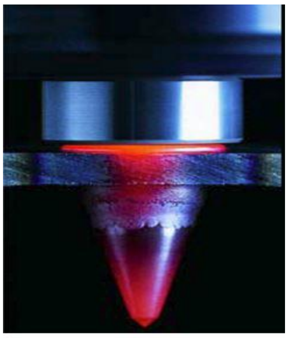


Figure 4.7 tool reached at the maximum level to create bush [7]

Step 4

Stop feeding at depth. The tool has formed a forged rim on top of the material.

Step 5

The Drilling tool is retracted out of the Bushing, to the final position above the material, ready for repositioning for the next operation.

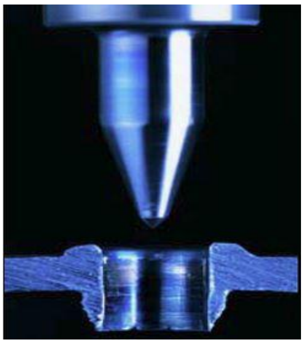


Figure 4.8 Retract of the tool creating drilled hole [7

Step 6

In the form tapping process, the sequence is identical to conventional tapping. To feed out the tapping tool, the rotation is reversed. The process is without making any chip.

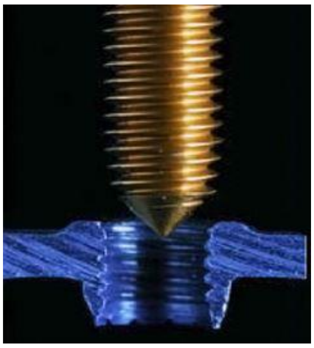


Figure 4.9 Results after tapping [7]

4.5.Failure modes in tightening

The load P involved in tightening can be related to various types of stresses in the screw and material. These stresses are calculated using $\sigma = P/A$, where the area A depends on the surface area of the particular stress. The tightening torque causes stresses in the screw and work plate that fasten them together. In the first stage of tightening, the stresses cause elastic deformation, which means that if the screw is removed (or tightened), there would be no permanent deformation. Plastic, or permanent, deformation occurs when one of the stress levels of the screw or material reaches its respective yield strength. If we exceed the ultimate tensile strength of a material, failure will occur. We calculate the forces P and torque T that would produce these yield stress levels to prevent ever reaching the u. for our model we consider three types of failure modes that might occur during tightening: stripping failure in the work plate material, bearing failure in the near plate material, and breaking of the screw.

4.5.1. Shear stress

Shear stress is a stress that occurs at an area due to tangential force acting on that area. When the engaged threads can no longer advance downwards, the torque applied to the screw creates an upward force on the threads of the work plate material. This force produces shear stress along the surface of a vertical cylinder with diameter D_S within the work plate. The magnitude of the shear stress caused by a load P acting on a surface area A_S is

$$\tau_S = \frac{P}{A_S} \tag{4.1}$$

If τ_S is larger than the yield stress of the work plate material, stripping will begin. If τ_S exceeds the ultimate shear strength of the work plate material, stripping will occur and there would be nothing holding the screw in the material because the threads of the screw have sheared off the formed threads in the work plate. At this point, if we were to remove the screw threads on the surface of a cylinder with a height of $n_t p$, the number of engaged threads times the pitch. This leads to surface area A_s (shown ib Figure 10).

$$A_s = \pi D_s n_t p \tag{4.2}$$

whereD_s is the major diameter of the screw. The shear stress in the tap plate material due yo the applied torque is

$$\tau_s = \frac{P}{\pi D_s n t_p} \tag{4.3}$$

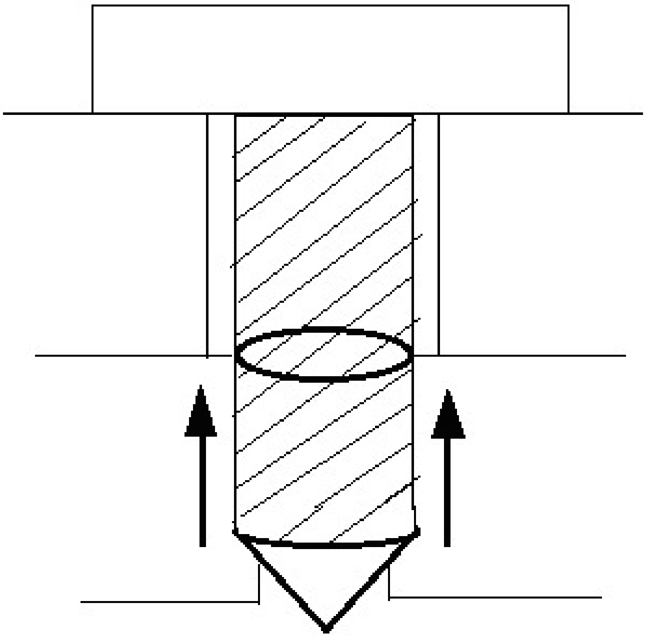


Figure 4.10 Area of Shear stress

4.5.2. Bearing stress

When the head of the screw is seated on the near plate, the downward force on the near plate creates a compressive stress in the near plate, known as bearing stress. The bearing stress that the near plate material experiences from the screw head due to the tightening torque is

$$\sigma_s = \frac{P}{A_b} \tag{4.4}$$

where the area under compression is the contact surface of the near plate and screw head. This contact surface is an annulus with outer diameter equal to the screw head diameter D_{sh} and inner diameter equal to the near hole diameter D_n, shown in figure 11, so that

$$A_b = \pi \frac{D_{sh}^2 - D_n^2}{4} \tag{4.5}$$

Combining those two equations gives us the bearing stress

$$\sigma_b = \frac{4P}{\pi\left(D_{sh}^2 - D_n^2\right)} \tag{4.6}$$

If this bearing stress exceeds the ultimate strength of the near plate material, the near plate would be permanently dented in the shape of the annulus with area A_b.

4.5.3. Tensile stress

During and after tightening, the screw experiences tension. This is because the screw head is being pushed upward by the stress in the near plate material and the engaged screw threads are being pushed downward by the stress in the formed threads in the tap plate material, shown in figure 4.10. Due to the complex geometry of a screw, we cannot analytically determine the cross sectional area used to calculate the stress. Experimental testing has shown that the cross-sectional area used to calculate the tensile stress of a screw can be approximated by the following:

$$A_t = \pi (r_t)^2 \tag{4.7}$$

where

$$r_t = \frac{D_p + D_r}{4} \tag{4.8}$$

The pitch diameter D_p is the diameter at which the distance between the threads and the width of the threads are equal. For a screw with symmetric threads,

$$D_p = \frac{D_s + D_r}{2} \tag{4.9}$$

The tensile stress developed is

$$\sigma_t = \frac{P}{A_t} = \frac{64P}{\pi (D_s + 3D_r)^2} \tag{4.10}$$

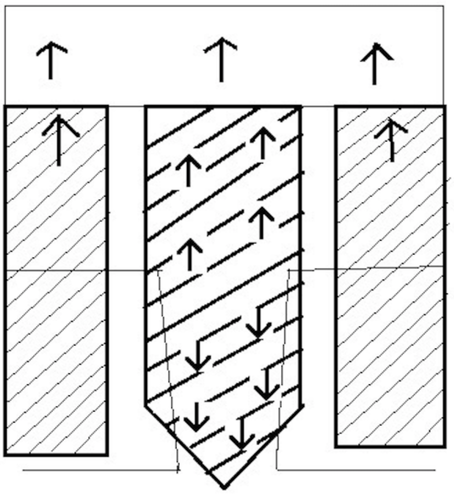


Figure 4.11 Diagram showing tensile stress developed in the screw

4.5.4. Torsional stress

Torque exerted on the head of the screw and resistance to rotation in the engaged threads of the screw causes torsional stress τ_t in the screw. Torsional stress is calculated using the total shear stress at a certain radius caused by torque. In a simple bar, the maximum torsional stress occurs on the outer surface. For a screw, we take the outer radius as r_t. Taking T to be the torque exerted by the driver, and J as the polar second moment of area, $J = \pi r_t^4/2$, the torsional stress developed in the screw is described by the following:

$$\tau_t = \frac{T r_t}{J} = \frac{2T}{\pi r_t^3} = \frac{128T}{\pi\left(D_p + D_r\right)^3} \tag{4.11}$$

4.5.5. Effective Stress of screw

Screw failure results from a combination of its tensile and torsional stress. In order to compare screw failure to bearing and shearing material failure, we must represent the tensile and torsional stresses in the screw using one effective stress within the screw. The von Mises effective stress $\sigma^{|}$ uses the combination of distortion energies of various stresses at the same point to define an equivalent uniaxial normal stress $\sigma^{|}$:

$$\sigma^{|} = \sqrt{\frac{\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)}{2}} \tag{4.12}$$

Here σ_x, $\sigma_y$and σ_z are the tensile stresses in the x-, y-, and z- directions, respectively, and τ_{xy}, τ_{yz}, and τ_{zx} are the shear stresses in the x-y, y-z, and z-x planes, respectively. The applied torque causes no stress in the y- and z- directions nor in the y-z and z-x planes, so all of these values are zero. Because the tensile stress is in the z-direction, $\sigma_z = \sigma_t$, and because the torsional stress is in the x-y plane, $\tau_{xy} = \tau_t$. Therefore, the effective stress in the screw is given by

$$\sigma^{\mid} = \sqrt{\sigma_t^2 + 3\tau_t^2} \tag{4.13}$$

This effective stress incorporates the torsional stress into the normal tensile stress, and can be related to the load using

$$\sigma^{\mid} = \frac{P}{A_t} \tag{4.14}$$

Since the screw head creates a discontinuity of the cross-section, a stress concentration factor k may be incorporated to account for the relatively high localized stress just below the screw head. If the effective stress of the screw exceeds its ultimate strength, then the screw will fracture, usually directly below the screw head due to this localized stress.

4.6. Torque required to overcome internal stress

In this section, we will derive a formula that computes the torque required to lift a load P. we will first consider the simple case of a screw ($\beta = 0$) and then insection 6.2.2 we will extend this to self-tapping screws with symmetric threads ($\beta_1 = \beta_2 = \beta > 0$).

4.6.1. Two-dimensional model

We will first look at a simplified analogy of a screw during the tightening process. In the next section we will extend it to parameters that better suit our purpose.

The process of tightening the screw is analogous to a power-lifting load. When making this comparison, it is important to note the differences between a power screw and self-tapping screw. A power screw uses square threads ($\beta = 0,$ shown in figure 13) to convert applied torque into linear motion. In addition, a power screw lifts a load that is just the weight of an object, while the load for a self-tapping screw is a load corresponding to stresses of the materials. An example of a power screw is a basic car jack which is used to lift a vehicle off the ground for maintenance and repair.

