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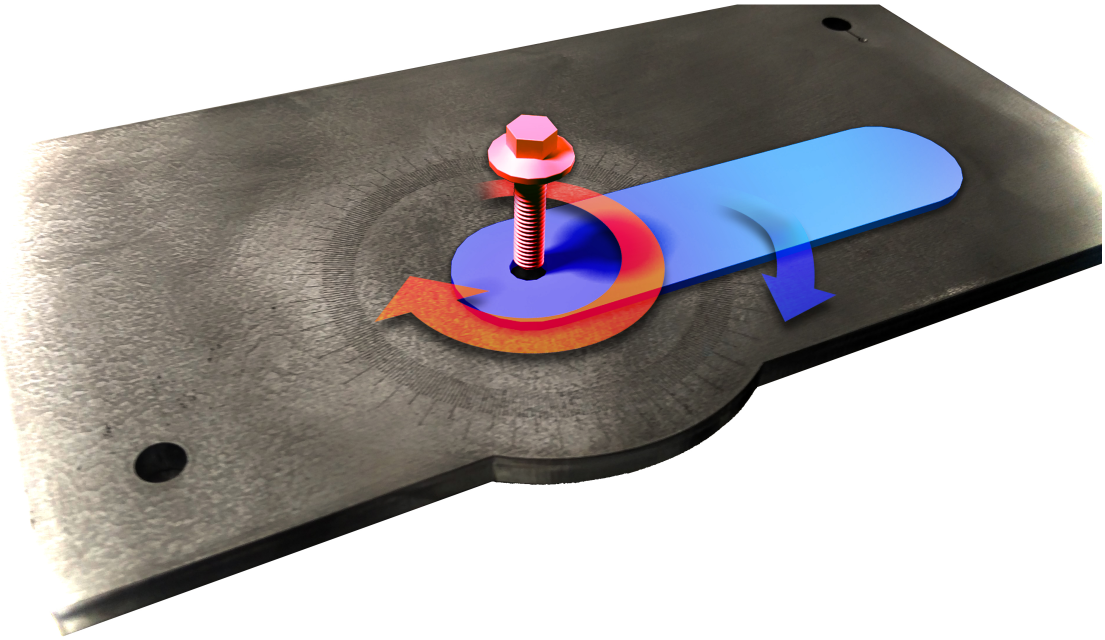

Rotational effects on components from bolting

A study in how different factors affect rotational displacement of components

Master's thesis in Product Development

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Gothenburg, Sweden 2017

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Cover: A picture taken of the surface plate that was used during experiments, with a computer rendered test component, bolt and arrow overlaid.

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Abstract

The purpose of this project was to find and map correlations between different parameters and the resulting rotational displacement of a component being bolted.

The background to this thesis emanates from a problem encountered at Volvo where components tend to rotate as they are bolted to the car body. One component in which this is visible is the car hood, where about 50% of the hoods on a specific car model have to be adjusted post-assembly. The project was therefore mostly conducted at Volvo Cars in Torslanda. During the work a number of experiments were carried out using both generic components as well as components specific to a Volvo vehicle. A finite element simulation model was developed, yet only using a static simulation. It can however be used as a starting point for the development of a dynamic model.

One of the projects most important result is the effect of SEMS bolts, that is, a bolt with a pre-assembled washer. When using a washer, the rotation and the exerted torque of the component are both reduced, on an average, by a factor of 2.2 at a minimum. This factor was consistent across most component materials. However, the rotation was 18 times greater of components made from aluminium when no washer was used. Our studies show that the relation between the transferred torque between bolt and component and the final rotation of the component seem to be linear.

Another result observed is the effect of oil applied between component, bolt, and the underlying surface. When oil is applied between bolt and component the transferred torque is reduced by a factor of two. On the other hand, when oil is applied between component and the underlying surface the rotation of the component is increased by a factor greater than five. The optimum angular velocity of bolting was found to be between 200-220 RPM. At lower angular velocities, the nut runner has a longer period of time to make the component rotate before it is locked into place by the axial tension. At higher speeds, it becomes difficult to get accurate readings because the nut runner jumps out of place.

During the studies, a wide distribution of the results was observed. Additional iterations would most certainly have produced more reliable results and, thus, a better understanding, but time, material availability, as well as access to the tools were limited.

Sammanfattning

Projektets syfte var att hitta och kartlägga samband mellan olika parametrar och den resulterande rotationen av en komponent som skruvas fast.

Bakgrunden till detta arbete var företaget Volvo Cars problem med rotation som uppkommer vid fastskruvning av komponenter, bland annat vid montering av framhuven på personbilar. I nuläget korrigeras cirka 50% av bilarnas framhuvar efter fastdragning på den bilmodell som observerats under projektet. Den större delen av projektets arbete kom att utföras i Volvos Cars lokaler i Torslanda. Under detta arbetets gång har experiment gjorts på generiska komponenter och Volvospecifika delar. Under experimenten har moment uppmätts av fastsatta komponenter och även slutgiltig rotation. En Finit-Element-modell har även tagits fram, dock endast i en statisk simulering, men vilken kan användas som startpunkt i utvecklingen av en dynamisk modell.

En av projektets viktigaste resultat var effekten av SEMS skruvar, dvs. skruvar med förmonterad bricka. När en skruv har bricka minskar den totala rotationen och det överförda momentet till komponenten med minst en faktor 2.2. Detta värde gällde flesta material, dock upptäcktes även att aluminium gav en faktor 18 gånger mer rotation utan bricka. Värt att notera är att förhållandet mellan överfört moment från skruv till komponent och slutgilting rotation av komponent verkar vara linjärt.

Ett annat resultat var effekten av olja mellan komponent, underlag och skruv. När olja appliceras mellan skruvhuvud och komponent minskar överförd moment med en faktor två, men när olja appliceras mellan komponent och markplatta ökar komponentens rotation med minst en faktor 5. Optimal hastighet på dragning slutade på mellan 200-220 RPM. Vid lägre hastigheter har momentdragaren längre tid på sig att sätta komponenten i rörelse innan den låses fast av dragspänningen, och vid högre hastigheter blir det svårt att få konsekventa resultat eftersom dragaren sliter sig loss vid rycket som uppstår.

Något som upptäckts under experimentens gång var den stora spridningen av resultat. Fler itereringar hade gett ett bättre medelvärde, men tiden, materialtillgången och tillgång till verktyg var begränsade.

Preface

This master's thesis is written as a conclusion to the master degree of product development at Chalmers university of technology. It has been executed in collaboration with Volvo Cars AB.

We would like to thank:
Dag Johansson, technical expert and supervisor to the project who was always there to criticize/discuss our plans and results.
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Nomenclature

CM4D Coordinate Measurement Machine Management Mechanism for Data, page 31

DoE Design of Experiments, page 11

FEA Finite Element Analysis, page 11

SEMS Bolt with preassembled washer, page 15

TTT Turn to Tighten, page 3

1
Introduction

This chapter will introduce the genereal background and purpose of this work.

1.1 Company overview

The car manufacturer Volvo Cars is a well known Chinese owned Swedish company that was founded in Sweden 1927. It was founded as a subsidiary company from the Swedish company SKF, but in 1935 Volvo became its own company without a majority held by SKF. Since its creation, Volvo has been producing cars with a Swedish market in mind, but was also quickly expanded to export to other countries as well [1]. Volvo today has over 90 000 employees and are producing cars in 18 countries. Volvo's core values are safety, quality and care for the environment. This in turn gives a strong incentive for the company to have a high emphasis on high-tech cars with a lot of features in order to reach their core values[2].

1.2 Problem background

The Robust Design and Tolerancing department at Volvo Cars works with geometry assurance, to make the products as robust as possible. This means that the assembly of products become less sensitive to geometric variation on both suppliers and Volvos own components.

However, not all deviations are easy to anticipate. This master's thesis will investigate the rotational displacement of a component caused by bolting. Specifically, investigations will be made into displacements caused by twisting when the torque is transferred from the bolt to the detail being fastened. There are numerous papers and research results concerning the stresses and deformations caused by the axial tension of bolting. What is lacking is research on how the torque of the bolting mechanism is transferred to the component being fastened, and in turn causing stresses/deformation by rotating the detail in this process.

One of the areas of the vehicle where this issue is most noticeable is the car hood, where rotational dislocations have been noticed after the hinges have been fastened to the car body. Because of this, the hinges of the car hood will be used in some of the experiments.

1.3 Purpose

The purpose of this master's thesis is to find and map a correlation between different parameters in the assembly which can be controlled (such as type of bolt, bolting sequence, torque, thread pitch, angular velocity, and friction), and the resulting rotational effect. Using the results of the experiments, an effect summary will be created, which can be used to accurately predict changes in the resulting effect caused by the bolting as a cause of altering parameters. This will help Volvo to prevent the problem rather than applying quick fixes when the problem is already present on the assembly line.

1.4 Problem Formulation

The problem investigated is as follows: How do different factors such as torque, thread pitch, speed, friction, bolt type, bolting sequence and material type contribute to the rotational displacement of a component when it is being bolted? The outcome of the project should be a method which would make it easier to anticipate the geometrical deviation caused by the rotational effects.

1.5 Research Questions

The present research questions are:

- What are the critical variables that affect the rotation of the component?
- What are the correlations between the respective parameters and the rotational displacement experienced by the component?
- Can the effect be simulated in a Finite Element (FE) software?

1.6 Limitations

The project will be subject to a few limitations:

- Being a master's thesis, this project is limited to 800 hours / student, resulting in a total of 1600 hours.
- The main components that the tests will be conducted on will be the lower part of the front panel hinge for the Volvo model 426. This is where the rotational effect has been the most present and it will serve as a model for all other similar components as well.
- The components on which the physical tests will be conducted on should have a maximum of two nut/bolt fastening points to the car body. The two fastening points should be in the same plane.
- The tests will only be carried out on bolted joints between two components.
- The dimensions of the nuts and bolts will be kept constant.

2

Theoretical Basics

Even though the process of bolting can be affected by over 200 different factors, there are a few main areas that one should know about in order to understand the process; among these input torque, angle of turn, tension and friction [3]. These will be briefly explained below, plus some other relevant concepts.

2.1 Input torque

Input torque is the variable which most bolting is defined by. When bolting, electric nutrunners are often set up so that they stop when they reach a certain input torque. Usually when bolting, two input torques are specified. The first one is at a lower torque than the target, but until the first torque is reached, a higher angular velocity is used. Once the first torque is reached, the second and higher torque is the new target, which the machine will reach while using a lower angular velocity. This procedure is set in place to increase the accuracy of the final torque and to reduce the jerk experienced by the operator.

2.2 Angle of turn

Angle of turn is usually what is used after the second input torque has been reached while bolting. When the second torque is reached, an extra angle of turn is added to the bolt as displayed in figure 2.1. This is used for several reasons, one of them being that two of the same bolts can have different amount of friction due to variations in production. This means that reaching a certain torque on two separate bolts can result in two different axial tensions. To reduce the effect of this, an extra angle is added to the procedure at the end, since turning a certain angle will be the same angle regardless of the friction of the bolt. This type of bolting with both torque and angle is called TTT (Torque Turn to Tighten).

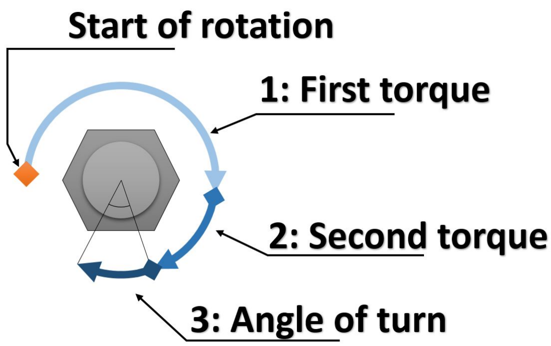

Figure 2.1: A visual representation of the bolting sequence. The degrees rotated in each sequence are not to accurately represented, only the order in which they are performed.

2.3 Tension

Tension in the bolt is what causes the parts to be pushed towards each other after bolting. A bolt can be theoretically replaced with a metal spring. One end of the spring is the head of the bolt, and the other end is at the nut. In order to put a certain final tension into a spring, the force desired will have to be applied into the spring to reach the same tension. This tension will push the bolted parts towards each other once the bolting is done, and keep them there. The only difference with just having a spring and having a bolt is the threads. The spiral threads are used in the same way a vehicle would climb a high mountain using a spiraling road on the mountain instead of using a straight line to the top. The threads have a low angle, which creates a gearing effect with a high ratio when rotating the bolt. This allows for the mechanical “spring” that is the bolt to be tensioned a lot more than a normal spring using the same force.

2.4 Friction

Friction is present in several parts of the bolting, but can be divided into two areas; underhead friction and thread friction as seen in Figure 2.2. The friction can be adjusted by using different coatings and materials, but in the end most of the energy will still go towards friction. Only 10 % of the energy used while bolting will end up as elastic energy in the bolt, and this can be even lower if the friction is higher. If the underhead friction is altered, the bolting torque will have to be adjusted to reach the desired axial tension. Even though energy is lost as heat from friction while bolting, friction should not be totally avoided. The friction is what keeps the bolt from unscrewing itself. Without the friction the bolt would simply rotate back up after the bolting.