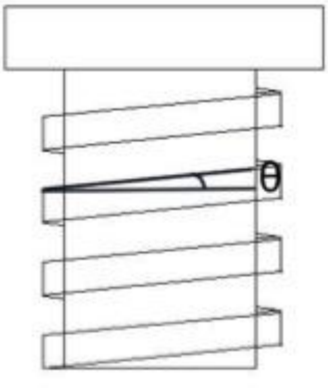
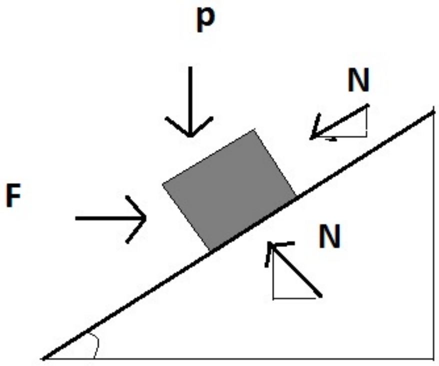


Figure 4.12 Power Screw with square threads

Since a power screw uses square threads, all of the forces can be broken down into two components shown in Figure 9. The inclined plane represents a thread that has ben unwrapped from the screw, while the rectangle on the inclined plane represents a mass on the thread. This mass creates a load P that acts down on the screw threads. In section 6.1 we will relate the load P to material properties. N is the normal force of the threads pushing on the mass. The friction force μN is the coefficient of friction between the two materials μ times the normal force N. F is the force caused by the applied torque. There is no acceleration, so the net force is zero, and therefore $\sum Net_x = 0$ and $\sum Net_y = 0$ where Net_x and Net_y are the horizontal and vertical components of the net force, respectively. This leads to the following:



P- load from tap plate threads
F- force from applied torque
N- normal force
μN- friction force

Figure 4.13 Unwrapped thread section with labeled forces

$$Net_x = F - \mu N\, cos\, \theta - N\, sin\, \theta = 0 \tag{4.15}$$

$$Net_y = N \cos\theta - \mu N \sin\theta - P = 0 \tag{4.16}$$

which leads to

$$F = P \frac{\mu \cos\theta + \sin\theta}{\cos\theta - \mu \sin\theta} \tag{4.17}$$

The magnitude of torque T_1 required to exert a force of magnitude F is the force times the radiuss at which it acts, given in equation below.

$$T_1 = P \frac{\mu \cos\theta + \sin\theta}{\cos\theta - \mu \sin\theta} \left(\frac{D_s + D_h}{4}\right) \tag{4.18}$$

4.6.2. Three dimensional model

Now consider a self-tapping screw. A self tapping screw uses non-square threads ($\beta > 0$) to convert applied torque into compression and tension in the materials involved, resulting in a snug fit between the screw, near plate, and tap plate. With the addition of the thread-crest half-angle (β), there is a third component that must be taken into account when finding the normal force N, shown in Figure 10, essentially a perpendicular cross-section of figure 8 but with $\beta > 0$.

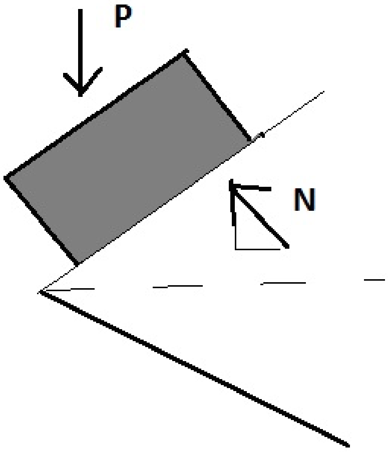


Figure 4.14 Cross-section of thread showing the effect of $\boldsymbol{\beta}$

The load P, however, does not change. the normal force found in equation 6.8 and 6.9 changes by a factor of $\cos\beta$. This leads to the following:

$$F - \mu N\cos\theta - N\sin\theta\cos\beta = 0 \tag{4.19}$$

$$N\cos\theta\cos\beta - \mu N\sin\theta - P = 0 \tag{4.20}$$

which leads to

$$F = P\frac{\mu\cos\theta + \sin\theta\cos\beta}{\cos\theta\cos\beta - \mu\sin\theta} \tag{4.21}$$

The torque T_1 required to exert this force is

$$T_1 = P\frac{\mu\cos\theta + \sin\theta\cos\beta}{\cos\theta\cos\beta - \mu\sin\theta}\left(\frac{D_s + D_h}{4}\right) \tag{4.22}$$

The effective load P is the force on the threads related to internal stresses of the material.

4.7. Torque required to overcome screw head friction

When the screw head comes into contact with the near plate and continues to rotate, there is friction between the bottom of the screw head and the top of the near plate. This friction force opposes the direction of motion and has magnitude equal to the normal (downward) force times the coefficient of friction between the two materials μ. The torque T_2 required to overcome this force T_2 is this friction force times the average radius at which the friction force is acting,

$$T_2 = \mu P \left(\frac{D_{sh}+D_n}{4}\right) \tag{4.23}$$

Where D_{sh} is the screw head diameter, D_n is the near hole diameter, and P is the load exerted on near plate.

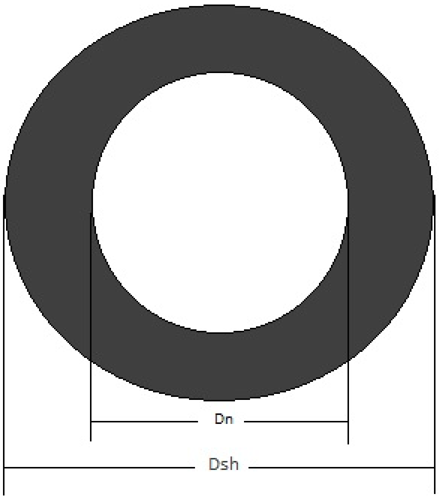


Figure 4.15 Diagram of annulus of contact between screw head and near plate

4.7.1. Total tightening torque

The total torque T required to overcome the forces occurring during the tightening process is the sum of the individual torques. This leads to

$$T = P\left(\frac{\mu\cos\theta+\sin\theta\cos\beta}{\cos\theta\cos\beta-\mu\sin\theta}\left(\frac{D_s+D_h}{4}\right)+\mu\left(\frac{D_{sh}+D_n}{4}\right)\right) \tag{4.24}$$

4.7.2. Calculating the yield torque

We define yield torque as the torque that first causes the stress in either the screw or material to go beyond its respective yield stress level, causing plastic deformation. The yield strengths are σ_{ym} for the material and σ_{ys} for the screw. In ductile materials, the shear strengths are taken to be half the values of the normal strengths, leading to shear yield strengths of $\tau_{ym} = \sigma_{ym}/2$ for the material and $\tau_{ys} = \sigma_{ys}/2$ for the screw. We substitute these yield strengths into their stress equations 6.1, 6.2, and 6.7 to calculate the loads P_s , P_b and P_{Screw} causing shear failure, bearing failure, and screw failure, respectively.

$$P_s = \tau_{ym}(\pi D_s n_t p) \tag{4.25}$$

$$P_b = \sigma_{ym}\left(\frac{\pi\left(D_{sh}^2 - D_n^2\right)}{4}\right) \tag{4.26}$$

$$P_{Screw} = \sqrt{\sigma_{ys}^2 + 3\tau_{ys}^2}(\pi r_t^2) \tag{4.27}$$

Since we do not know the distribution of the load P within the screw, tap plate, or near plate, we assume that P_s, P_b, and P_{Screw} all bear the entire load caused by the torque. By doing this, we may be over estimating each of these loads because in reality, the total load may be unevenly distributed throughout the system. We define the maximum allowable load P_{max} as the minimum of these loads. This is the load at which the first failure mode will begin to occur.

$$P_{max} = min\{P_s, P_b, P_{Screw}\} \tag{4.28}$$

The maximum torque that can be applied during tightening is the torque that corresponds to the maximum load which can be obtained using equation mentioned above(P_{Screw}).

$$T_{max} = P_{max}\left[\frac{\mu\cos\theta + \sin\theta\cos\beta}{\cos\theta\cos\beta - \mu\sin\theta}\left(\frac{D_s + D_h}{4}\right) + \mu\left(\frac{D_{sh} + D_n}{4}\right)\right] \tag{4.29}$$

4.8. Mechanical Properties of Bolts

Bolts are most often made of steel. Like most metals, steel is elastic, at least as long as the strain does not exceed the “elastic limit” beyond which permanent deformation occurs. Within the “elastic limit”, a metal part such as a bolt follows Hooke’s law, that is to say that the strain that is the elongation is proportional to the stress, that is load as shown in the graph.

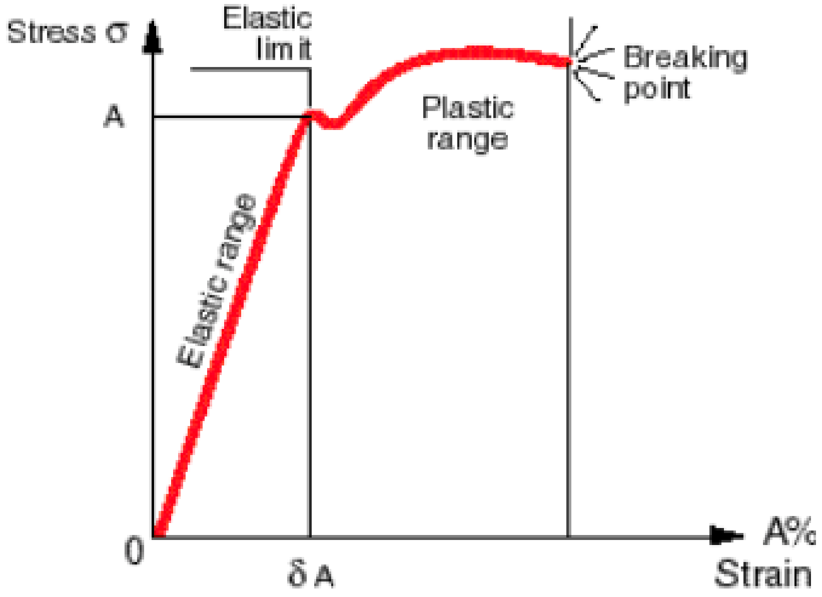


Figure 4.16 Stress-Strain curve for bolt [11]

Any tightening method must ensure that the stress in bolt never exceeds point "A" (the elastic limit or "yield point"), both during the tightening operation and when the assembly is later exposed to efforts during operation.

The following property of the material influence the structural mechanics:

Young's modulus or Traction elastic modulus (E):

$$E = \frac{F}{S} / \frac{\Delta l}{l} = \frac{Fl}{S \cdot \Delta l} = \frac{\sigma \cdot l}{\Delta l} \tag{4.30}$$

where, F=traction force

S=cross-section

l =length

Δl= elongation

$\frac{\Delta l}{l} = \frac{\sigma}{E} = \frac{F}{S \cdot E}$for steel E : 200 000/210 000 MPa

Poisson's ration or lateral strain index (ν)

$$\nu = \frac{\Delta d}{d} / \frac{\Delta l}{l} \tag{4.31}$$

for steel: 0.27/0.30

for aluminium: 0.33/0.36

for rubber: 0.49

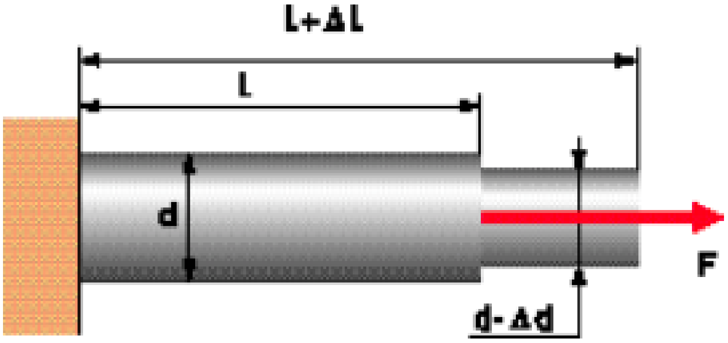


Figure 4.17 Dimensions of a bolt [11]

Compressibility coefficient (K):

$$K = \frac{dV}{dP} = \frac{3(1-2\nu)}{E} \tag{4.32}$$

for liquids k≅0

Shear modulus of elasticity (G):

$$G = \frac{E}{2(1+\nu)} \tag{4.33}$$

for steel: 77000/82000 MPa

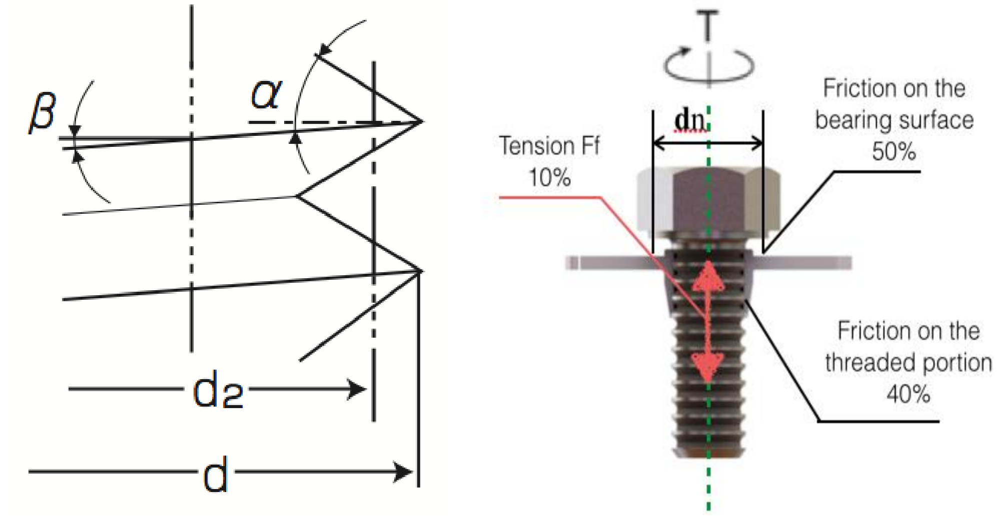
Ultimate tensile stress: Rm

Elastic limit or “yield Point”: Re

Maximum elongation at breaking point: A%

4.9. Relation btween Bolt and Torque

The tensions and frictions acting on the bolts can be represented as given ib below figure. The axial tension, Ff, contributes 10%, the friction on the bearing surface is the largest point of contact and thus it is the majority contributor,i.e. 50% and the friction acting on the thread portion is the remaining 10%. The rotational and detailed sketch of the friction acting on the bolt can be represented in the figure given below.



(a) (b)

Figure 4.18 (a) Detail drawing (b) Rotational drawing [10]

We assume and consider the friction acting on an ordinary joint is similar to the friction acting in joints by Friction Drilling. Thus torque can be derived as:

$$T = Ff\left\{\frac{d_2}{2}\left(\frac{\mu}{cos\alpha} + tan\beta\right) + \mu_n\frac{d_n}{2}\right\} \div 1000 \tag{4.34}$$

where

T : Torque (Nm)

Ff : Axial tension (N)

d2 : Pitch diameter (mm)

dn : Pitch diameter of threaded portion

μ :Friction coefficient of threaded portion

μn : Friction coefficient of bearing portion

α : Half angle of screw thread (ISO screw 30°)

β : Lead angle (tan β)

Also, Friction on the threaded portion is given by μ/cos α,

Tension, Ff is given by tan β, and

Friction on the bearing surface is given by μn*(dn/2)

Thus formula for the bolt can be written as

$$T = K.d.Ff \text{ or } Ff = \frac{T}{K.d} \tag{4.35}$$

Where K : Torque coefficient and

d : Nominal size of screw (mm)

Now, Torque Coefficient,

$$K = \frac{1}{2d}\left\{d_2\left(\frac{\mu}{\cos\alpha} + tan\beta\right) + \mu_n d_n\right\} \tag{4.36}$$

Where d is the nominal diameter (mm).

4.10. Factors of defective torque coefficients

As our method is experimental, there are no wide information about the factors that effect the torque. So, considering factors effecting in a general bolt tightening technique, Lubrication, Machine factors of the bolted joint, Environment, Tightening speed and Reutilization of screw, all these effect the torque coefficient. The relation between tightening torque and axial tightening tension is plotted in the graph below.

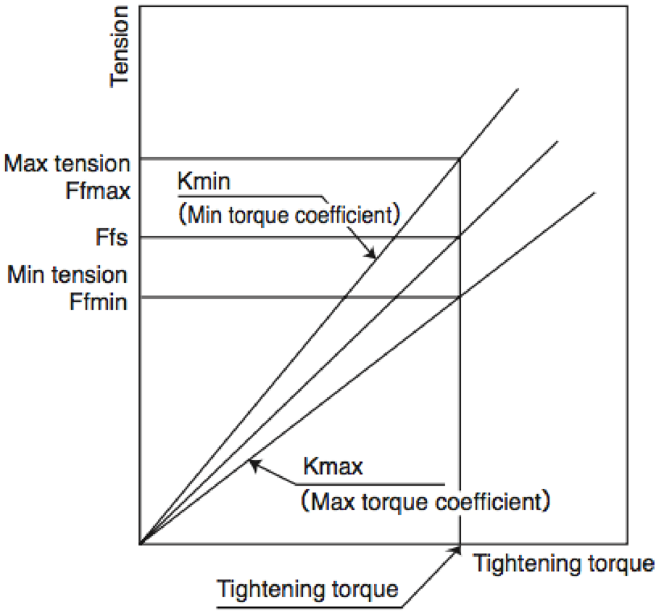


Figure 4.19 Tightening torque Vs Axial tension [17]

4.11. Joint coefficient

While considering the dynamic characteristic of the joint, the increase of tightening torque with the rotation of the bolts should be studied. Joint coefficient is identified as the relation between tightening torque and rotation of bolt as shown in the figure given below.

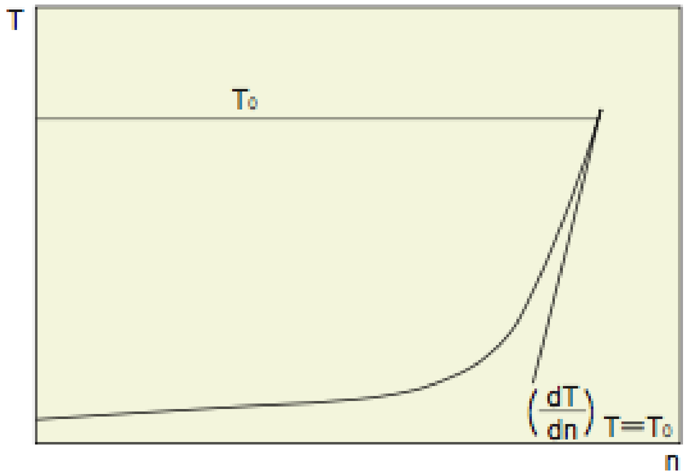


Figure 4.20 Torque Vs Turns of rotation [17]

Joint coefficient (e) on $T=T_0$ for this joint is defined as,

$$e = \frac{1}{T_0}\left(\frac{dT}{dn}\right)_{T=T_0} \tag{4.37}$$

where n : turns of rotation

T_0: Tightening torque

Using rotation angle (θ) in the above equation, we get

From θ=360n dθ=360dn

$$e = \frac{360}{T_0}\left(\frac{dT}{d\theta}\right)_{T=T_0} \tag{4.38}$$

where θ is the angle of rotation.

4.12. Nut Factor Determination

The nut factor is defined in the equation $T = KDF$,is not derived from any engineering principles, but is arrived at experimentally to make the equation valid. The relationship between the torque applied to the fastener and the tension created from the resulting bolt elongation is described by $T = KDF$. T is the torque, K is the nut factor, D id the bolt diameter and F is the bolt tension.

5. EXPERIMENTAL PART

5.1. Materials used for the Experiment

For our experiment we have used five materials for the analysis, i.e, Stainless steel, DC 06 Steel, Aluminuim alloy, Copper and Titanium. The properties of these materials are briefly described below.

5.1.1. Aluminium alloy

After iron, aluminium is now the second most widely used metal in the world. The properties include: low density and therefore low weight, high strength, superior malleability, easy machining, excellent corrosion resistance and good thermal and electrical conductivity are amongst aluminium's most important properties. It is also very easy to recycle.

One of the best known properties of aluminium is that it is light, with a density one third that of steel, 2.700 kg/m3. The low density accounts for it being lightweight but this does not affect its strength. Aluminium alloys commonly have tensile strengths of between 70 and 700 MPa. The range for alloys used in extrusion is 150 – 300 MPa. Unlike most steel grades, it does not become brittle at low temperatures. Instead, its strength increases. At high temperatures, strength decreases. At temperatures continuously above 100°C, strength is affected to the extent that the weakening must be taken into account. Compared with other metals, it has a relatively large coefficient of linear expansion. This has to be taken into account in some designs.

Aluminium is easily worked using most machining methods – milling, drilling, cutting, punching, bending, etc. Furthermore, the energy input during machining is low. It's superior malleability is essential for extrusion. With the metal either hot or cold, this property is also exploited in the rolling of strips and foils, as well as in bending and other forming operations and is an excellent conductor of heat and electricity. An aluminium conductor weighs approximately half as much as a copper conductor having the same conductivity. Features facilitating easy jointing are often incorporated into profile design. Fusion welding, Friction Stir Welding, bonding and taping are also used for joining.

Aluminium reacts with the oxygen in the air to form an extremely thin layer of oxide. Though it is only some hundredths of a (my)m thick (1 (my)m is one thousandth of a millimetre), this layer is dense and provides excellent corrosion protection. The layer is self-repairing if damaged. Anodising increases the thickness of the oxide layer and thus improves the strength of the natural corrosion protection. Where aluminium is used outdoors, thicknesses of between 15 and 25 ¥im (depending on wear and risk of corrosion) are common and is is extremely durable in neutral and slightly acid environments. In environments characterised by high acidity or high basicity, corrosion is rapid.Aluminium is a non-magnetic (actually paramagnetic) material. To avoid interference of magnetic fields aluminium is often used in magnet X-ray devices.After oxygen and silicon, it is the most common element in the Earth’s crust and also their compounds also occur naturally in our food.

The Aluminium alloy used for our experiment is 5754 aluminium. Its chemical composition is given in table below.

Table 5.1 Chemical composition of 5754 Aluminium [16]

Chemical element	**Si**	**Fe**	**Mn**	**Mg**	**Al**
% by mass	0.4	0.4	0.5	2.6-3.2	Balance

5.1.2. Copper

Copper, atomic weight 63.546 is a soft, malleable and ductile metal with very high thermal and electrical conductivity from the group of coinage metals in the periodic table.

Coppers mechanical properties depends on its state and are defined by its lattice structure. Copper has good formability and toughness at room temperature and also at reduced temperature. Increasing the temperature steadily decreases coppers strength properties. Also at around 500°C the coppers technical plastic properties decrease. Due to this behavior, cold forming or hot forming at 800 to 900°C of copper is proper. Cold forming increases the strength properties but results in ductility decreasing. In the as cast state, the copper has strength of 160 MPa. Hot rolling increases coppers strength to 220 MPa. Copper has a good ductility and by cold deformation it is possible to reach the strength values close to the strength values of soft steel. Other characteristic of copper is discussed in the table given below.