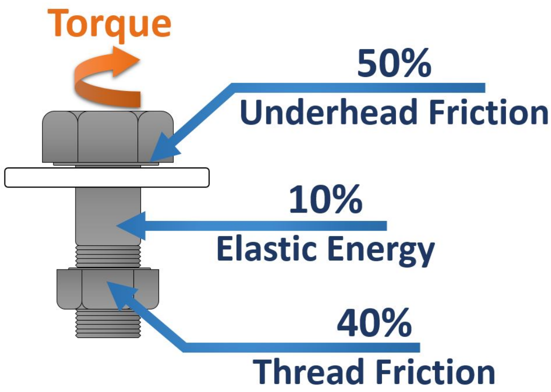

Figure 2.2: The three areas where energy from the bolting operation is distributed. Note that the frictional energy is converted into heat.

2.5 SEMS-Bolts and flange bolts

During this project there will be several mentions of the two bolt types SEMS and flange. The definition of a flange bolt is that is has a flange below the gripping area for the tool, as seen in figure 2.3. This flange has the task of smoothing the connection between the underhead and the component being bolted. Without the flange, the hexagon would scratch unevenly on the surface of the component, making visible marks. The SEMS-bolt, named after it being pre-as**SEM**bled, has a flange as well, plus a washer that is stuck around the bolt but still free to rotate. This is sometimes also referred to as a bolt with an "unlosable" washer. A picture of a SEMS-bolt can be seen to the right in figure 2.3.

Figure 2.3: The two types of bolts used in this project. A standard M8 flange bolt to the left and a M8 SEMS-bolt to the right.

2.6 3-2-1 Positioning

Many of the parts fastened with bolting or other means at Volvo use the 3-2-1 positioning in order to fully lock the component in place. The name refers to the fact that there should be three connections in one plane for example the X-plane connected to the component, two connections in the Y-plane and one connection in the Z-plane[4]. By doing this, the component is securely locked in place. It it also with this principle that problems with tolerances are avoided. A typical example of how to bolt a part with respect to the tolerances can be seen in figure 2.4. Many of the components at Volvo use the type fastening as seen in the figure.

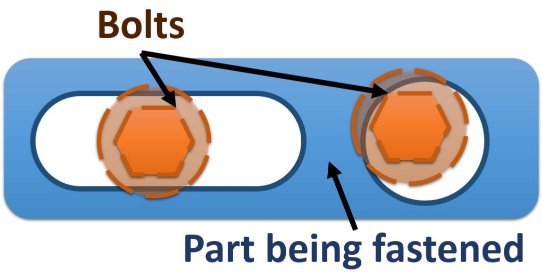

Figure 2.4: A component in blue being bolted by orange bolts. The left hole is made like a slit and the right hole has a larger diameter than the bolt. This allows for variations within the tolerance on the components and it still being able to be adjusted to its correct location.

3
General method

This chapter will explain the methods used in this project.

3.1 Starting method

Before this project started, a prestudy was conducted at Volvo by Dag Johansson[1](January 2017) showing very little previous research on this subject in particular, which in turn led to this project. To be certain that no literature was missed, a separate literature study was conducted at the start of this project. The search terms used were "rotation of components during bolting" and "under-head friction" plus several similar terms. Just like in the previous literature study, there were no signs of literature focused on this particular problem. It became clear that the experiments would have to be designed to test a wide variety of factors, since most effects and correlations were unknown. The method decided upon was to have several iterations, where focus would shift from theory to verifying via experiments, and then analyse the results from that experiment. Analysing results from the experiments yielded new knowledge and spawned theories that was tested in new experiments.

3.2 Choosing the experiment

The experiments chosen at first were in large chosen to test some basic theories such as how friction and washers affected the outcome. Later experiments tested variables such as the angular velocity of the nutrunner, mass of the component and the off-centering of the component around the bolting hole.

[1]Dag.johansson@volvocars.com

3.3 Designing the test rig for experiments

The experiment rig was designed so that tests could be executed by placing a generic component in contact with a metal plate, and bolt it with one or two bolts using a nutrunner, and record the results. The output which was intended to be recorded was the torque transferred from the bolt to the component, and the actual rotation of the component.

To be able to perform the experiments, a few assumptions were made:

- The results should be useful on more than just a specific case on a specific component. This meant that the tests were to be performed on components with a simple geometry. The hinges on the front of the car where the effect had been observed were to be included in some of the tests, though most of the tests were to be conducted on components with simple geometry. This would also exclude as many unknown factors as possible. For the same reason, the surface area of the test rig would also be designed as generic surface more than the front area of a car.

- To avoid potential problems with the test rig being worn out after each test, the rig was designed so that rig parts that would be worn out could easily be replaced. This also allowed changing of the material type that was used in some of the experiments to test different frictions etc.

With all these stipulations, the test rig was designed as seen in figure 3.1. The following paragraph describes the test rig in greater detail.

A "Base Plate" constitutes the base of the test rig. This plate has two holes designed to fit with Volvo's own test rigs. Volvo's test rigs are huge steel platforms that are anchored into the earth many meters below to remove all unwanted forces and vibrations from external sources. "Base Plate" also have two hexagon shaped holes that are used for securing the nuts for the experiments. The hexagons are made so that a normal M8 nut cannot rotate inside of it. The nuts used in these holes are meant to simulate the holes for bolting on the car with one exception; the nuts mounted on the cars are "non-threaded nuts". These nuts are void of threads, and will get their threads from the first bolt that is bolted through the nut. Although the car and the test rig are different in this aspect, this does not affect the end result; the extra torque that is needed to create the threads are applied at the start of the bolting process. The event that the experiments are testing are at the end of the bolting process. When the bolt head reaches to the component surface, the threads have been formed and are working as a normal threaded nut.

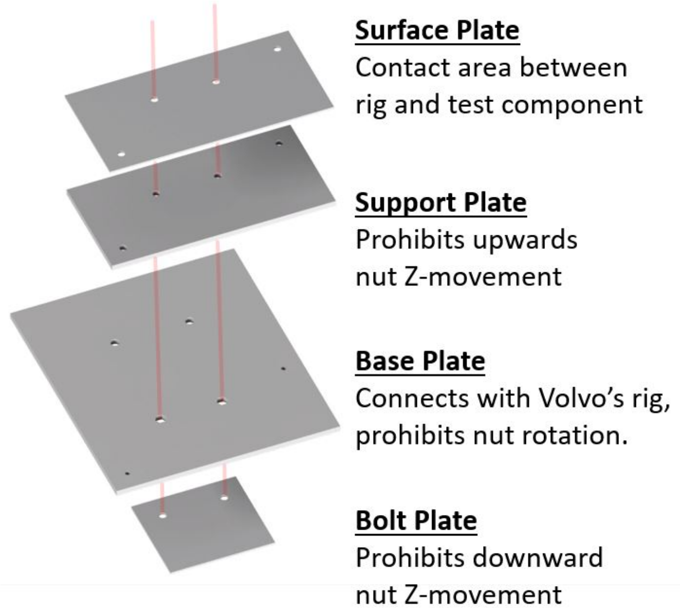

Figure 3.1: Overview of the four plates that were used in the test rig for most of the experiments.

On top of the "Base Plate" there is a part called the "Support Plate". This part has the task of withstanding the vertical force from the nut. Already on the first test, it became clear that the nut produced a large counter force upwards when being bolted, causing the plate above to get deformed. Originally the thickness of the "support plate" was set to 3 mm, but after the discovery of the "Volcano effect", it was increased to 8 mm. This "Volcano effect" can be seen clearly in figure 4.3 on a 3 mm plate.

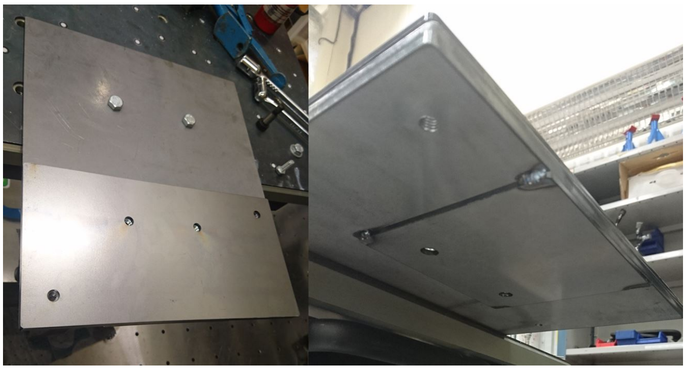

Figure 3.2: Two pictures of the finished rig, the left picture is from above and the right picture from below.

The plate on the top is called the "Surface Plate" and have the same profile as the "Support Plate", with the difference being that the thickness is only 3 mm. There were a total of 16 Surface Plates made, 4 in each material; Galvanized Steel, stainless steel, black steel and aluminium. The material data for these materials can be found in appendix A.3. These plates are used for the contact between tested component and simulated car surface.

The last plate needed for the test rig is the "Bolt Plate", which only purpose is to keep the nut from falling down before the bolt threads has enough contact to keep the nut in in place.

3.3.1 Nutrunners

During the project, there were two electric nutrunners used for the experiments. The reason for there being more than one is that the first nutrunner used was discovered not to be able to reach the desired angular velocity used in production of the cars. The two nutrunners used were:

- Tensor ETV DS72-30-10 (max RPM 800)
- Tensor ETV DS92-370-HAD (max RPM 170)

For the nutrunners, the following control system was used:

- Power Focus 4000-G-HW : Controller for electrical assembly tools

More data and information about these systems can be found in appendixes A.1, A.2 and in reference [5]. The whole system can be viewed in figure 3.3.

Figure 3.3: The tool with 800RPM and the Power Focus controller.

3.3.2 Test components and their materials

The need for test components to perform experiments on during the project was immense. Volvo Torslanda has a machine park with tools and materials, which facilitated the acquiring of test components. To create the components, a laser cutter at Volvo was used. The laser worked with files made from the program CATIA V5, which made the process of creating parts easy.

The metals used during the project for the test components were stainless steel, galvanized plate, black steel and aluminium. The material data for these exact metals that were available at Volvo can be found in appendix A.3.

3.4 The software Toolstalk

Toolstalk[6] Power Focus was used to communicate with the tool during the experiments. This software offers many variables to tweak the settings with of the nutrunner in real time. The most commonly changed variables for these experiments were angular velocity and angle of turn.

3.4.1 Design of Experiments and JMP

During the projects DoE (Design of Experiments), a full factorial design was used, meaning that every variation of the variables were tested to get a full picture of the physical relationships. This proved to be a good idea, since the variance at each measuring point was high. If a more sparse DoE had been made, there would have been problems finding any correlations at all. To easier discover links between the variables changed and the results of the experiments, the software JMP[7] was used. This software has a built in support for Excel which makes it possible to transfer data between the two.

3.5 Finite Element Analysis

During the project, FEA (Finite Element Analysis) was used to simulate the bolting sequence. The program used for this was Ansys Workbench [8].

4
Experiments

The experiments being done can be divided into four groups:

- Preliminary Experiments
- Primary Experiments
- Complementary Experiments
- Production Experiments

4.1 Preliminary Experiments

In most of the preliminary experiments, the force experienced by the component was measured 100 mm from the point of rotation. The force experienced by the component was assumed to reflect the amount of rotation that the component would have had if the rotation was not stopped by the force gauge. A sketch of the setup and a picture from the actual setup can be seen in figure 4.1.

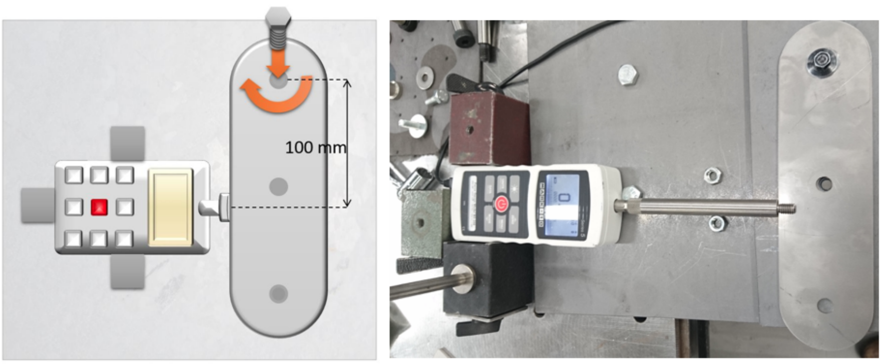

Figure 4.1: The experiment set up with a force gauge 100 mm from the center of rotation.

In some of the later experiments, there was a larger emphasis on collecting the actual rotation rather than the torque experienced. To measure this, a protractor was glued to the surface of the "Surface Plate", which later was changed for a plate with the protractor engraved onto its surface, as seen in figure 4.2.

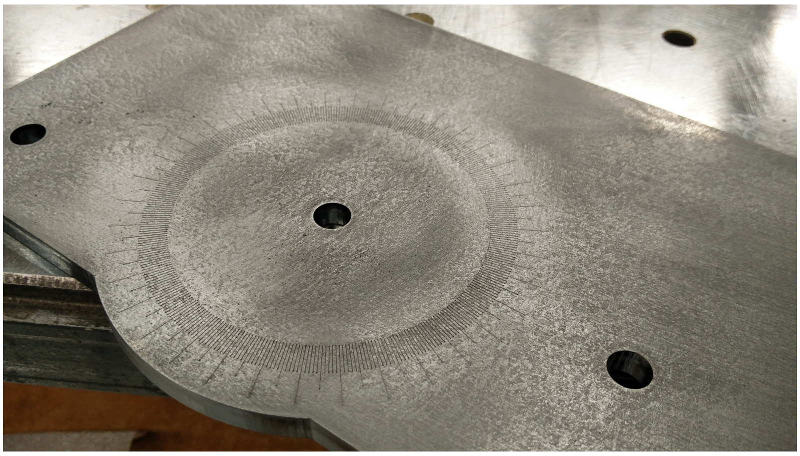

Figure 4.2: Surface Plate with degrees.