5.1.3. Titanium

Titanium is an advanced practical metal with abundant merits which is durable under severe conditions and environments because of its particular properties, i.e. light, strong and stainless. Titanium is indispensable to advanced technologies, because it further displays excellent ability in forms of pure titanium or titanium alloys in addition to its original properties. Some of its peculiar features are:

Light weight – with a specific gravity of 4.51, Ti is about half as heavy as copper and approximately 40% lighter than steel.

Excellent corrosion resistance (to sea water) – Ti is as corrosion0resistant as platinum in sea water. This is better than any other major metals.

High strength - titanium is some 6 times as strong as Aluminium and twice as strong as iron per weight.

Non-toxicity fit for the human body - safe and friendly to the human body – no metallic allergy.

Non-combustibility (heat resistance) – titanium mill products have also been approved as non-combustible materials.

Titanium exhibits some superb properties in terms of physical, chemical and designing characteristics.

- Shape memory property
- Non-magnetism
- Hydrogen absorbing property
- Short radioactive half-life
- Cryogenic property
- Fissionability
- Superconductivity

5.1.4. DC06 steel

DC06 Steels are micro-alloyed with Titanium (Ti) and/or Niobium (Nb). This analysis is further modified by additions of Carbon and other minor elements, which contribute specific effects either to control mechanical properties or to improve corrosion resistance. The corrosion resistance steels is attributed to a surface phenomenon, passivity. When oxygen comes in contact with the surface it forms an invisible film, which protects the underlying metal from rusting and corrosion under severe environment.

Table5.2 Chemical composition of DC06 Steel [30]

Chemical elements	C	Mn	P	S	Ti
%, by mass	0.02	0.25	0.02	0.02	0.3

There are almost as many uses for DC06 Steel as there are problems of corrosion, temperature and strength. Because of its high tensile strength, corrosion resistant qualities and ability to attain a mirror-like finish it is one of the most versatile of all metals. Applications include its use in the petroleum, chemical, food, plumbing, transportation and oil equipment industries to mention just a few.

Apart from corrosion resistance, the various grades of steel offer a range of excellent mechanical properties. Strength is the mechanical property which is the first and foremost important property. It is the ability of the material to bear a load without too much deformation and without breaking.

Ductility is another important mechanical property. It is the amount which a metal can stretch before breaking. If a material has high ductility, then it can be formed into different complex shapes.

Mechanical properties of the materials used is briefed in the below given table.

Table 5.3 Mechanical properties of metal alloys used

Properties	Copper	Aluminium 5754	Titanium	DC06 steel	S235 JR
Density (kg/m^3)	8800 - 8940	2600 - 2800	4510	7861	7700 - 8030
Melting point (°C)	1082	660	1668	1371 - 1454	1430
Elastic modulus (GPa)	117	70 - 79	100 - 120	190 - 210	190 - 210
Poisson’s ratio	0.34	0.33	0.33	0.27	0.27 - 0.3
Tensile strength (MPa)	172 - 220	230 - 570	234	270 - 350	360 - 510
Yield strength (MPa)	62 - 69	215 - 505	138	170 - 180	235
Percent elongation (%)	40-50	10 - 25	54	40	15

5.1.5. S235JR steel

S235jr steel plate can be regarded as carbon and low alloy steel. This plate is one mainly of carbon and low alloy steel which is mainly used to build ship, bridge, belongs to high strength sheet. The chemical composition of S235JR steel are:

Table 5.4. Composition of S235JR steel

Chemical elements	C	Mn	P	S	Si
%, by mass	0.22	1.60	0.05	0.05	0.05

S235 offers high yield strength and tensile strength and is supplied with a variety of treatments and test opinions to ensure it is a highly usable steel in your various projects. It is a low carbon, high tensile strength structural steel which can be readily welded to other weldable steel. With its low carbon equivalent, it possesses good cold-forming properties. The plate is produced by fully killed steel processes and supplied in normalized or controlled rolling condition.

The application of S235JR includes structural application in freight, transmission towers, dump trucks, cranes, trailers, bull dozers, excavators, forestry machines, railway wagons, dolphins, penstocks, pipes, highway bridges, building structures, oil and gas platforms, offshore structures, shipbuilding, power plant, palm oil equipment’s and machineries, fans, pumps, lifting equipment’s and port equipment’s.

5.2. Test equipment arrangement

To get to know about the mechanical allowable torque and the recommended tightening torque we have conducted experiment in different materials. Stainless steel, DC 06 steel, Copper, Aluminium and Titanium plates are used to check for the maximum allowable torque for friction drilling and is deeply studied for the failure cause, i.e whether the material is failed or bolt is failed for tightening.

The experimental setup is as shown in the block diagram given below.

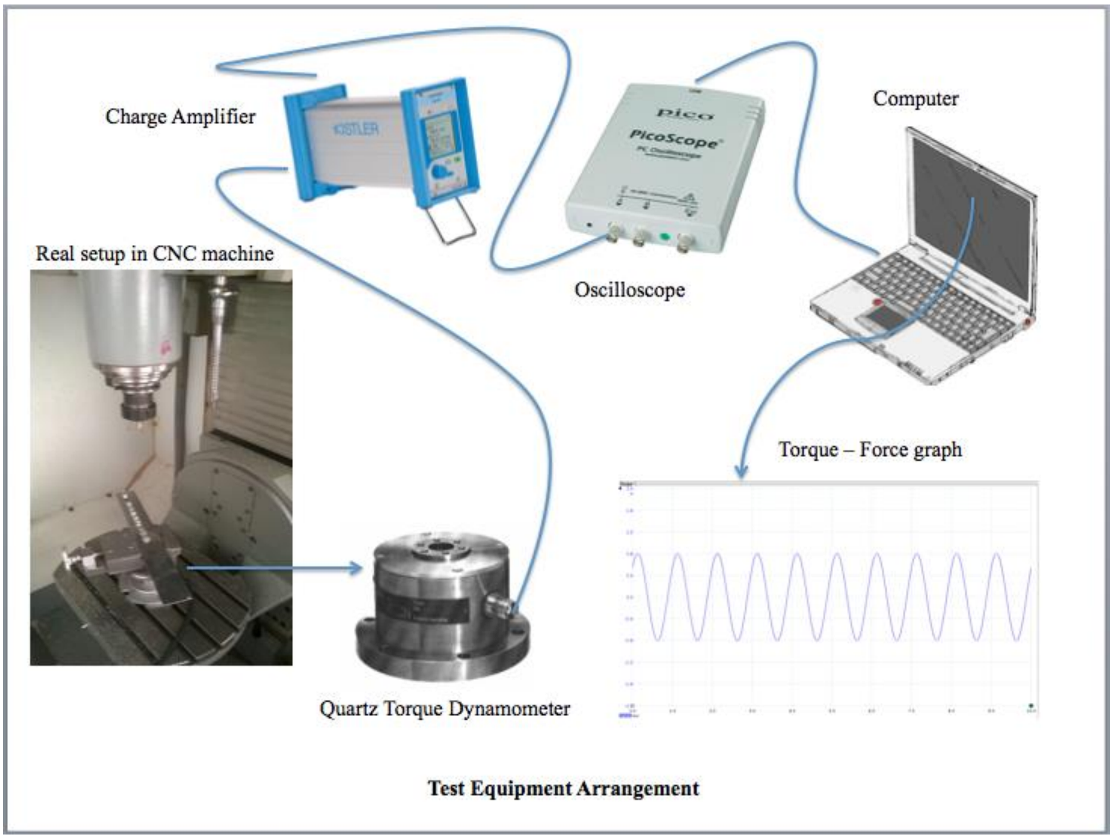


Figure 5.1: Test equipment arrangement

Tests involved measuring the applied torque and the clamp force provided by the bolt simultaneously using data collection equipment. All the tests involved applying a torque to the nut with the bolt head held stationery. A quartz torque dynamometer was inserted into the test joint so that the force and torque applied to the bolt head could be measured. The quartz torque dynamometer was connected to a charge amplifier, which in turn was connected to an oscilloscope. This was connected to a computer via an USB lead. The computer was used to record the tightening force and torque of the bolt values to the given material with the help of PicoScope software. The torque was applied to the bolt via a socket connected to the chuck of the CNC machine in a steady rpm.

Graphs of tightening torque for different materials could then be produced. The allowable stress could then be found out using the graph and then can be compared and analysed with the conventional type of mechanical fasteners for the allowable maximal stress.

The equipment used for the experiment are described as follows:

1. CNC Milling machine

The material to which the test is to be conducted is clamped on the table with the Quartz Torque Dynamometer attached to it. The spindle is attached to a drill bit and then thread bit, with the help of a spindle adaptor, to drill the hole and thread the inner part of the plate respectively. Then the spindle is attached to a socket to test the tightening torque of the bolt, which is fastened in the above-performed threaded hole.

Figure 5.2: CNC Milling machine used for our experiment (DECKEL MAHO)

2. **Quartz Torque Dynamometer**

Quartz torque dynamometer is basically for measuring the torque acting around the sensor axis. The compact dynamometer possesses an especially high sensitivity. The very lightweight top plate supporting the measuring object guarantees a high natural frequency, enabling torques to be measured on small high-speed motors.

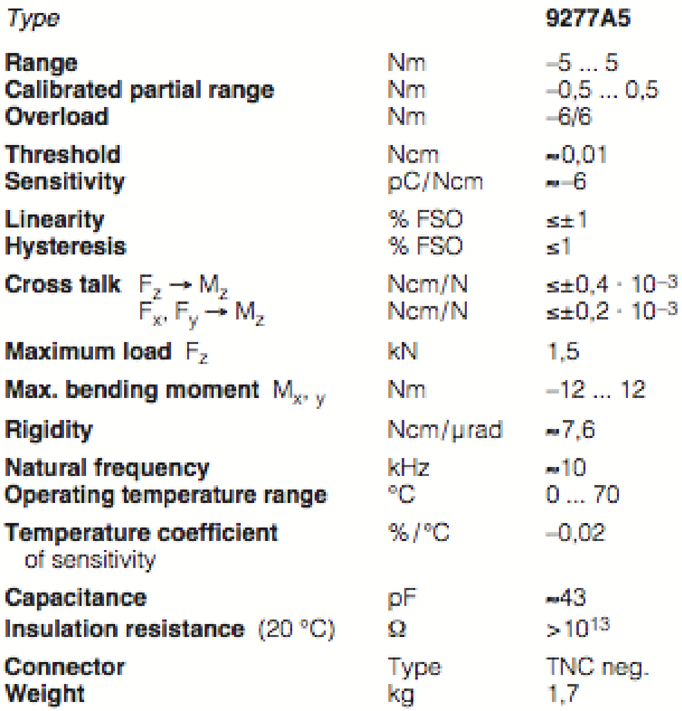
The dynamometer consists of a torque sensor, which is fitted under high preload between a base plate and a top plate.

Figure 5.3: Quartz torque dynamometer [21]

The sensor contains a set of shear sensitive quartz disks. The arrangement of the disks is realised in a way to yield an electric charge, which is proportional to the torque Mz acting around the axis of the dynamometer. The charge is led via an electrode to the

TNC connector. The technical data of the amplifier is briefed below.