4.1.1 Preliminary Experiment 1 , bolting by hand

Since little was known about bolting in the first experiment, a manual test was performed to generate understanding. The experiment was conducted by bolting a hinge, seen in figure 4.23, by hand with the help of a wrench. This experiment helped with shaping the next experiment, and was also the first time where the "Volcano Effect" was detected as shown in figure 4.3. The "Volcano Effect" was named after the fact that the metal surrounding the hole was deformed upwards, in an area roughly the same size as the nut underneath.

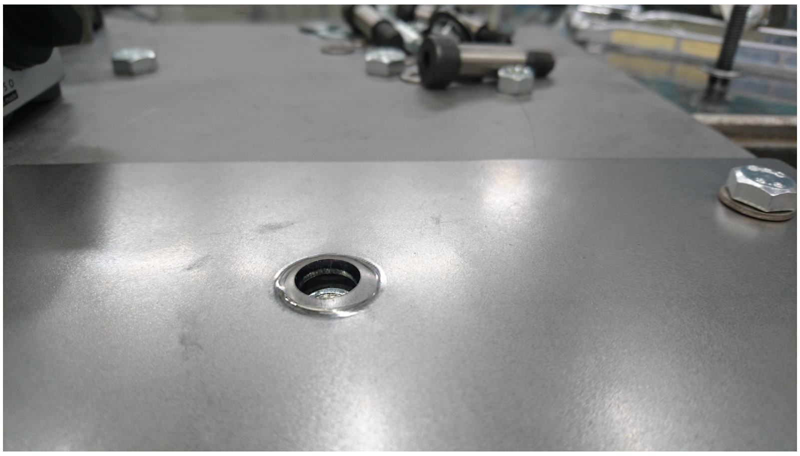

Figure 4.3: The "Volcano effect" on a 3 mm stainless steel plate.

4.1.2 Preliminary Experiment 2: Varying underhead configurations

Preliminary Experiment 2 was performed while still in the cradle of theories since none of the theories had been physically tested. The theories included how the transferred torque would be affected by a washer and lowered friction. For this experiment a test component as seen in figure 4.4 was used. Four different configurations were tested:

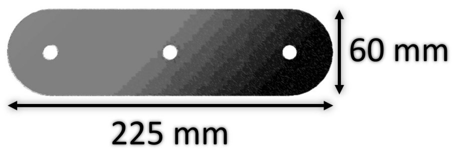

Figure 4.4: Component used during Preliminary Experiment 2, 3 mm stainless steel.

- **No washer, no oil**
  The first test consisted of bolting the component without any special conditions, see figure 4.5.

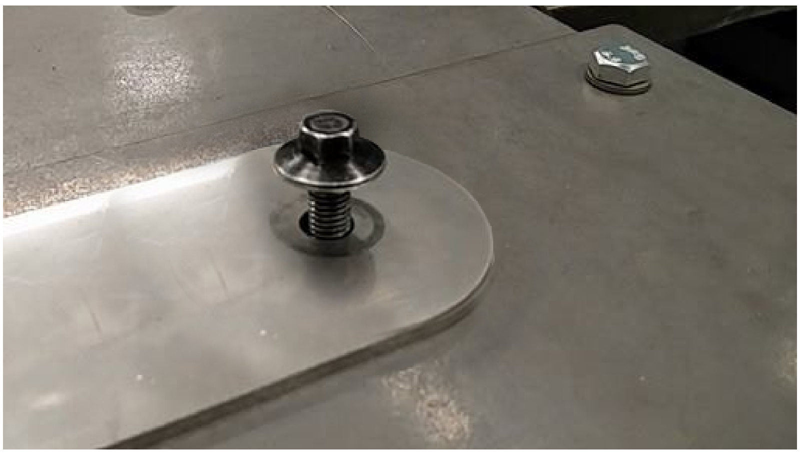

Figure 4.5: Bolt and component.

- **Small washer**
  The next test included a small washer between the bolt and the component, as seen in figure 4.6. In theory this would decrease transferred torque. This bolt with washer is in practice the same as a SEMS-bolt, as explained in chapter 2.5.

  .

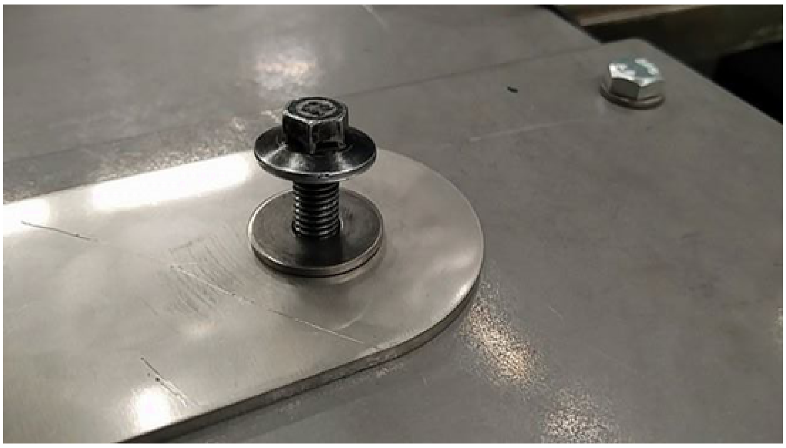

Figure 4.6: Small washer between the bolt and the component.

- **Large washer**
  To determine if the size of the washer had any significance in the bolting process a larg washer was tested, figure 4.7. The diameter of this washer was the same as the diameter of the component, 60 mm.

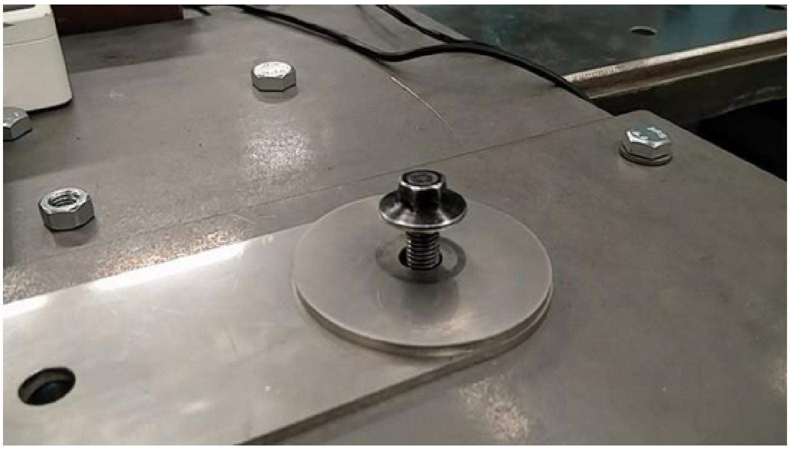

Figure 4.7: A large washer between the bolt and the component.

- **Oil applied between bolt head and component**
  Finally at the end of this batch of experiments, the transferred torque was measured with a layer of oil applied between the bolt head and the component, figure 4.8.

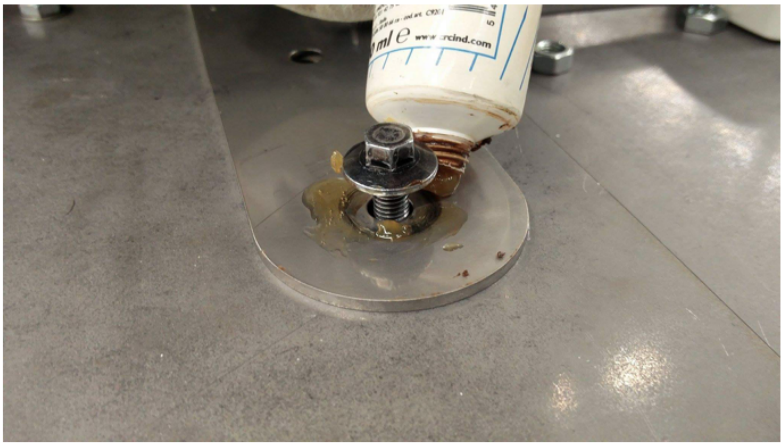

Figure 4.8: Oil between bolt head and component.

The results of these tests are shown in figure 4.9:

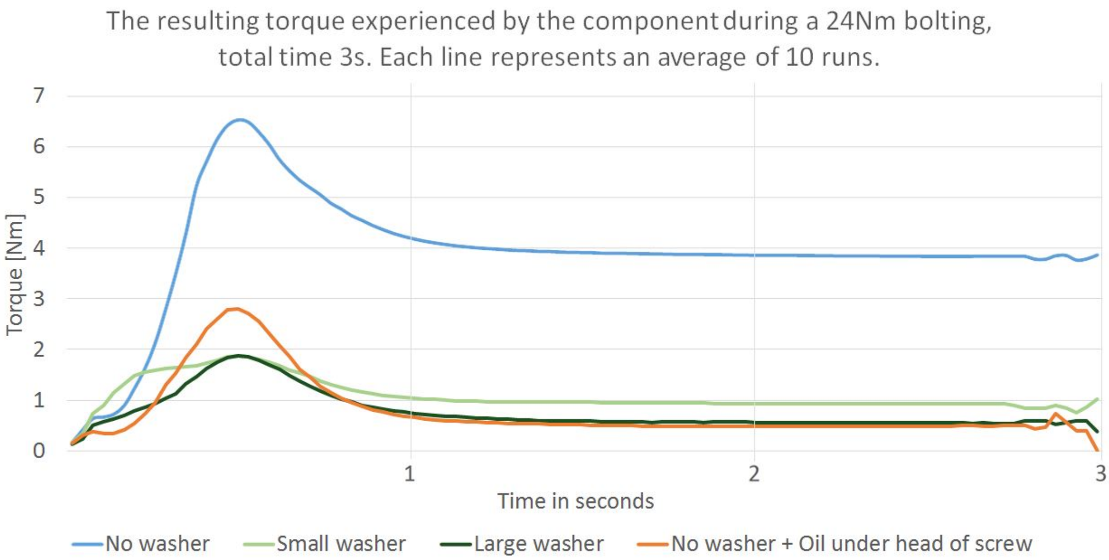

Figure 4.9: Preliminary Experiment 2 results. All three configurations with more than just a bolt show lower torque on component.

As shown in 4.9 there was a noticeable change in transferred torque both when using washers and when a layer of oil was applied. The different configurations resulted in about the same change in torque, with a factor from 2,6 to 3.

However, it should be mentioned, as explained in chapter 2.4, that applying oil between the bolt head and the component affects the final axial tension and may result in a sub-optimal bolt joint.

4.1.3 Preliminary Experiment 3, repeatability

Preliminary Experiment 3 was executed to investigate if it would be possible to repeat the bolting process with the same approximate distribution of the results without replacing the bolt, nut, or component.

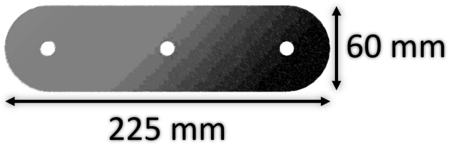

Figure 4.10: Component used during Preliminary Experiment 3, 3 mm stainless steel.

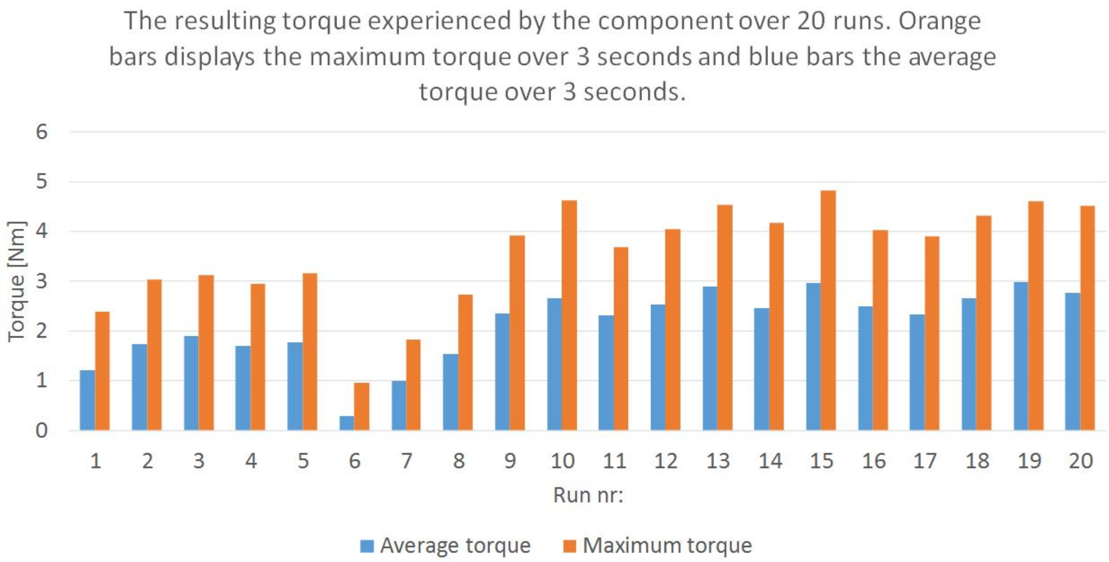

Figure 4.11: Preliminary Experiment 3.1 results. The resulting average and maximum torque were varying over time when using the same parts for the experiment.

As shown in figure 4.11, there was a tangible difference over time both when it comes to the maximum and average transferred torque from 20 boltings where neither bolt, nut, or component were replaced.

Following this, the experiment was redone but with unique bolts for each test. The results were as seen in figure 4.12.

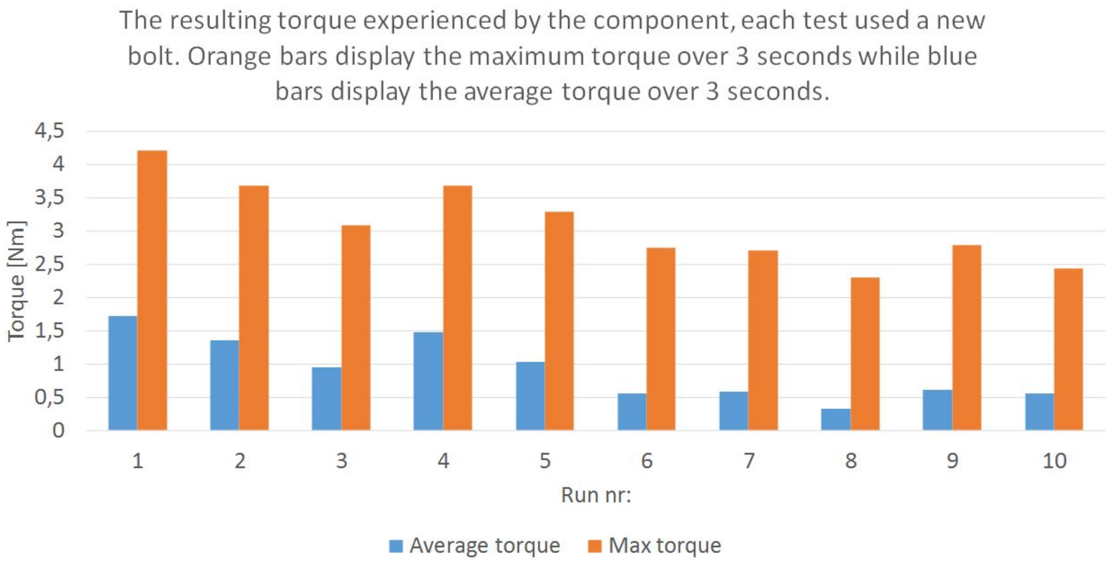

Figure 4.12: Preliminary Experiment 3.2 results. Even when the bolt was changed for every run, the results were varying. A trend of lower and lower torque transferred was also visible.

The results that can be gathered from both of these graphs show that there is a difference in output data depending on the replacement of certain bolting components. This insight lead to the bolting processes carried out in chapter 4.2, Primary Experiment, were performed on brand new bolts, nuts, and components for each of the tests, to reduce the effect of wear.

4.1.4 Preliminary Experiment 4, angular velocity

Preliminary Experiment 4 was executed to investigate correlations between the transferred torque and the angular velocity of the nutrunner. The theory was that at higher velocities the bolt would not have time to start rotating the component before the axial tension locked it in place. The experiment was carried out by using four different velocities, with ten boltings for each velocity. Because of the angular velocity capabilities of the nutrunner used (Tensor ETV DS92-370-HAD) being limited to 170 RPM, and the angular velocity of the second torque stage of the bolting being limited to 40% of this, the velocity levels used for this experiment were 17, 35, 51 and 68 RPM. More information about the nutrunner can be found in appendix A.2. The component used is shown in figure 4.13.

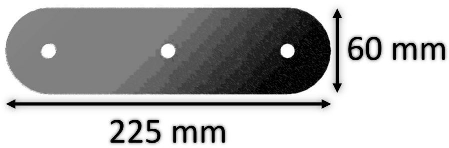

Figure 4.13: Component used during Preliminary Experiment 4, 3 mm stainless steel.

As shown in figure 4.14, the results from this experiment were unclear. It shows a decrease in torque measured at higher speeds than the slowest, but the trend seemed to change when increasing the angular velocity even more. Angular velocity seems to have an impact on the results nonetheless, which led to the variable being included in the later Primary Experiment.

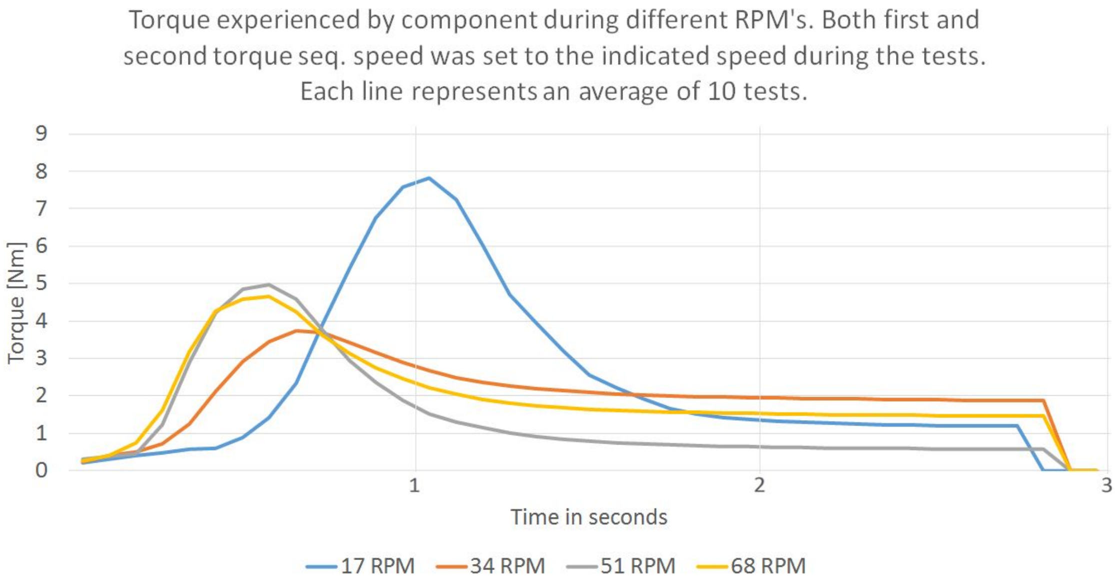

Figure 4.14: Preliminary Experiment 4 results. The results indicate that lower speeds could result in higher torque.

4.1.5 Preliminary Experiment 5, The Drop

Preliminary Experiment 5 was a stepping stone to the primary experiment. This is why a new component, figure 4.15, was designed for this experiment. This component came to be called **The Drop**. The drop was designed to easily read and determine the rotation using the protractor on the surface plate, as seen in figure 4.16.

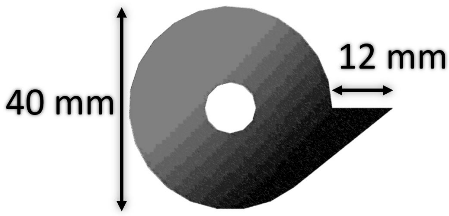

Figure 4.15: Component used during Preliminary Experiment 5, 3 mm stainless steel.

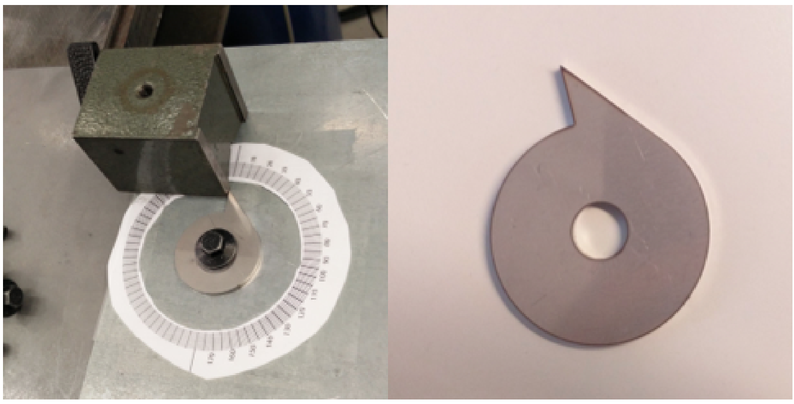

Figure 4.16: "The Drop" created in the laser cutter.

The experiment was primarily carried out to investigate the repeatability of this new component, and secondly to see how/if it would be possible to read the actual rotation thanks to the new design.

The results from this experiment were unclear at best. The components were bolted, loosened, honed, and bolted again, but the rotation measured for every single bolting was 0°. The theory as to why this occurred was that it had to do with the relative positions between the component and the bolt. It was also theorised that the shape of the Drop component could affect the rotation. This led to a redesign of the component which can be seen in chapter 4.1.7.

4.1.6 Preliminary Experiment 6, Off Center

The preceding experiment generated a new theory: All holes designed for bolts on Volvo are designed larger than the bolts radius for tolerance purposes, as explained in chapter 2.6. Even if this allows for some adjustments, it also creates the problem of the hole not being centered around the bolt when bolting. In effect, this would lead to one side of the bolted component having more contact with the underhead of the bolt than the other side while and after bolting. This asymmetric relation showed indications of causing the component to rotate.

To investigate the effect of this, a new experiment was designed. The design was to use washers with a significantly larger inner diameter than the bolt diameter to test displacement. A circle was drawn in the Surface Plate to indicate where the washer was centered. Several boltings of both the washer being centered and the washer being off centered were made.

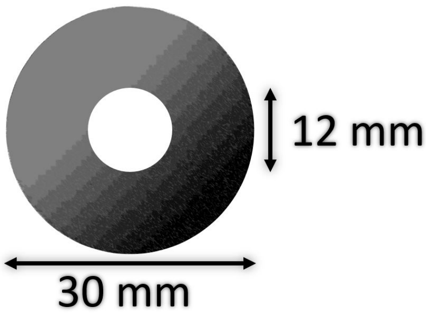

Figure 4.17: Component used during Preliminary Experiment 6, 2 mm stainless steel.

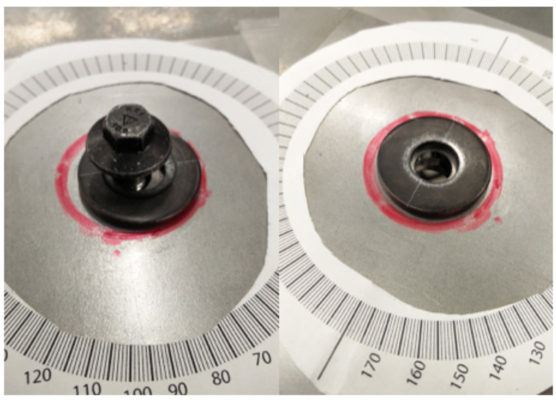

Figure 4.18: To the left; Washer off center. To the right; Washer in center.

This experiment did not yield any usable results, except for more examples of components not rotating. Off centering the washer had no effect on the outcome, which meant that there were some other factor at play that made the components become locked in place.

4.1.7 Preliminary Experiment 7, troubleshooting

Preliminary Experiment 7 was carried out as a trial and error session to discover why there was a measured rotation in the factory, yet the rotation was unable to be recreated in a controlled environment. Earlier experiments had shown a torque on the component, but not all boltings caused actual rotation of the component. What appeared most plausible was that, on the production line, there was some form of coating or frictional disturbance which was missed during the design of the test rig. After further discussion with the supervisor the conclusion was that there was a layer of oil left from the forming of the car body. This insight gave way to an experiment using a layer of oil between component and surface plate, which then generated rotational displacement. Because of this, all following experiments had a controlled amount of oil applied with a pipette between the component and the Surface Plate.

The component was also redesigned to look as in figure 4.19 for several reasons. The shape of the Drop component was showing indication of being one of the reasons for why the component was not rotating. The small radius of the Drop could mean that the edge of the component was pressed down harder because of its proximity to the bolt. The edges of the components caused a lot of problems, since laser cutting a component created sharp edges that could grab into the underlying surface. This meant that a larger radius around the bolt hole could help with this effect. Another concern was the accuracy of the reading, since the Drop was so small in radius. This meant that rotation of a unit smaller than one degree would be very hard to measure. The new component was longer and this provided a longer lever for measuring.

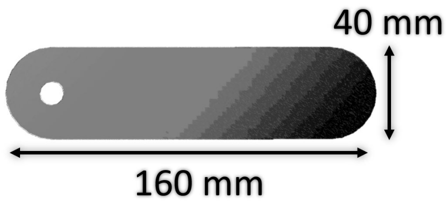

Figure 4.19: Component used during Preliminary Experiment 7, 3 mm stainless steel.

4.2 Primary Experiment

The Primary Experiment was the most extensive one of all experiments, and was planned in order to find links between several of the variables.

4.2.1 Design of primary experiment

In order to create an experiment that would yield accurate information, a lot of time was put into designing the experiment.

4.2.1.1 Choosing the variables

When the Primary Experiment was designed, all of the information acquired during the preliminary experiments were taken into consideration. This simplified the process of choosing what variables to include. The primary experiment differed from the other experiments in the amount of variables that were included, and systematically varied. To create a reliable mathematical model, a full factorial experiment was decided upon where all combinations of variables were tested.

The following parameters were chosen for the experiment:

- **4 Component materials:**
  - Galvanized plate
  - Stainless Steel
  - Black steel
  - Aluminium
- **2 Masses of component:**
  - 300g
  - 600g
- **3 Angular velocity of second torque:** (First torque angular velocity being 800 RPM)
  - 160 RPM
  - 200 RPM
  - 240 RPM
- **2 Types of bolt**
  - SEMS bolt
  - Flange bolt
- **Total number of experiments:** 48 ($= 4 \cdot 2 \cdot 3 \cdot 2$)

There were several reasons for the choice of these parameters. Material was chosen because of the assumption that varying material properties would have an impact on the results. These four materials was used because they were the most common in car components, and also because they were readily available to cut from the laser. To acquire more materials than the four materials selected was deemed to be outside of the projects scope.