Table 5.5: Technical data of the amplifier [21]



Type		**9277A5**
Range	Nm	–5 ... 5
Calibrated partial range	Nm	–0,5 ... 0,5
Overload	Nm	–6/6
Threshold	Ncm	≈0,01
Sensitivity	pC/Ncm	≈–6
Linearity	% FSO	≤±1
Hysteresis	% FSO	≤1
Cross talk $F_z \rightarrow M_z$	Ncm/N	≤±0,4 · 10^{-3}
$F_x, F_y \rightarrow M_z$	Ncm/N	≤±0,2 · 10^{-3}
Maximum load F_z	kN	1,5
Max. bending moment $M_{x,y}$	Nm	–12 ... 12
Rigidity	Ncm/µrad	≈7,6
Natural frequency	kHz	≈10
Operating temperature range	°C	0 ... 70
Temperature coefficient of sensitivity	%/°C	–0,02
Capacitance	pF	≈43
Insulation resistance (20 °C)	Ω	>10^{13}
Connector	Type	TNC neg.
Weight	kg	1,7

The Quartz Torque Dynamometer is mounted on the base of the CNC milling machine along with the clamp on which the material to be tested is clamped. The output from the dynamometer is connected to the Kistler Charge Amplifier.

3. Charge Amplifier

The function of a charge amplifier is to convert the charge signal from the sensor into a proportional output voltage. The amplifier used in our experiment was Kirstler Single-Channel Laboratory Charge Amplifier.

Figure 5.4 Charge Amplifier [24]

Before starting the experiment we have to set the range and sensitivity to 10 kN and -3.726 pC/N respectively while measuring force and the range and sensitivity to 25 Nm and -189.7 pC/Nm respectively to measure torque. The operation display is as shown below.

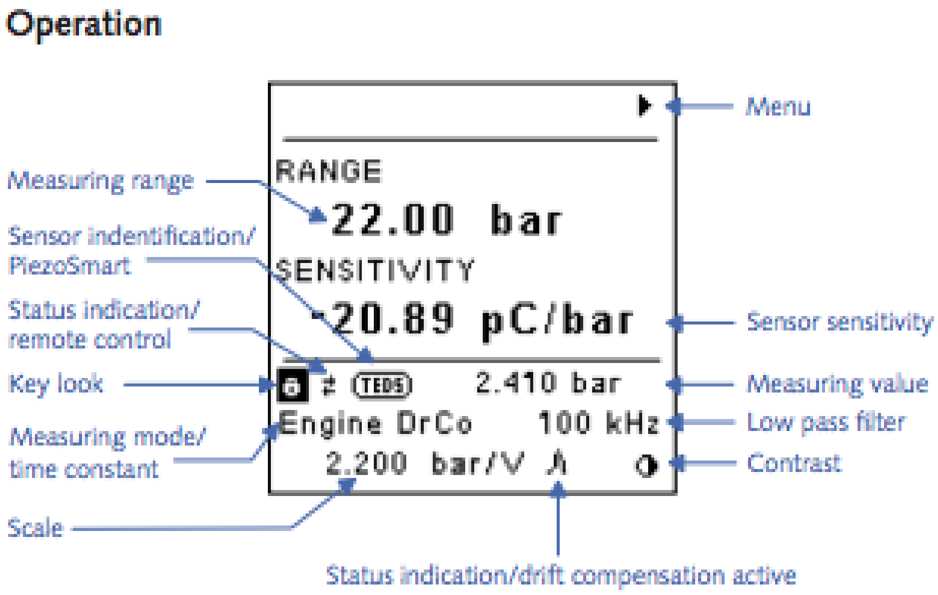
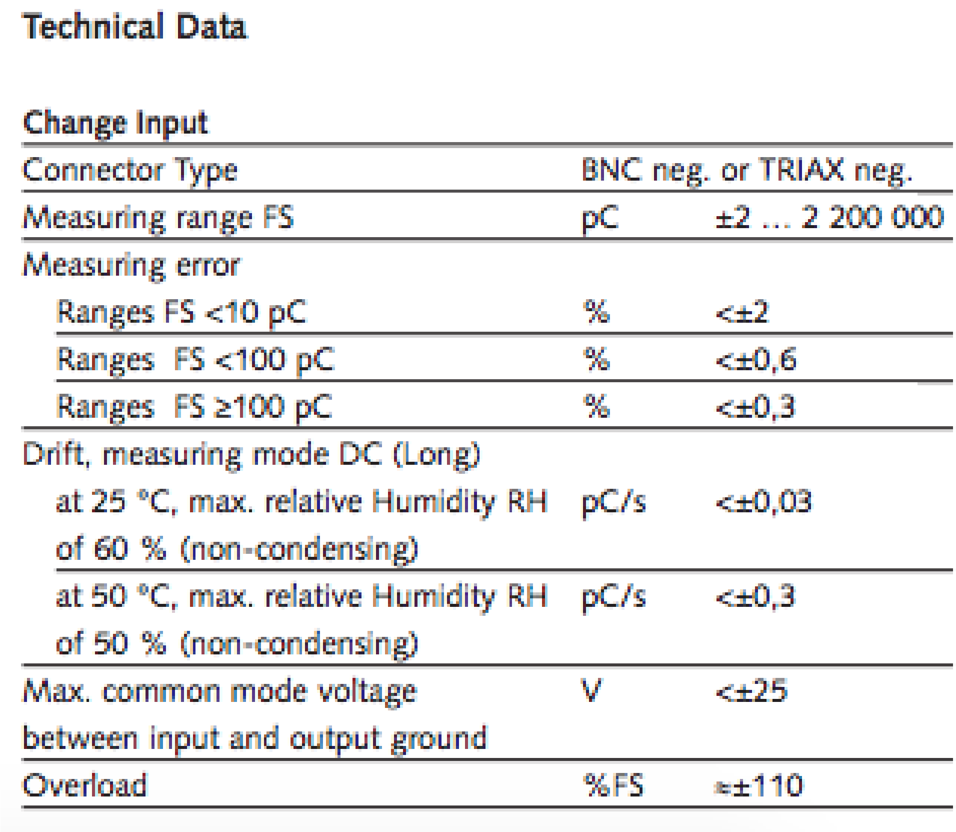


Figure 5.5 Operation monitor of charge amplifier [24]

The technical data of the charge amplifier used for the experiment is given below.

Table 5.6: Technical data of charge amplifier [24]



Technical Data

Change Input		
Connector Type	BNC neg. or TRIAX neg.	
Measuring range FS	pC	±2 … 2 200 000
Measuring error		
Ranges FS <10 pC	%	<±2
Ranges FS <100 pC	%	<±0,6
Ranges FS ≥100 pC	%	<±0,3
Drift, measuring mode DC (Long)		
at 25 °C, max. relative Humidity RH of 60 % (non-condensing)	pC/s	<±0,03
at 50 °C, max. relative Humidity RH of 50 % (non-condensing)	pC/s	<±0,3
Max. common mode voltage between input and output ground	V	<±25
Overload	%FS	≈±110

4. **Oscilloscope**

The charge amplifier and computer is connected via an oscilloscope. Oscilloscope is used to observe the change of an electrical signal over time, such that voltage and time describe a shape which is continuously graphed against a calibrated scale.the converted voltage can be viewed in computer in the graph format in PicoScope software.A typical oscilloscope can display alternating current (AC) or pulsating direct current (DC) waveforms having a frequency as low as approximately 1 hertz (Hz) or as high as several megahertz (MHz). High-end oscilloscopes can display signals having frequencies up to several hundred gigahertz (GHz). The display is broken up into so-called horizontal divisions (hor div) and vertical divisions (vert div). Time is displayed from left to right on the horizontal scale. Instantaneous voltage appears on the vertical scale, with positive values going upward and negative values going downward.

The oscilloscope used in our experiment is PicoScope 3000 series oscilloscope.

Figure 5.6: Oscilloscope (3000 series) [30]

5.3. Procedure undergone for the tightening test

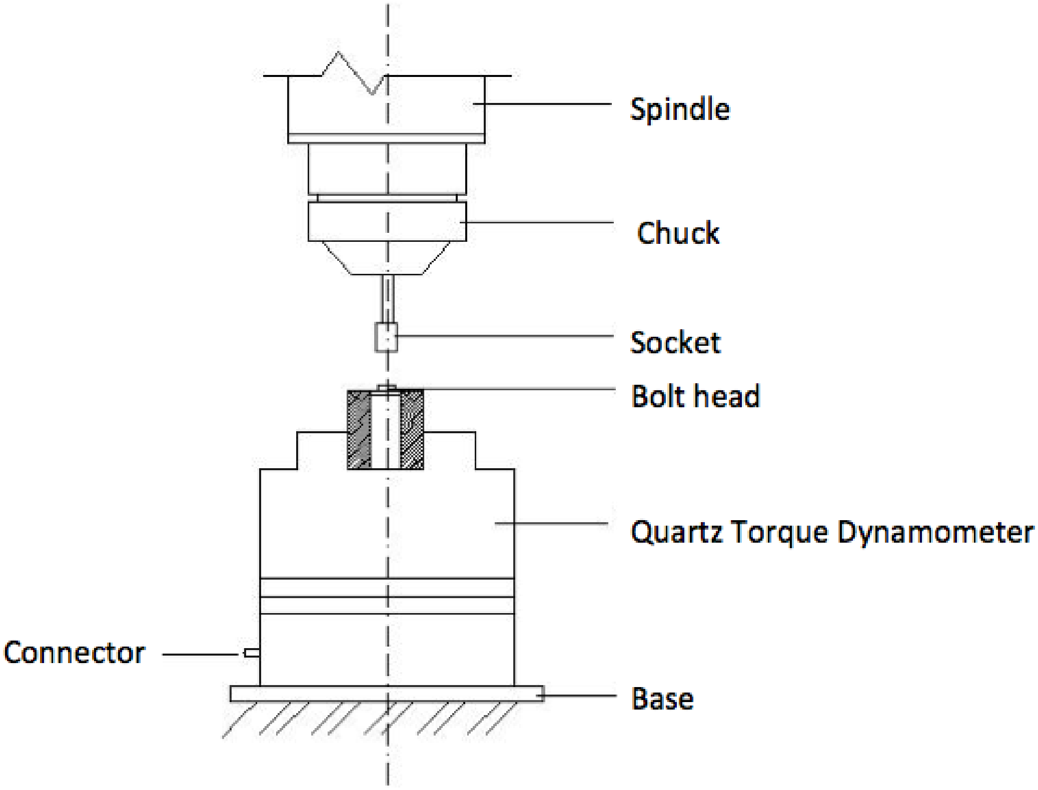


Figure 5.7: Schematic view of the apparatus for the tightening test

The schematic view of the experiment shows us how it works. The feed rate and spindle speed is entered into the CNC machine and then the workpiece i.e, the thin walled different material is clamped on to the base one after another and is first drilled with 2000 rpm, feed rate of about 100. The same spindle speed is used to turn the same material by inserting a turning tool in the spindle replacing the drilling tool. Now in the created internal thread of the plate, an M 8.8 bolt is tightened by hand. It is then checked for the tightening torque and force with the help of Quartz Torque Dynamometer transmitting the vibration to the charge amplifier. The vibration is converted into electrical signals by the charge amplifier and is passed on to the oscilloscope. Now the oscilloscope which is connected to the computer gives the vibration to a graphical reading in the PicoScope software by converting the electrical signals from the charge amplifier to the graphical representation.