Angular velocity was chosen because of the discovery in preliminary experiment, chapter 4.1.4, that using different angular velocities will give a variation in the transferred torque. The interval was centered around 200 RPM, the same angular velocity is used in bolting of the hood that is fastened to the car body.

Different bolt configurations were one of the variables which showed the most effect on the results, as shown in chapter 4.1.2. Whether the SEMS bolts are superior to the flange bolts when trying to prevent rotation of components was one of the most sought after results from Volvo, which made it obvious to include in the primary experiment. The number of different bolt types were initially three, where a bolt type with a thread pitch of 1mm was to be evaluated as well. The reason to why it was ultimately omitted from the test was that there was no bolt currently used at Volvo with 1mm thread pitch, and that the acquisition of such a screw would be difficult, according to Peter Falk, at the company Bulten[1]. This fact combined with the prediction that using a bolt with a lower thread pitch would cause the component being bolted to rotate more, ultimately lead to the elimination of that bolt from the experiment.

4.2.1.2 The setup

An idea was discussed with engineers at Volvo that there was a possibility that the rotation of the component was so small that the naked eye could not detect it on the current rig. After this idea was discussed, a change was made to the measuring process. The new measuring method, which can be seen in 4.20, used a laser mounted on the component being bolted, shown in figure 4.22. On this setup, rotations down to 0.1 °could be measured, using a custom made protractor as shown in figure 4.21.

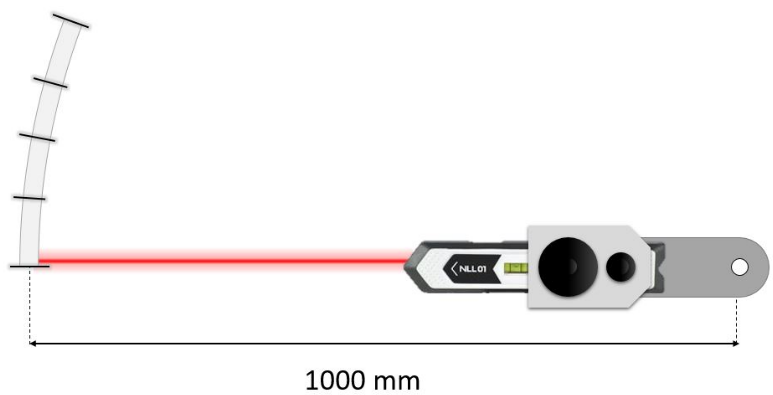

Figure 4.20: A visualization of the setup used in the Primary Experiment. The 1000mm distance between rotation center and protractor allows for readings of down to 0.1°with a laser.

[1] Peter.Falk@bulten.com

Figure 4.21: The protractor that was used for measuring the rotation of the component, held up by a mechanical arm. The radius of the protractors arc was 1000 mm and could measure up to 10 degrees.

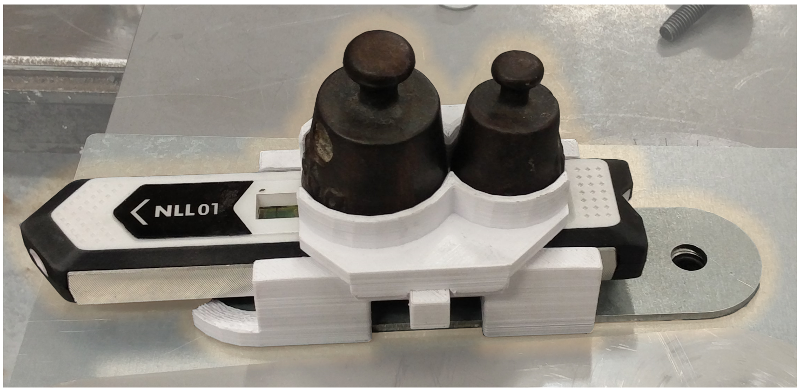

Figure 4.22: A component with the measuring laser and weights attached to it. The 3D-printed support had two sockets matching one 100g mass and one 200g mass.

4.2.2 Followup of experiment

The results which were gathered from the Primary Experiment did not give a clear enough understanding of how the angular velocity of the bolting, the mass of the component, and the friction affected the rotation. Because of this, a number of complementary experiments were subsequently carried out, in an effort to find correlations as well as gain understanding.

4.3 Complementary Experiments

After the Primary Experiment, more experiments were needed on some of the variables to create a better understanding. Complementary Experiments were made on angular velocity, mass and friction.

4.3.1 Complementary Experiment 1, angular velocity

An experiment was designed to provide a clearer view of how angular velocity affects rotation. For this experiment, it was decided to use one of the hinges of the car model where the rotation had been observed. However, because of the clunky shape of the hinge making it a difficult detail to work with, and the fact that only the lower part is needed for bolting it to the car body, it was decided to cut it in half. Keeping the hinges intact would require the consideration of a number of extra effects, including the center of mass being placed far from the support and the hinge acting as an elastic system which would start to oscillate. In order to disregard these effects, it was decided to cut the hinges in half. A picture of the finished half-hinge can be seen in figure 4.23.

Figure 4.23: The lower part of a hinge that was used during Complimentary Experiment 1 and 3.

Five different angular velocity settings were tested, and for each angular velocity four measurements were taken. At every angular velocity a completely new, unused hinge was used. The results from this experiment are shown in figure 4.24. There is a tendency of the rotational displacement being lower for a certain interval. However, these results were deemed insufficient, and it seemed unlikely that there is an extreme point at 220 RPM where all of the rotation disappears. This lead to Complementary Experiment 3, in chapter 4.3.3, where a much larger experiment of he same kind was carried out.

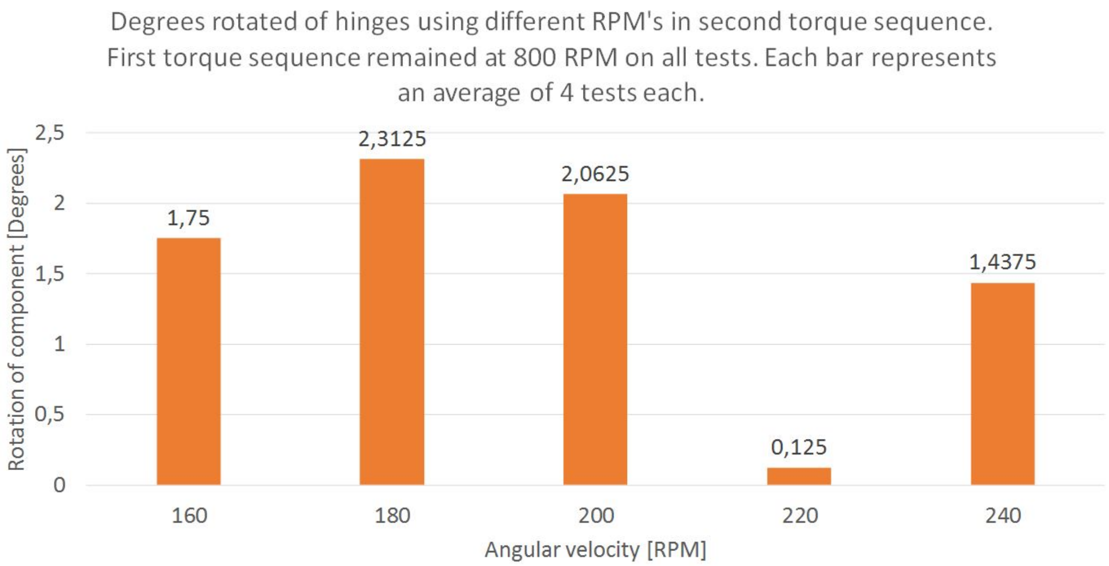

Figure 4.24: Complementary Experiment 1 results. The Experiment indicated that the rotational effects from bolting were significantly lower at just 220 RPM, but more experimenting was needed to confirm this.

4.3.2 Complementary Experiment 2, Friction

To attain accurate friction coefficients to use in the mathematical model, as well as for usage in the finite element analysis, a simple experiment was carried out. Components made out of the four materials, found in chapter 3.3.2, were made to slide on a surface plate made from galvanized steel. The results were as follows:

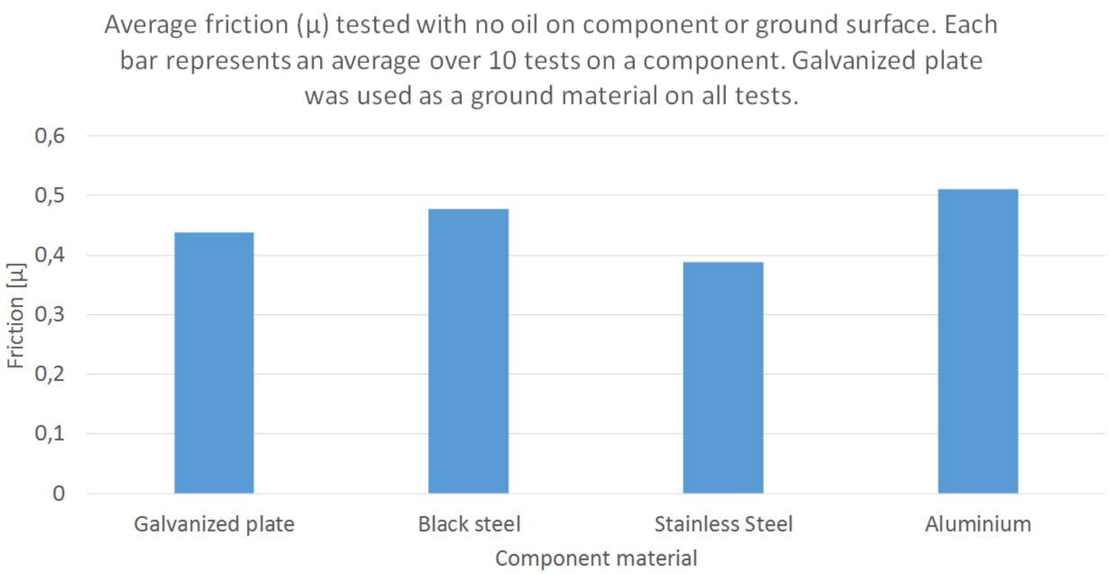

Figure 4.25: Complementary Experiment 2 results.

During these tests, an effect was observed that could be retroactively traced back to previous experiences with oiled surfaces. When using oil between two surfaces, there are three states that the system can be in, which are:

- Fluid film state
- Boundary lubrication state
- Vacuum state

In short, the state of the oil between the component surfaces has a huge impact on how the components behave while moving in contact with each other. A fluid film state reduces the friction down to almost zero, since the materials have no contact but a layer of oil in between[9]. This state is what is sought after when creating systems with a preferred low amount of friction, such as bearings. In the instance of these experiments on the other hand, having a fluid film in between the surfaces creates a lot of extra rotation, which is not to be desired.

Boundary lubrication state is arguably the most common contact type in the factory. This is due to that many of the production methods of the components involve oil in some way. The main component for the experiments, the hinge, is made with stamping. In the stamping process, a film of oil covers the component in order for the metal to easier be modified to fit into the mould. The boundary lubrication state between component surfaces is a combination of oil and metal contact[9]. This allows for some reduction in friction, but not as much as fluid film state. This state is where the experiments aimed to be at, since this was the closest to the case that was being observed in the factory.

The third and final state discovered to be present while testing was the vacuum state. This occurs when the oil has been reduced to an even thinner version of the boundary lubrication after the oil has been pushed to the edges of the component. The low pressure between the surfaces causes them to stick together, even when being turned over 180 degrees.

All three types of contact discovered during the experiments were in some way present when applying oil. The difficult part was to make sure that the system tested was kept at boundary lubrication, since this is the state that the parts in production was theorized to be in. When too much oil was applied, the component moved many times more than they normally do. When the oil ran out between the components, they stuck to each other and would not move at all. It was decided that these oil effects is a chapter that a lot more time could be put into, but it would not be justifiable to dive too deep into just one of the contributing factors of the problem.

4.3.3 Complementary Experiment 3, Angular Velocity

Following the insufficient results regarding angular velocity from both the primary experiment and the first complementary experiment, a more extensive experiment was carried out. This experiment was performed in a similar manner as complementary experiment 1, with the cut hinges, but with a much large number of boltings. In total, a hundred tests were performed: twenty tests per angular velocity. The angular velocity was varied between 160 and 240 RPM.

The result from this experiment is presented in chapter 6.2.

4.3.4 Complementary experiment 4, mass/inertia

An experiment investigating different moments of inertia of a test component was carried out. The component weighed 300, 400 and 500 gram each and was bolted with flanged bolts. The results from these tests showed no visible correlation between inertia and amount of rotational displacement. This could be due to that the range of the masses was too low to discover any correlation, or that the test had some other unknown flaw. After this test was completed, it was decided that no more experiments would be done to further investigate inertia. To create bigger components with greater range of inertia to test on could be interesting, but no more time was available for testing in the project.

4.4 Production Testing

The production testing was conducted on the assembly line, specifically where the hood is fastened to the car body through the hinges. The standard bolt was replaced with a SEMS-bolt, seen in figure 2.3, and the deviation of the hood was measured. The measurements were logged in CM4D (a software used to store measurements) which makes it possible to compare with results from bolting the standard bolt. However, because of the newly constructed section of the assembly line for this specific vehicle, a few problems arose, as they do in the ramp-up phase. One of the more severe issues was that the measurements made by the assigned machine were input incorrectly, which resulted in corrupt data. This rendered the results of this experiment inconclusive.