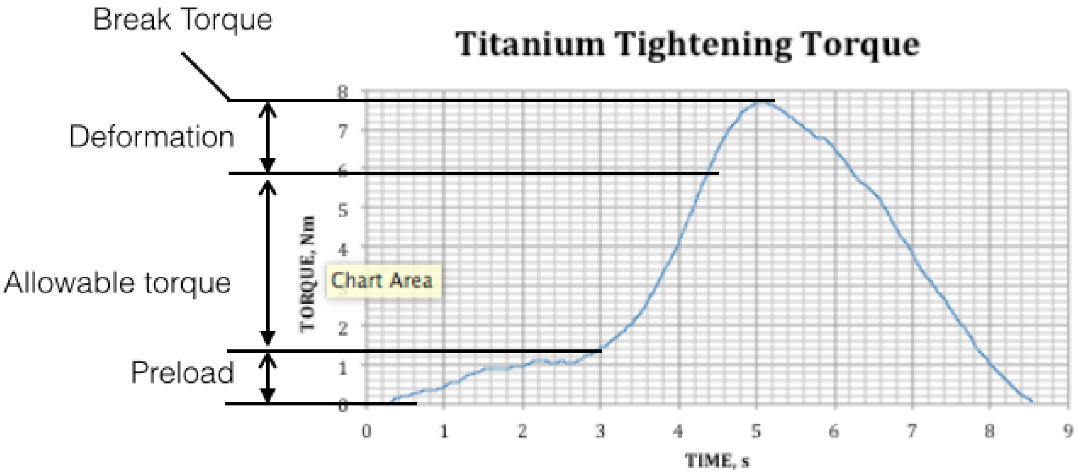
We have done experiments for each material i.e, aluminium alloy, copper, titanium, S235JR steel, and DC06 steel for drilling, tapering and tightening. First stage of the experiment is to connect all the devices as per the test equipment figure arrangement. Make sure that the charge amplifier is set to 0 before starting the process of drilling, tapering or tightening. Now the thin plate is clamped on to the base of the machine and is tightened. The spindle speed and feed rate is loaded in CNC machine according to the standard general data and the machine is switched on. The drilling process starts and the work piece is drilled meanwhile its graphic representation is seen and stored with the help of picoscope software. In the same-drilled hole we create thread by tapering it by tapering tool. The spindle with the drill tool is replaced by tapering tool. After tapering, the tool is replaced by a socket. The workpiece now has an interior formed thread in which a standard M8.8 bolt is screwed in by hand to the maximum. Now with the help of CNC machine further tightening is made and checked for the maximum allowable tightening and the point at which the bolt or the workpiece fails. The graphs derived from the experiment is given below and explained.

5.4. Analysis of the experimental output

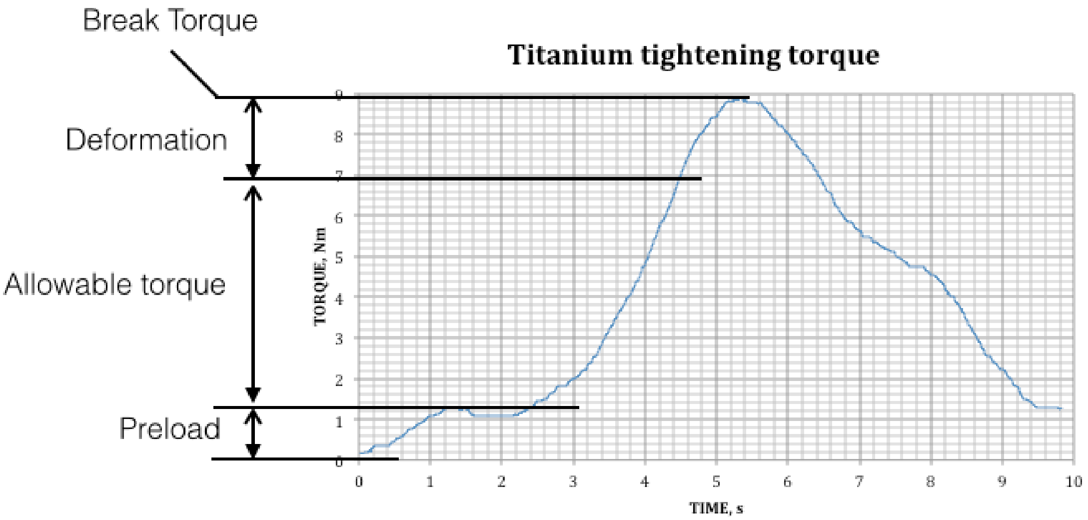
The first thin walled material we considered is Titanium alloy. It is checked for both tightening torque and force and the most optimal graphs are given below with descriptions on it.The material after the experiment, a cross-section is shown below.

Figure 5.8: Cross-sectional view of Titanium plate with bolt

In the figure 5.9; 5.10, the preload, which is the axial tension permitted to the bolt before elongation due to torque is pointed. Also the permitted torque or the safety are upto which the torque can be applied is marked as allowable torque. The deformation of the material is shown next and after the deformation, the component fails. This point is marked as the break torque.

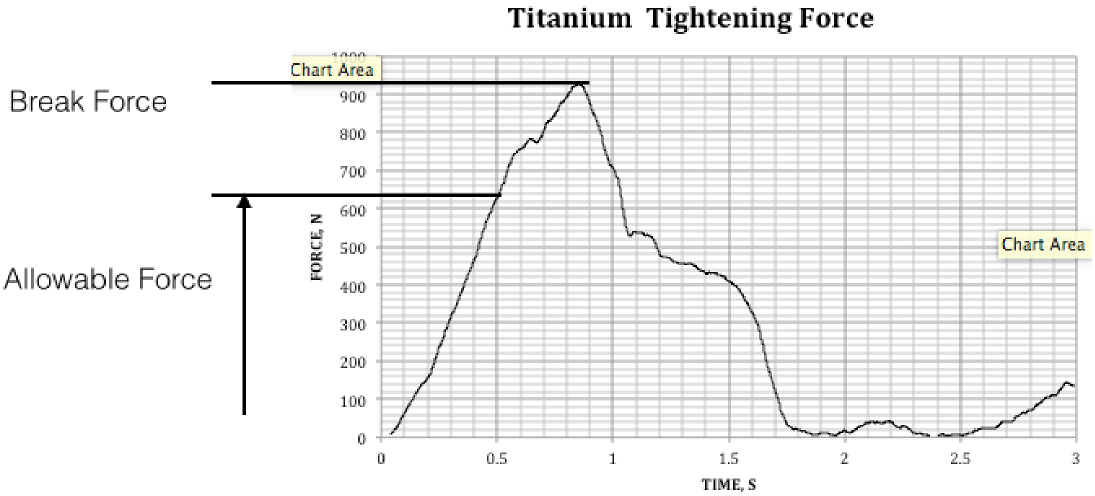


(a)

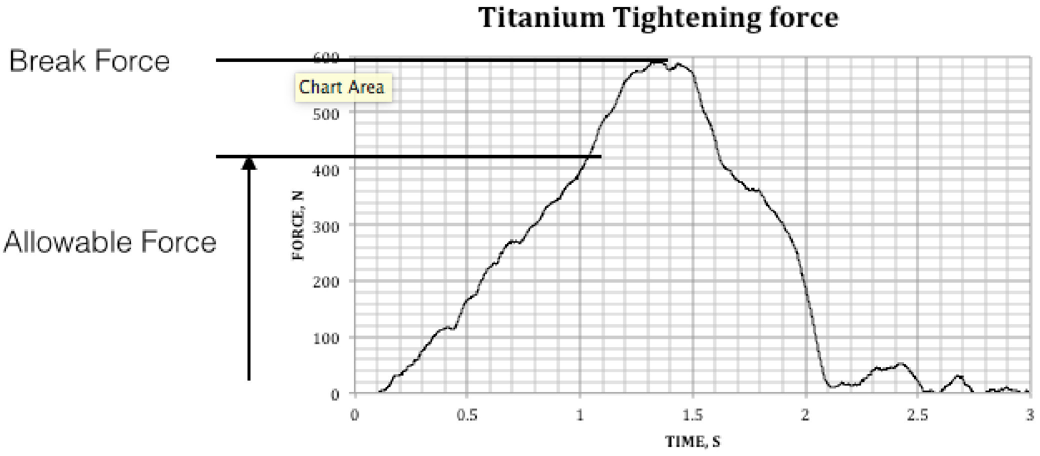


(b)

Figure 5.9: (a) and (b) Tightening Torque of Titanium



(c)



(d)

Figure 5.10: (c) and (d) Tightening force of Titanium

From the above graphs its clearly understood the allowable torque and allowable force of the Titanium thin walled material for Friction Drilling. Also the point at which both the torque and force is understood. Its pointed in the table given below.

Table 5.6:Titanium allowable Torque/Force and Failure point

For Titanium	Allowable measure	Breaking/ Failing point
Tightening Torque	2 – 6 Nm	8 – 9 Nm
Tightening Force	≅500 N	600 – 900 N

From the experimental graph nut factor, K can also be calculated from the equation

$$K = \frac{Tc}{FD} \tag{10.1}$$

Where T : Torque

C: constant, 1000 taken since diameter is in mm

F : Force applied

D : Diameter of the bolt

Since in our experiment, torque and force could not be calculated to a tightening at the same time, from the graph, for Force and Torque same time is taken and measure like wise.

At time , say 0.5 sec,

F= 600 N, T = 0.5 Nm, c=1000, a constant and D=6 mm (for our bolt)

$$K = \frac{0.5 \times 1000}{600 \times 6} = 0.14 \tag{10.2}$$

After the experiment with titanium, we did next for S235JR steel. The graphs are then derived for the force and torque for tightening. The maximum allowable torque and maximum allowable force are calculated for the same, also the point at which the material fails for both the parameters is noted. The cross-sectional view of the S235JR steel thin walled material after the experiment is done, is shown below:

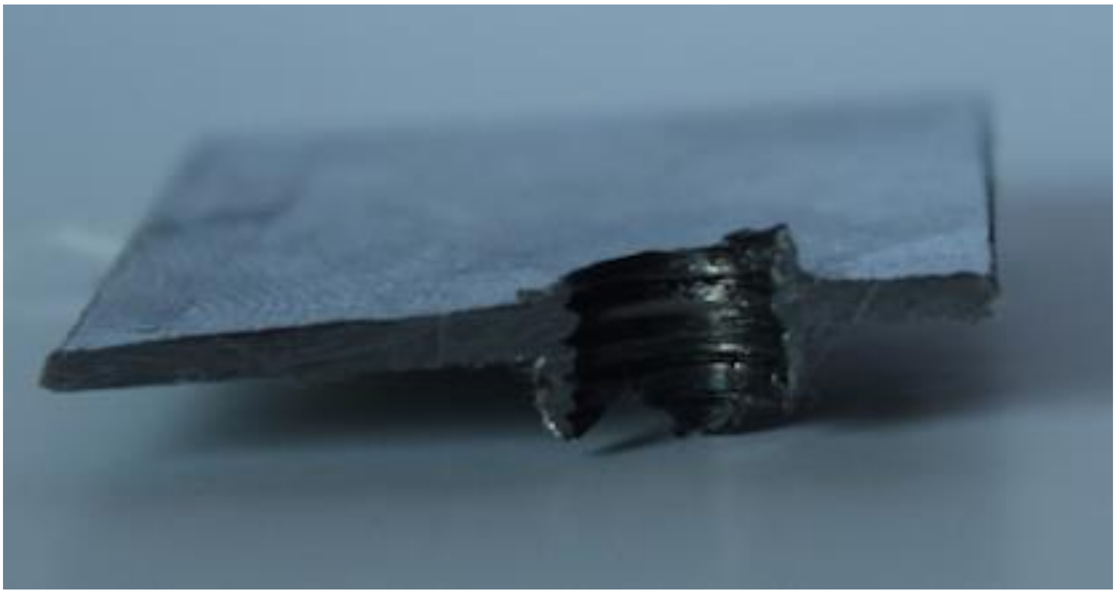


Figure 5.11: Cross-sectional view of S235JR Steel after tightening

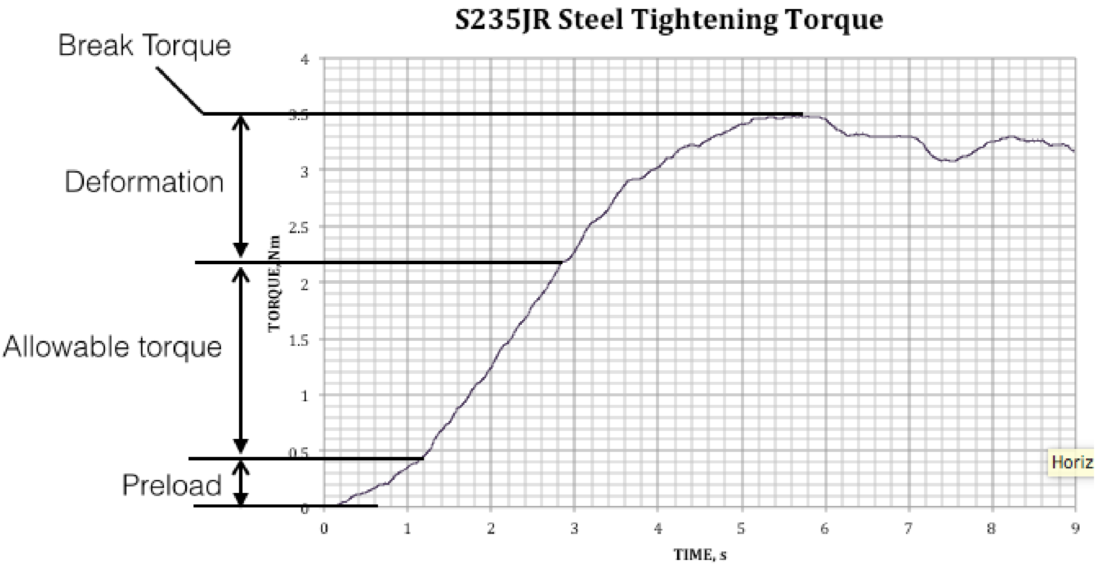


Figure 5.12 Tightening torque of S235JR Steel

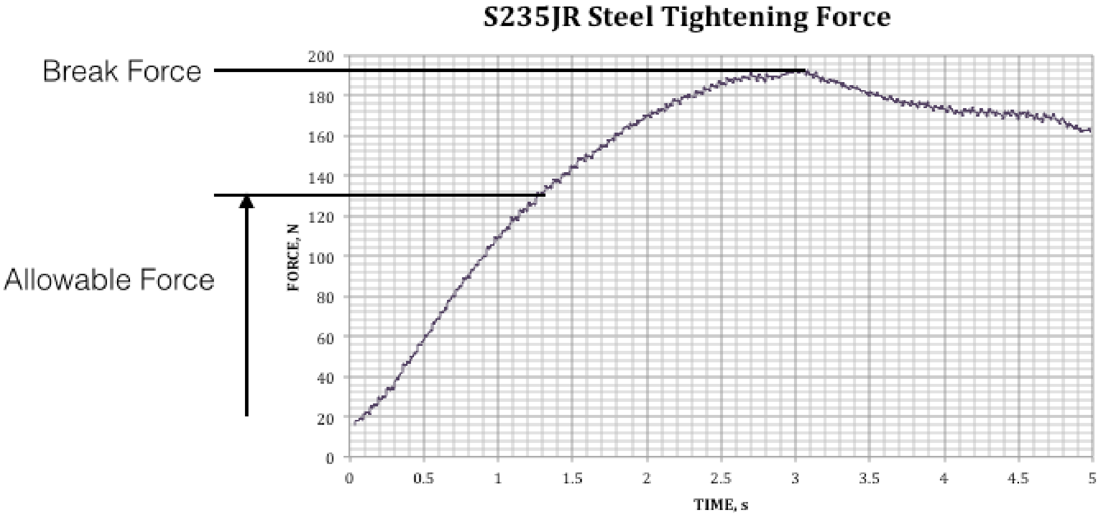


Figure 5.13: Tightening Force of S235JR Steel

From the above graph the allowable torque and breaking point for tightening torque can be determined as shown in figure. The figure shows the tightening force graph. Here allowable force and break force can be determined and is pointed in the table given below.

Table 5.7:S235JR Steel- allowable Torque/Force and Failure point

For S235JR Steel	Allowable measure	Breaking/ Failing point
Tightening Torque	0.5 – 2.5 Nm	3.5 Nm
Tightening Force	≅130 N	190 N

Here also the nut factor, K can be calculated similarly as calculated above.

$$\text{Nut factor, } K = \frac{Tc}{FD} \tag{10.3}$$

In this case we take the parameters at time, say 1 second.

At 1 sec, T = 0.4 Nm, c = 1000, F = 110 N and D = 6mm.

Applying,

$$K = \frac{0.4 \times 1000}{110 \times 6} = 0.6 \tag{10.4}$$

The other material which is used for the experiment are Aluminium alloy, Copper and DC06 steel. The graphs for the above said materials are plotted for tightening torque and the allowable torque and break point is determined. The cross-sectional view of the DC06, and Copper thin walled material is shown below in the figures 5.14 ,and 5.15 respectively.

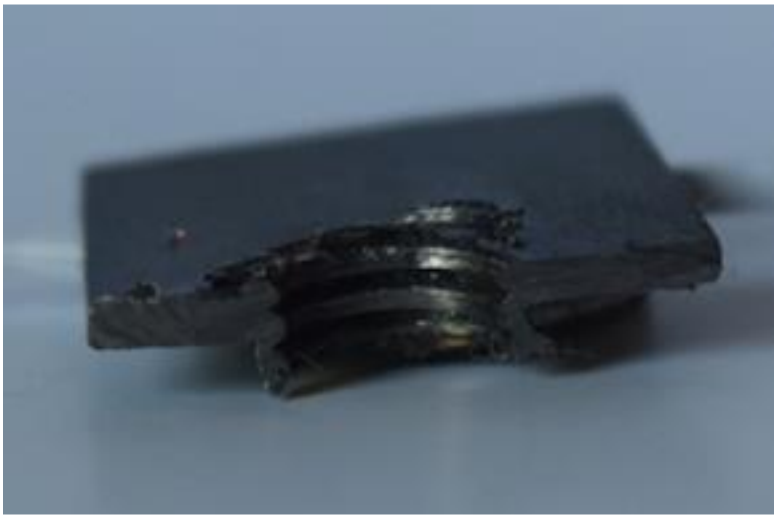


Figure 5.14: Cross-sectional view of DC06 steel after tightening

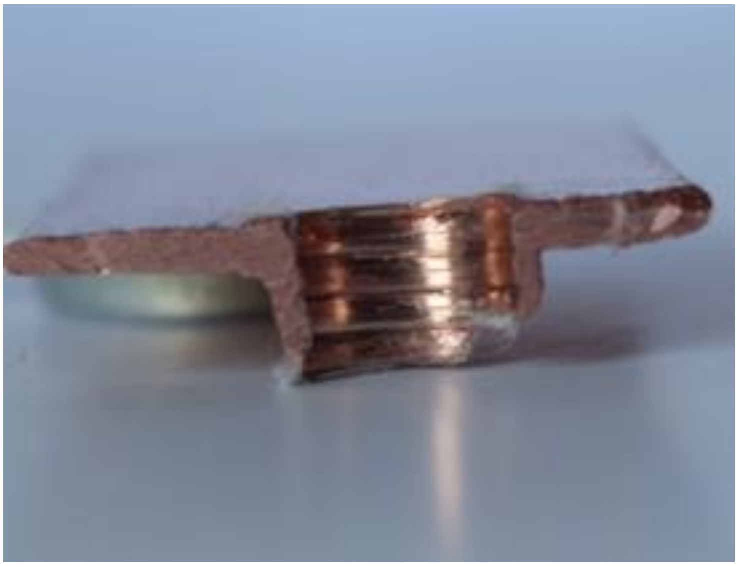


Figure 5.15 Cross-sectional view of Copper after tightening

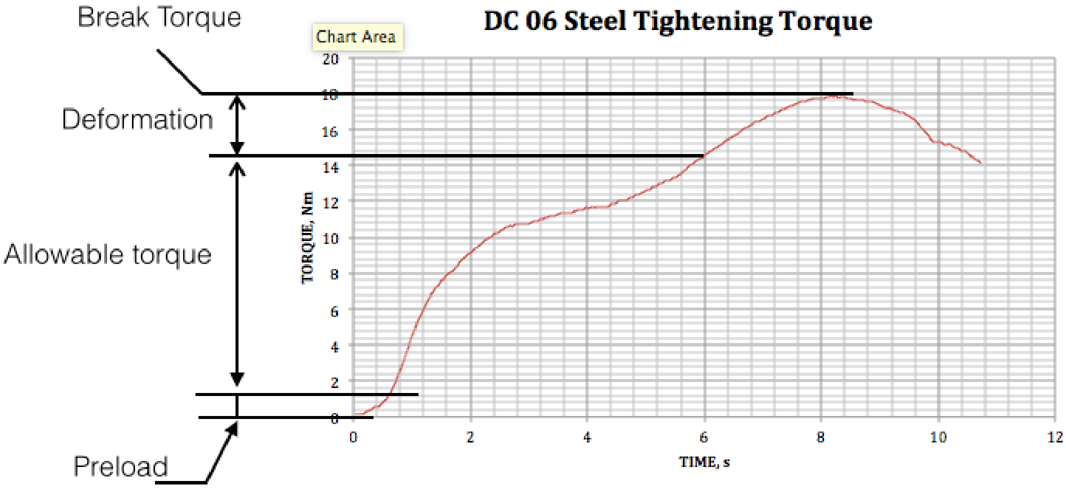


Figure 5.16 Tightening Torque for DC06 Steel

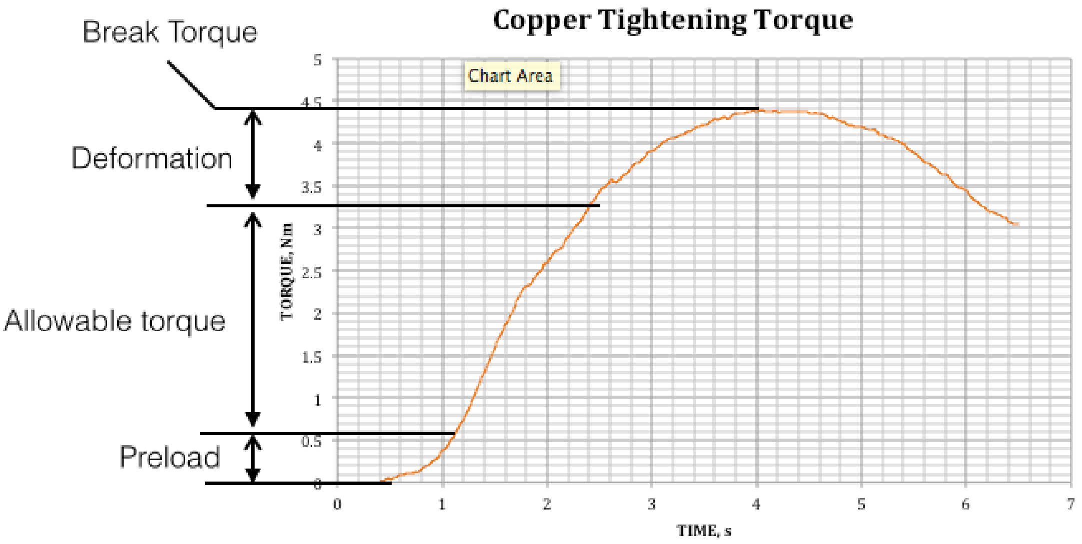


Figure 5.17 Tightening Torque for copper

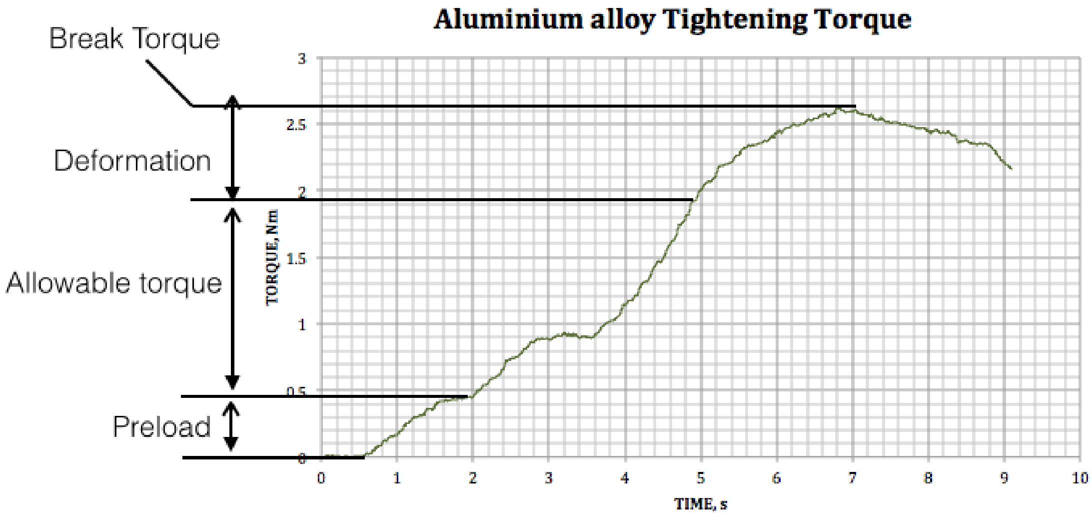


Figure 5.18 Tightening Torque for Aluminium alloy

From the above shown graphs, allowable tightening torque and breaking point for tightening for different materials is derived and tabulated.

Table 5.8 Allowable Torque and Break Torque for different materials

For Tightening torque	Allowable Torque	Break Torque
DC06 Steel	2 – 14 Nm	10 Nm
Copper	0.5 – 3.3 Nm	4.4 Nm
Aluminium alloy	0.5 – 2 Nm	2.6 Nm

There is no certain experimental values for the tightening torque for the bolt which is joined by the Friction Drilling process. So whatever my results are, can be considered as an experimental results for the thin walled plates joined by Bolt with the help of Friction

Drilling process. To summarize our experimental results, the whole results can be tabulated as shown below.

Table 5.9 Summary of the experimental results

Material	**Preload (Nm)**	**Allowable torque (Nm)**	**Break Torque (Nm)**
Titanium	1.2	2 - 6	8 – 9
S235JR Steel	0.5	0.5 – 2.5	3.5
DC06 Steel	1.5	2-14	18
Copper	0.6	0.5 – 3.3	4.4
5754 Aluminium	0.5	0.5 – 2	2.6

Comparing the results from our experiment we can come to the conclusion that DC06 Steel is the toughest material of all, since for the failure it needs 18 Nm torque and the least tough material is 5754 Aluminim, as it needs only 2.6 Nm torque for the failure. Other materials such as S235JR Steel, Copper and Titanium has a break torque of 3.5 Nm, 4.4 Nm and 8 to 9 Nm respectively. Also the allowable torques for each material are also listed. The same experiments are to be conducted for different kinds of material for different dimensions of bolt to determine torque experimentally for this kind of joint as it has no pre-known values for the same.

CONCLUSION

The mechanism of fabricating threads for thin walled materials done by the Friction Drilling process is studied and the tightening test is done with a standard bolt. From the tightening test, the various materials are undergone tightening by CNC machine with a steady rotation of 10 rpm and the readings of the vibration are taken and graphs are plotted for the Torque and Force for the materials respectively. From the graphs the maximum allowable tightening torque and Force is determined. The nut factor is also calculates with the help of the plotted graph.

Since there are no known standard values for the Friction Drilling process, the findings from this paper could be considered as standard for this technique for the five materials considered. It is recommended that more investigations about the tool wear and its effects and also the technique for tightening, is to be done in many variety of materials with all the available dimensions of bolt as this could be the next most and widely accepted technique to join thin walled plates in manufacturing sector.

REFERENCE:

1. J.E Shigley and C.R Mischke, Mechanical Engineering Design, 6th Ed., McGraw-Hill Higher Education, 2001
2. S.F. Miller, S.B. McSpadden, H. Wang, R. Li, A.J. Shih, Experimental and numerical analysis of the friction drilling process, ASME Journal of Manufacturing Science and Engineering, 2004, submitted for publication
3. Miller, S. F., Tao, J., & Shih, A. J. (2006). Friction drilling of cast metals.*International Journal of Machine Tools and Manufacture*, *46*(12), 1526-1535.
4. Miller, F S.; Shih J. A. 2007, Thermo-mechanical finite element modeling of the friction drilling process. Journal of Manufacturing Science and Engineering 129: 531-538.
5. Thread bushing; http://www.thermdrill.com/threaded-bushing-flowing-drill-instead-of-rivet-nut(as seen on 12-03-2015)
6. Thermal drilling; http://www.autospeed.com/cms/article.html?&title=Thermal-Drilling&A=110952 (as seen on 18-03-2015)
7. Process of drilling; http://www.flowdrill.com/parameters(as seen on 18-03-2015)
8. Advantages of drilling; http://www.formdrill.com/english/manual.htm (as seen on 02-05-2015)
9. Tightening torque; http://www.tohnichi.com/torque.asp (as seen on 02-05-2015)
10. L. Seneviratne, F. Negmoh, S. Earles, and K. Althoefer, Theoretical modeling of the self-tapping screw fastening process, Proceedings of IMechE, Part C, Journal of Mechanical Engineering Science, 215 pp.135-154, 2001
11. A. Leo, S. Manivanna, and J. Potter, Mathematical Model of the Torque for Screw Insertion Process, MQP paper at WPI, Worcester, MA, 2006
12. Steel, L. (2012, April 5). Technical card gruppo lecefin. Retrieved May 20, 2015, from http://www.lucefin.com/wp-content/files_mf/s235jren.pdf
13. http://www.steelspecs.com/EN10025-2/EN10025-2S235JRSTEELPLTAE.html
14. ELSNER, A. (2005). Properties of Deep-Drawing Steels. Advanced Hot Rolling Strategies for IF and TRIP Steels, 5(ISBN 90-407-2591-8), 147-147.
15. Norbourn Company Inc.; http://norbourn.com/norbourn_hardware (as seen on 05-05-2015)
16. The Aluminium Automotive manual; EAA Aluminium AutomotiveManual, Version: 2015 ©European Aluminium Association
17. Bolt Science(2008, February 18) Report on Torque-Tension tests on fasteners coated with Lubrisilk synthetic grease

18. Ralph s. Shoberg, P.E,(2011), Engineering Fundaments of Threaded Fastener Design and Analysis, PCB Load & Torque, Inc.
19. Elsner Alexander (2009). Advanced hot rolling strategies for IF and TRIP steels, Delft University Press
20. Richard T. Barrett, NASA Reference Publication 1228(March 1990), Fastener Design Manual.
21. TOHINICHI TORQUE HANDBOOK, Vol. 7, Technical data, Tightening Reliability.
22. Z. Marciniak, J.L. Duncan, S.J. Hu, (2002), Mechanical of Sheet Metal Forming, Butterworth-Heinemann
23. Scott F Miller, (2006), Experimental Analysis and Numerical Modeling of the Drilling Process.
24. K.F.J. Ellwood, D. Fesko, and D.R. Bauer, An Axisymmetric Model for Thread Forming in Polycarbonate and Polypropylene Screw and Boss Fasteners, Polymer Engineering and Science 44 (8) (2004) 1498-1508.

25. M. Kerkhofs, M.V. Stappen, M. D'Olieslaeger, C. Quaeyhaegens, and L.M. Stals, The Performance of (Ti,Al)N-coated Flowdrills, Surface and Coatings Technology 68/69 (1994) 741-746.

26. P.W. Bridgman, Effects of high hydrostatic pressure on the plastic properties of metals, Reviews of Modern Physics 17 (1) (1945) 3-14.

27. Introduction to thermal drilling; http://www.danly-te.com(as seen on 02-04-2015)

28. Forces acting on bolt; http://www.wayneboltandnut.thomasregister.com(as seen on 02-04-2015)

29. C. Chen and R. Kovacevic, Thermomechanical modeling and force analysis of friction stir welding by the finite element method, Proc. Instn Mech. Engrs 218 (C) (2004) 509-519.

30. V. Soundararajan, S. Zekovic, and R. Kovacevic, Thermo-mechanical model with adaptive boundary conditions for friction stir welding of Al 6061, International Journal of Machine Tools & Manufacture 45 (2005) 1577-1587.

31. M. Song and R. Kovacevic, Numerical and experimental study of the heat transfer process in friction stir welding, Proc. Instn Mech. Engrs 217 (B) (2003) 73-85

32. J.S. Strenkowski, C.C. Hsieh, and A.J. Shih, An Analytical Finite Element Technique for Predicting Thrust Force and Torque in Drilling, International Journal of Machine Tools and Manufacture 44 (2004) 1413-1421.

33. M. Reis, R. Louro, P.J. Morais, L. Santos, and H. Gouveia, Microstructural Characterisation of 5083 Al Alloy Joints Friction Stir Welded, Materials Science Forum 514-516 (2006) 510-515.

34. M. Guerra, C. Schmidt, J.C. McClure, L.E. Murr, and A.C. Nunes, Flow patterns during friction stir welding, Materials Characterization 49 (2003) 95-101.

35. R.W. Fonda, J.F. Bingert, and K.J. Colligan, Development of grain structure during friction stir welding, Scripta Materialia 51 (2004) 243-248.

36. S.F. Miller, H. Wang, R. Li, and A.J. Shih, Experimental and numerical analysis of the friction drilling process, ASME Journal of Manufacturing Science and Engineering (2004).