To bring about a test on the assembly line requires months of planning and approval from several levels of management, which was done before the bolting project was set in motion. As such, the project group was not in charge of any of the tasks associated with the assembly line testing, and was just a recipient of the results. This project would have benefited from the results, but was not dependent on those results since many other experiments were carried out.

5

Finite Element Analysis

The finite element analysis is best described in three steps, namely the different model stages. These represent the different stages in the physical experiments, which is what the FEA was supposed to simulate. To be able to correlate the FEA with reality, the measured rotation from the physical experiments is compared to the displacement in the FE model. The FE model first and foremost shows deformation of a model, but it can also be interpreted as displacement when looking at certain points in the model.

5.1 Step 1, First Model

For the first step, a very primitive model of an arbitrary bolt joint was created in CATIA V5. This was done prior to any physical experiments had been attempted, to be able to early on develop an understanding and a work procedure in Ansys which could be used throughout the project.

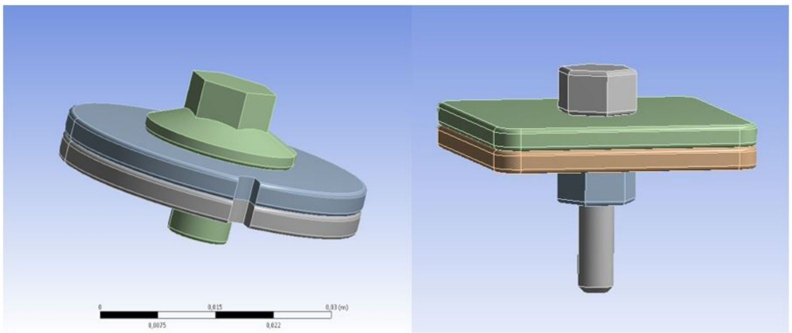

Figure 5.1: The first FEA attempt, showing two versions of a bolt, nut and two parts being bolted.

As shown in figure 5.1, a few different versions were created. These models were created before any insight about how to use contact surfaces or bolt threads in finite element calculations was gained. The results from this first FE-test were not suitable for future use, but knowledge was gained and the simulation was a stepping stone into the next stage.

5.2 Step 2, Second Model

The next FEA effort was made in connection to the last of the preliminary experiments when "the Drop" had been designed, as previously seen in figure 4.16. This is also why it was used for the FEA simulation.

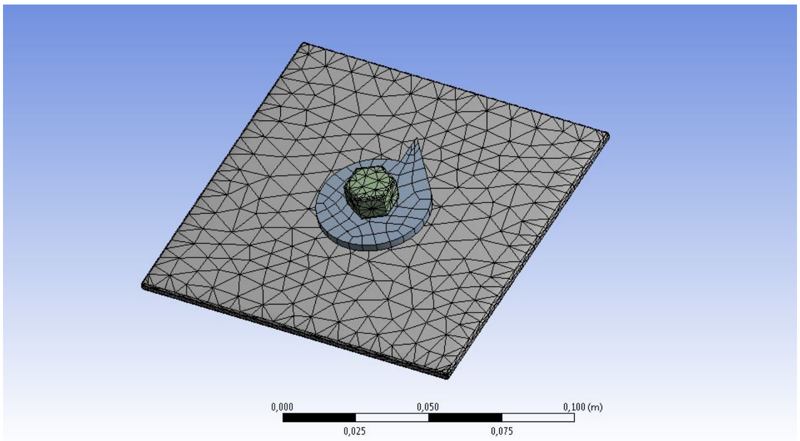

Figure 5.2: The meshed model of the Drop ready for simulation.

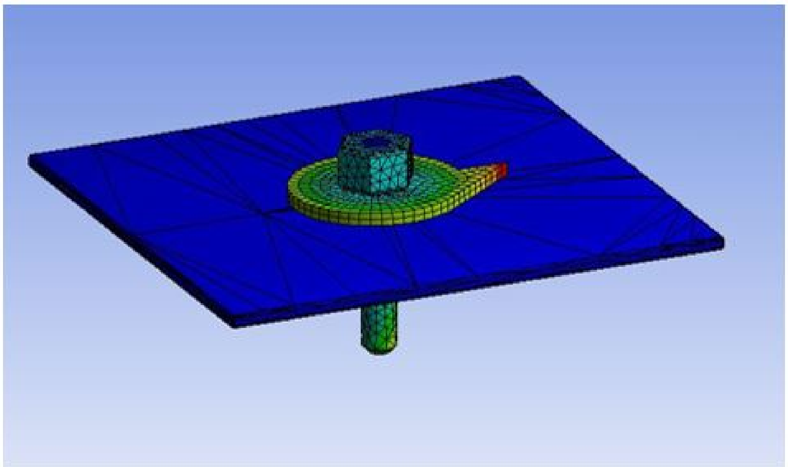

Figure 5.3: Analysis of the Drop

After a few simulation attempts a function was discovered in Ansys which allowed the user to define how the different parts would behave in relation to each other, using contact surfaces. The standard setting for the contact surfaces was "bonded", which means the two parts are locked to each other, and will for all intents and purposes act as one solid part. Since what was sought after was relative motion, it was not desirable to have them count as one object. To attain a displacement the surfaces were instead assigned "frictional" properties. In connection to these changes, another function was found and investigated, which enables contact surfaces to act as bolt threads without having to actually model them in CATIA V5. Finding the functionality was step one, understanding how to put it to work was step two. This proved difficult, which led to the project group contacted an employee at Ansys that could provide expert help.

5.3 Step 3, Final Model

After having to redesign the primary experiment after preliminary experiment 6, the final models for the FEA were created to mirror the components used in the physical tests. What followed was the simulation which closest replicated reality.

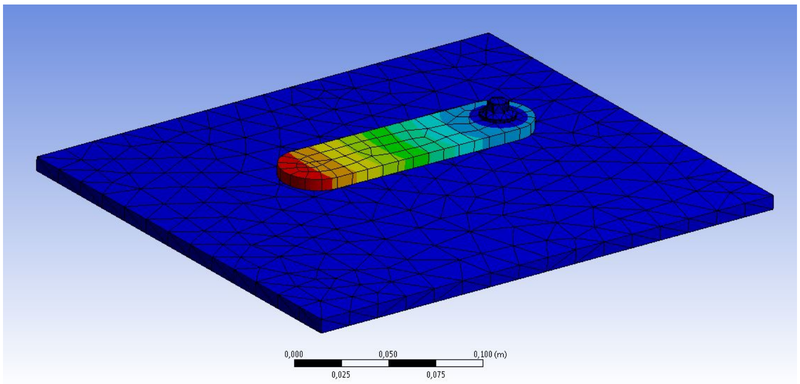

Figure 5.4: the final fem

The model was made as similar to the laser cut components used in 4.2 as possible, with exception to the thickness, which was increased to make sure the mass corresponded to that of the component with the mounted laser fixture. The contact surfaces were all assigned as frictional, with different coefficients of friction.

The simulation shows a deformation of 0.4 mm, which reflects a rotation of 0.162 degrees. This value is quite far from what was measured in reality, and the most prominent reason for this is that it only simulates a fraction of the process. After discussion with FEA-experts at both Volvo and Chalmers, the conclusion is that to model the whole sequence of events a dynamic setting is required. Furthermore, the possibility of creating a dynamic model was investigated, but ultimately rejected, since it would require enough time to make a whole new master's thesis.

6 Results and analysis

This chapter contains the results from the experiments that yielded the most relevant results. The chapter will also include an analysis of the presented results.

6.1 Primary Experiment

In this section, the results and analysis from the large DoE carried out in the primary experiment in chapter 4.2 will be presented. The primary experiment was successful, and the DoE provided a mathematical prediction formula which can be used to roughly estimate the expected rotation of a component in the experiment. The DoE also provided some insights as to which variables have the most influence on the resulting rotation.

6.1.1 JMP Effect Summary

The formula generated by the program JMP is not of much use outside the environment and setting in which the experiments were carried out. This is because of the output, rotation in degrees, is specific to the test rig and any numbers of estimated rotation in degrees from the prediction formula would only be applicable for just this test rig. This does not mean that the JMP model is without use. What can be collected and analysed are the effect summary, or weight, of the variables that were inserted into JMP. Changing parameters have a larger or smaller impact on the results depending on which one is altered, and this is summarized in the program. The effect summary from the prediction formula can be seen in figure 6.1.
The JMP effect summary was based from an attempt by the program to fit the results using a standard least square method and assigning values to the variables. A second degree factorial was selected to catch any relations that was not only connected to one variable, but to relationships between every combination of two variables as well. The highest contributor, material times bolt type, is the highest because of the following reason; The boltings performed with flange bolts and aluminium caused a massively higher rotation than all other cases. The JMP effect summary did somewhat already confirm what was established by the group before, that the material aluminium and bolt type had the most impact on the results. Lower down in the effect summary, figure 6.1, the variables mass times angular velocity can be found. It is clear from Complementary Experiment 3 in chapter 4.3.3 that angular velocity has an impact on the results. What is not clear is how changing the mass affects the results, though the theory is that a higher mass would cause the part

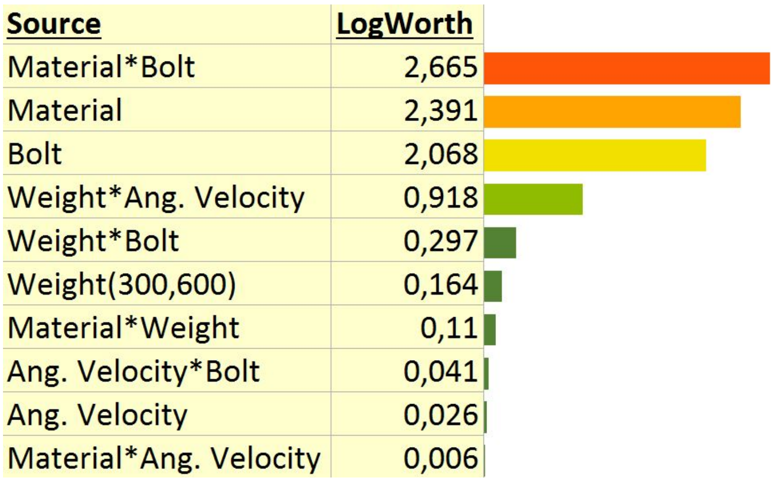

Figure 6.1: The effect summary from the program JMP of the Primary Experiment. Changing variables with larger LogWorth have a higher impact on the end result in form of rotational displacement.

not to rotate as much. The relationship mass times velocity could be a somewhat inaccurate assumption by the program based on biased data from the experiment, or an actual relationship that was not anticipated. Regardless in which case, the impact from those variables are not nearly as high as the material and the bolt variables.

6.1.2 Primary Experiment Results

The results are presented as graphs containing averages of interesting groupings in the data. The four main parameters material, mass, angular velocity and bolt type have been selected and their top three cross-relations based on the JMP effect summary are included in the data groups as well. One thing to note is that four of the results from the experiment, all four performed on aluminium components with flange bolts, showed a rotation far higher than any other previous results. This is believed to be because of the ductility of aluminium and the higher torque transferred by a flange bolt. This is an interesting effect that will be analysed and discussed later in the text, but for some of the comparisons the aluminium components will be ignored. Without omitting the extreme results, every correlations would be skewed by those few results.

6.1.2.1 Material

As seen in figure 6.2, aluminium components have by far the highest average rotation. This is mostly due to the effect seen in four out of the six aluminium plus flange bolt setups, where the metal deformed and created a grip for the bolt to turn the component much further than in all other tests.

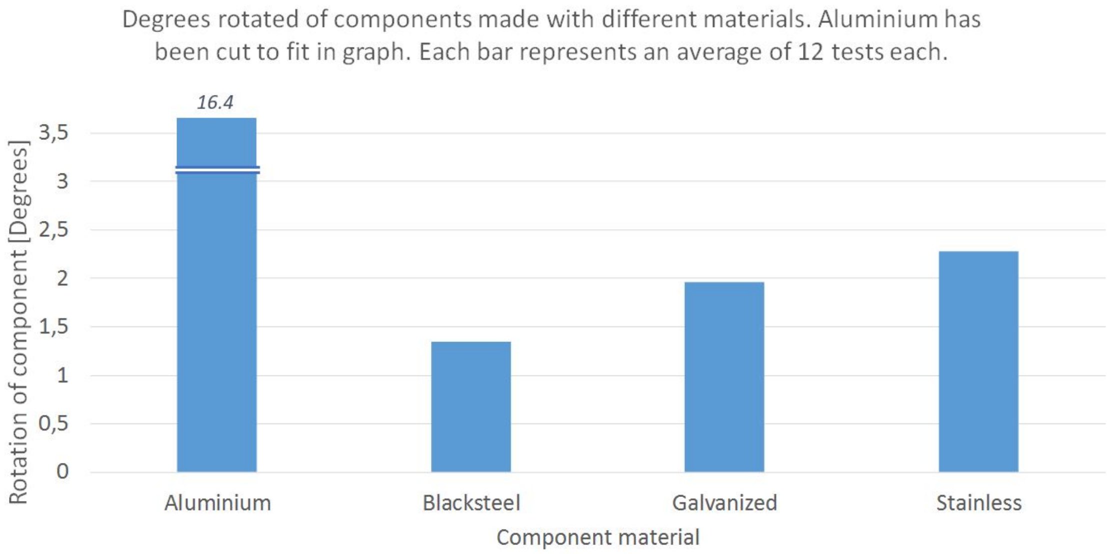

Figure 6.2: Figure shows average rotation for different component materials. Aluminium has a much higher average rotation than any other material. The other three materials show some difference in comparison, although this could be an effect of the large distribution of results.

6.1.2.2 Angular Velocity

As seen in figure 6.3, the effect that angular velocity has on the rotation is not entirely clear based on these results. Aluminium was omitted from the graph as the

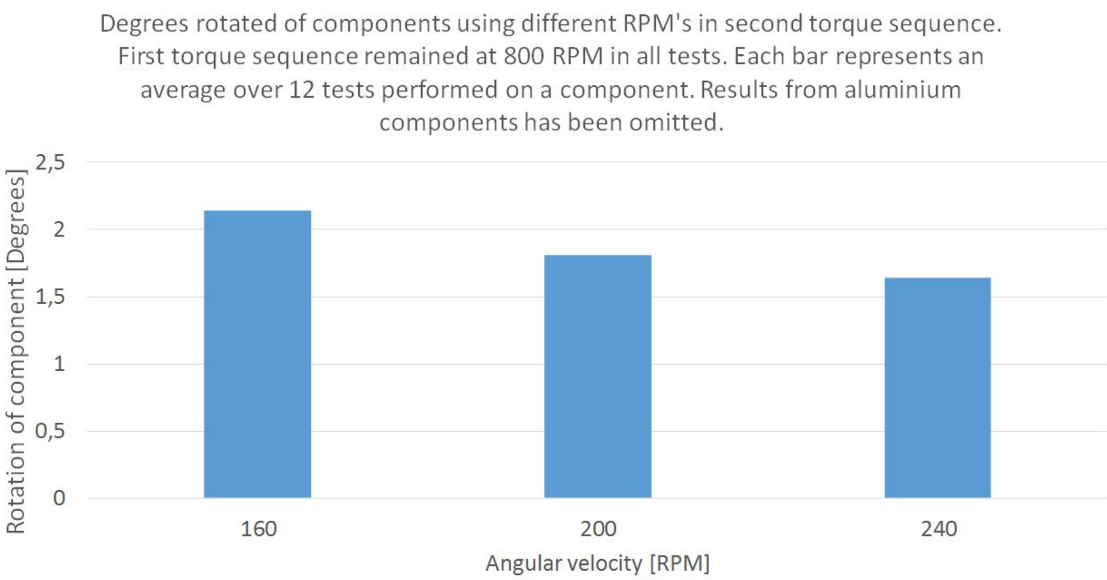

Figure 6.3: Figure shows rotation based on angular velocity. The results indicate a lower rotation when using higher angular velocities.

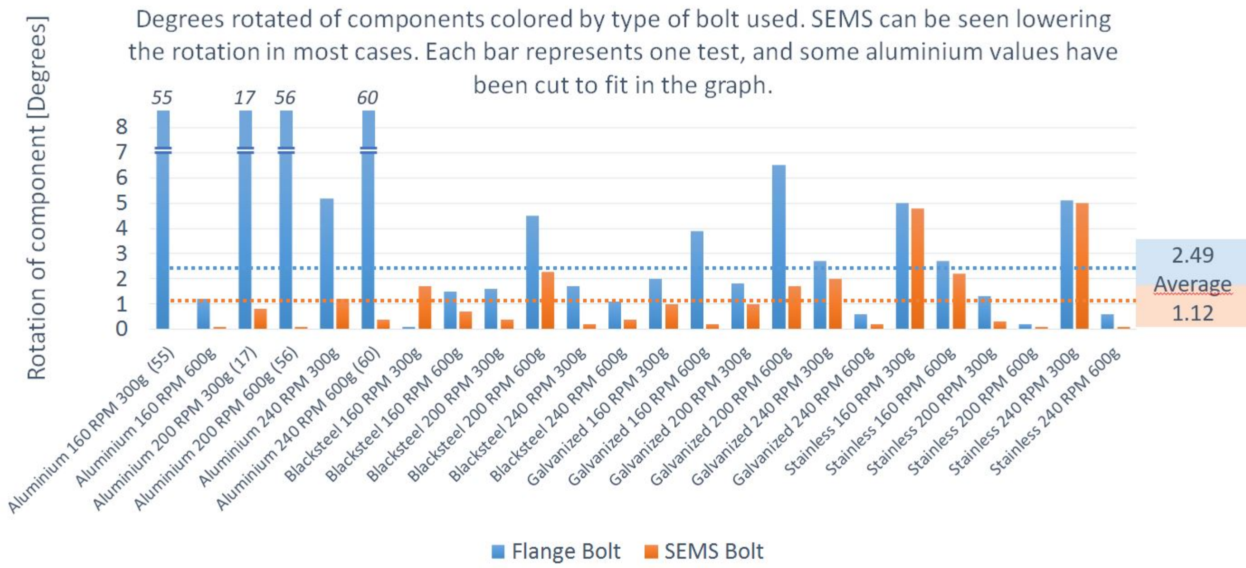

Figure 6.4: Degrees rotated of components, colored by type of bolt. The average of all tests shows a much lower rotation when using SEMS bolts.

specific material properties caused it to rotate excessively, which gave a false view of how the velocity impacted the rotation.

6.1.2.3 Bolt type

As seen in figure 6.4, using SEMS bolts instead of flange bolts is advantageous. The resulting rotation decreases in almost every case (one exception, "Blacksteel 160rpm 300g"). Worth to mention is also that the components made of aluminium, which is more ductile than the other metals, experienced a rotation 75 times higher when using a flange bolt than SEMS in average. The average rotation of a component, when not including the four extreme aluminium results, was 2,49 degrees for flange, and 1,12 degrees for SEMS bolt. This equals to a factor 2,2 less rotation with SEMS than with flange.

6.1.2.4 Mass

From the figure 6.5, there is a slight indication that a heavier component could be beneficial in reducing the rotation. However, since the difference between 300g and 600g was quite small (0.4 degrees), another experiment concerning mass was carried out. This can be found in 4.3.4. This complementary experiment did not give a clear correlation between the mass and the rotation, and the conclusion can seen in chapter 7.7.

6.1.2.5 Mass VS Bolt type

The results as seen in figure 6.6, show a rather unusual tendency that could just be a result from the large distribution or an effect that is explained in chapter 6.3.2.

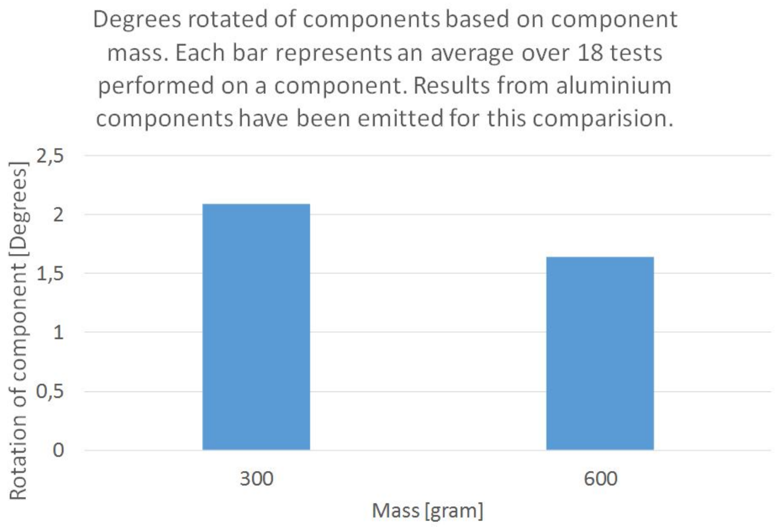

Figure 6.5: Figure shows average rotation for different masses. The averages show slightly lower rotation of heavier components.

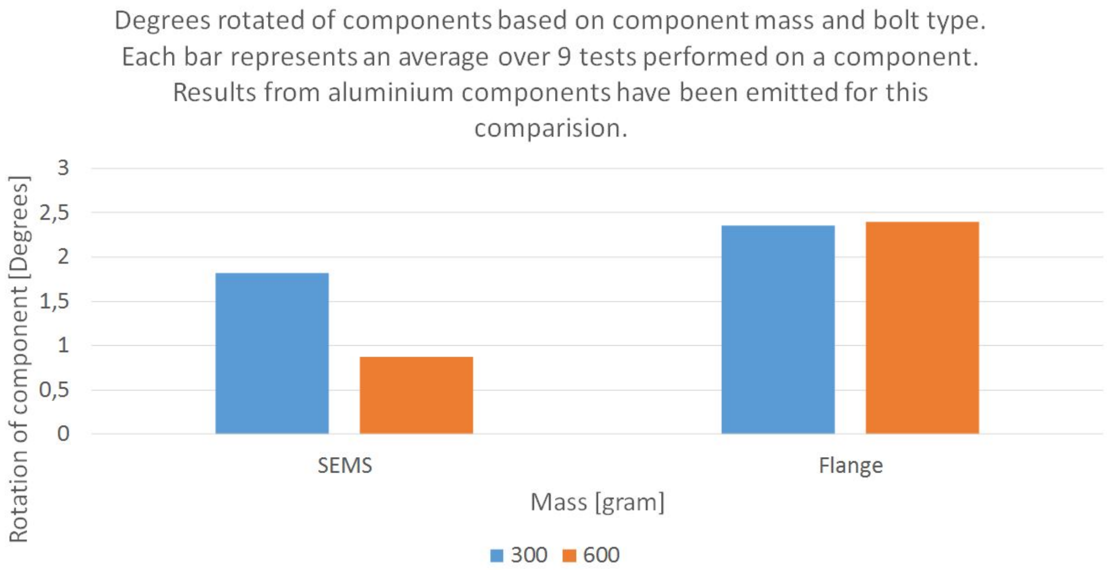

Figure 6.6: Figure shows average rotation for different masses divided by bolt type. The results indicate that SEMS bolts rotate heavier component less than flange, which might not be affected as much by the mass of the component. This could still be because of the high variance in the results.

6.1.2.6 Material VS Bolt type

6.1.2.7 Mass VS Angular Velocity

The data presented in figure 6.8 shows few indications of anything other than random data. If more tests showed the same results, there could be a case made for a local

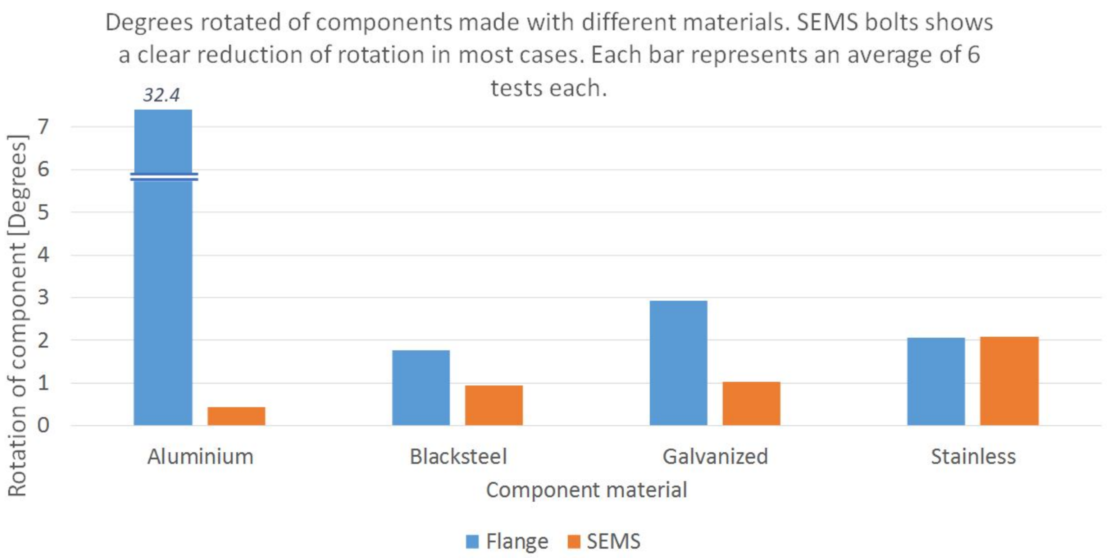

Figure 6.7: Figure shows rotation based on material and bolt type. Most materials showed a decrease in rotation from changing from flange to SEMS bolts.

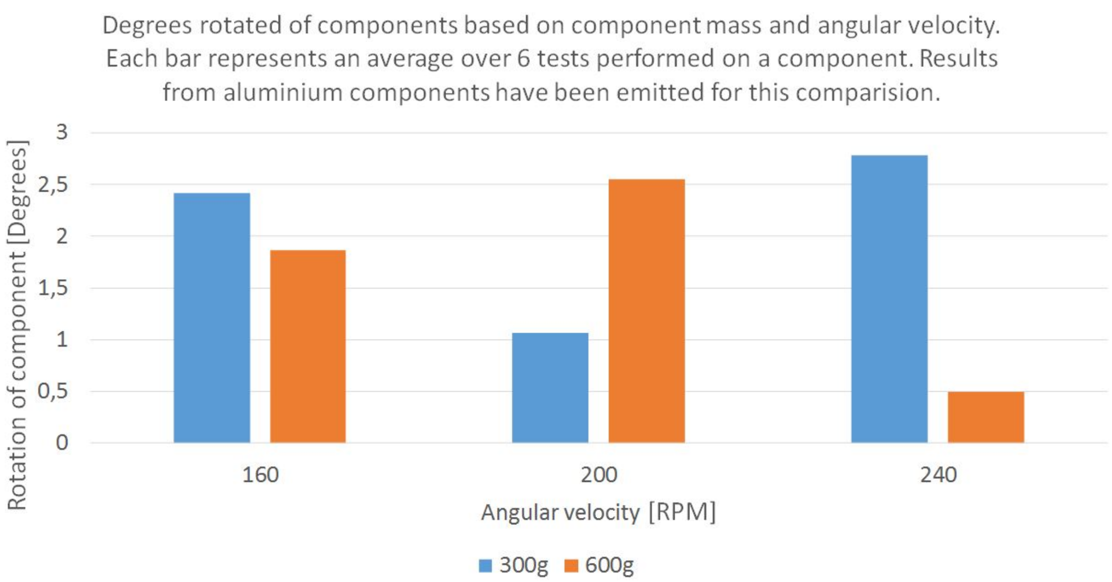

Figure 6.8: Figure shows rotation based on angular velocity and mass. No obvious relation was found when searching for a link between angular velocity and mass of the components.

low at 300g curve and a local high at 600g both at 200 RPM.

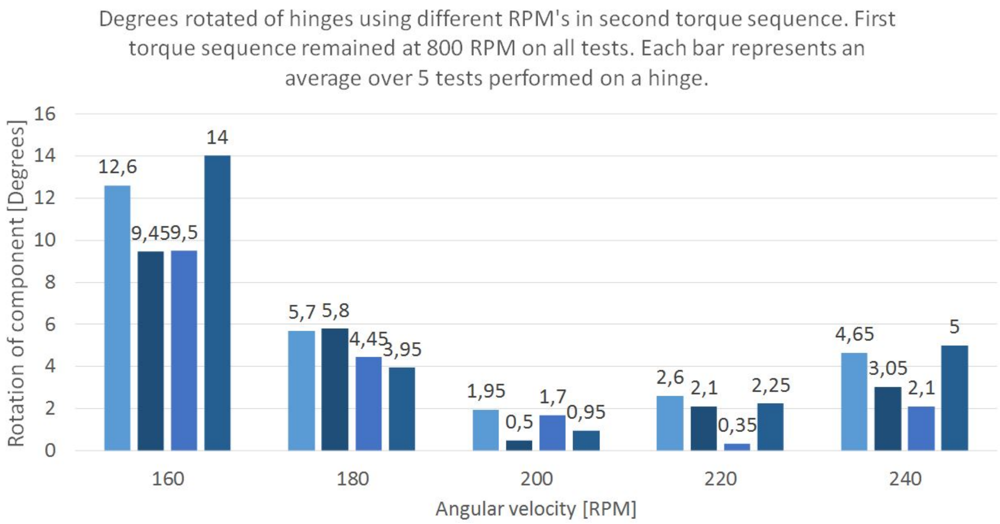

Figure 6.9: Figure shows rotation from different angular velocities. Results indicate a strong tendency that angular velocities around 200 RPM generates the least rotation.

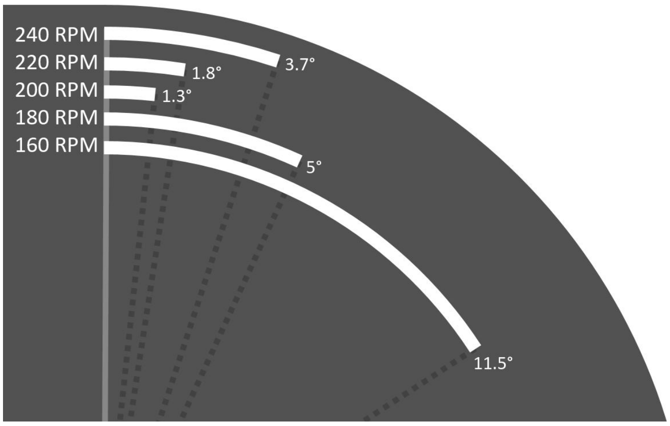

Figure 6.10: Complementary Experiment 3 results shown as rotation on a plane. The arcs angles have been exaggerated by a factor 5 for a clearer visual representation.

6.2 Complementary Experiment 3 results

Here follows the results from complementary experiment 3. For more information on how the experiment was performed, see chapter 4.3.3.

The results shown in figure 6.9 are very indicative of a local low in rotation around 200 which can be correlated with the results found in Complimentary Experiment 1 found in chapter 4.3.1. An optimal angular velocity for lowering rotation seems to be around 200-220 RPM. Another way to visualize the results can be seen in figure 6.10, where the bars have been replaced with arcs.

6.3 Analysis of the results

This chapter will present a number of hypotheses as to why some of the experiments produced their results. These are only theories as to what happens in the bolting sequence and have not been further tested.

6.3.1 Friction and "total grip"

As seen in the results in chapter 6.1.2.1, the different materials generated a differing range of rotation, aluminium in particular. One theory is, that a combination of friction and material ductility affects the outcome. A higher friction causes the component to rotate more, and a higher ductility increases the chance of a "total grip" to occur. The total grip effect can be seen in some of the aluminum tests when using a flange bolt. As to why this effect did not occur when using a SEMS-bolt, it could be argued that the larger area that distributed the pressure under the SEMS washer was enough to decrease the force per square millimeter to where the material did not deform. The other effect could be that the material still deforms, but the friction is still lower between the head of the bolt and the washer. This would mean that even if the washer burrows itself in the metal, the bolt head still slides on the washer until it is fully bolted.

6.3.2 Heavier components with flange and SEMS bolts

This theory is based on the difference between SEMS and flange bolts results when filtering the results by mass as well. The theory was initially that a heavier component would move less than a lighter component, as indicated in figure 6.5. The rotation of the components seems to be much more unaffected by changing the mass when using flange than when using SEMS bolts, see figure 6.6. The theory behind this phenomenon, supposed that it is not just a random abnormality in the data, is as follows; the bolt underhead not only transfers a torque, but a certain speed as well. Even if the grip between the component and the bolt was perfect and instant when bolting, the component would not rotate faster than the speed that the bolt is rotating at. If the case is that both the 300g and the 600g components reach the same rotational speed at the same time while being bolted, the only difference between the components when slowing down is the angular momentum. A heavier component takes longer time to slow down, and this, travels further than a light component. This effect, if existing, might only occur at a certain interval of mass and torque relations. The theorized reason as to why the SEMS bolts do not have this effect is that the washer delays or buffers the speed that would otherwise be transferred from bolt to component.

7

Conclusions

After numerous experiments and analyses, the project resulted in a number of conclusions. In this chapter, the conclusions will be presented and suggestions will be made on how they could be used for further development or research.

7.1 SEMS

What has been the most apparent during the analysis of the experiment, especially the DoE, is the effect of replacing the flange bolts with SEMS bolts. Using these bolts with a pre-assembled washer has shown a clear difference in rotation of the components. Solely observing aluminium, the resulting rotation using a SEMS bolt can be reduced by a factor of 75. Considering the other materials instead, the rotation is reduced by a factor of 2.2.

Recommendation: Using the results and analysis which have been presented in this master's thesis, the implementation of SEMS bolts in the assembly should be an obvious choice. Since the bolts which were used and experimented with had the same dimensions and coating, and also already exists in the Volvo database, the only reason not to make the change to these bolts would be if they were considerably more expensive. Yet another reason to introduce SEMS bolts is the increasing number of car components made from aluminium and plastic, which, as a result of the material being softer, has a higher risk of rotating.

7.2 Hardness

Yet another conclusion which can be drawn, in close connection to SEMS, is how the hardness of the material affects the rotation of the component. The results from the primary experiments show that aluminium which is softer than the other tested materials had a considerably larger rotation in comparison. This was especially the case when using the flanged bolt, which digs into the component.

Recommendation: When bolting a component made from a more ductile material (aluminum, plastic, etc.), the recommendation is to take precautions to counteract rotation. One way to do this is as mentioned earlier with a SEMS bolt.

7.3 Angular velocity

The correlation of angular velocity in the bolting process and the rotation of the component has been difficult to map out. It has required several complementary experiments to acquire reliable results to analyze. However, as shown in figure 6.9, the data points to a correlation similar to that of a second degree equation with a local minimum between 200-220 RPM.

Recommendation: When the hood of the car is bolted to the car body through the hinges, which has been the focus of this project, the angular velocity of the bolting is 200 RPM. This is appropriate according to the results form the experiments. If Volvo in the future would notice the rotation of another component, it would be potentially better to investigate if the velocity is at the appropriate interval, and if not, to change it.

7.4 Lubrication

When considering lubrication with oil, two different effects can occur; oil applied between bolt head and component transferred a lower amount of torque, and oil applied between the component and the surface plate increased the transferred rotation substantially. None of these results are very surprising, since friction has a substantial impact in the rotation of the component. However, another phenomenon was also observed using the oil. Depending on the amount of oil and conditions, one of three different cases can be observed, the fluid film, the boundary lubrication, and vacuum state, explained in chapter 4.3.2. This emphasizes the importance of a controlled process when applying the lubrication.

Recommendation: Since the introduction of new chemicals in the car body shop is very difficult, the process of applying oil between bolt head and component is practically impossible. However, the second alternative, to eliminate any excess lubricant from the car body prior to bolting and, thus, reducing rotation should be easier and could greatly decrease the rotation.

7.5 Off Center

During the execution of the preliminary experiments, the off-center effect was observed. This lead to an experiment investigating the effect of not aligning the hole of the component to the hole in the surface plate. This effect was, however, very difficult to map, and was very irregular, which is why it was omitted from the primary experiment.

Recommendation: Even though this variable was neglected in the primary experiment, it could very well be worth to investigate further in the future. Since a robust design process requires some holes to be larger to account for tolerances, the off-center effect will be present. This is why Volvo is recommended to investigate this phenomenon further.

7.6 The Volcano Effect

One phenomenon which was observed early in the project was the deformation of the thinner support plate when the nut was pulled upwards from the axial tension. This was an unforeseen effect, and not one which was to be included in the primary experiment. This is why it was eliminated by using a thicker support plate. The effect has also been noted in the production of the cars, where it makes the adjustment of bolted parts more difficult, since the component tends to realign with the deformation.

Recommendation: The effect was omitted from the experiment, since including it would have resulted in a rotation which had been inappropriate to include in a model or simulation. The recommendation is, however, to investigate the aspect further, since the effect was significant and since it has been observed in production (Dag Johansson 2017, oral communication, April).

7.7 Inertia

The conclusion from experimenting with the mass, and by that, inertia, of the component is unclear at best. In the primary experiment a difference in rotation is visible. However, the variation in results between the materials was significant enough that a complementary experiment focusing completely on inertia was designed. The results from this experiment were also extremely distributed, so much that a correlation was not found.

Recommendation: When it comes to further investigations on the relation between mass and rotation, it has been deemed to not be worth excessive time or resources. Since the ambition will always be to reduce the mass of the vehicle to improve, for example, fuel consumption, it seems unreasonable to increase the mass of a component for the sole advantage of reduced rotation.

7.8 Torque

Torque was a variable which was planned to investigate but was ultimately omitted. Since the bolting torque depends on the parameters of the bolt, it made no sense to change this at all, even to reduce rotation.

Recommendation: Even though the torque investigation was skipped from the experiments, it could be an important part in the future work with rotation. For example, with the development of a functional dynamic FE model, data from the change of bolting torque till be required to accurately simulate the bolting process.

7.9 Repeatability

The distribution of the results are very wide, even when new components, bolts and nuts are used. The system is very unpredictable, and there are also variables which are difficult to control such as: keeping the nutrunner in the same position for each test, positioning of the component relative to bolt throughout the process, coarsness of surfaces etc. This can be seen when comparing two results of the angular velocity tests in figure 7.1.

Recommendation: To achieve a statistical relevant impression of how the system acts, a substantial number of tests must be carried out. This was shown to be the case especially in the angular velocity experiment shown in the above graph.

7.10 FEA

The finite element analysis was of little use in prevention of the actual problem, but it could be a good starting point from which more development can be made. The insights made during this project, such as defining contact surfaces, should make further work with this concept easier.

Recommendation: The recommendation when it comes to the finite element analysis is to continue the development, and investigate the possibilities to create dynamic model.

7.11 Summary of conclusion

In order to achieve as little rotation as possible when bolting components, SEMS bolts should be used. The optimal angular velocity on the nutrunner is around

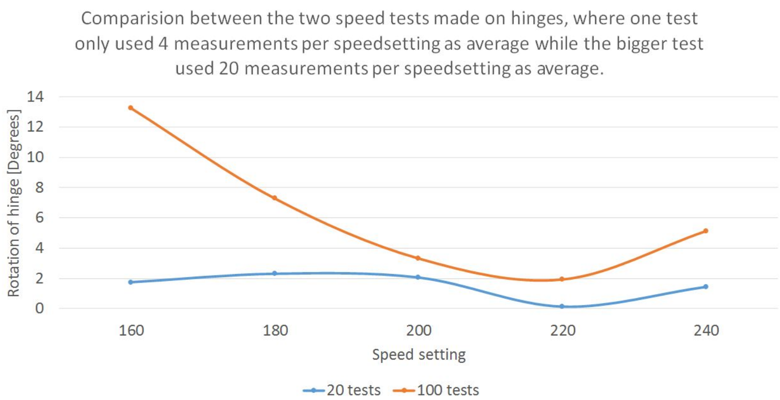

Figure 7.1: Comparison of the smaller angular velocity experiment and the larger one. When measuring 20 times instead of 100, a large part of the total picture was not gathered.

200 RPM, and any oil between the bolted components should be removed before bolting. Oil between component and underhead of bolt could be applied as well, even though this could change the final axial tension which should be closely monitored. Components made from more ductile materials, such as aluminium, have a chance of increased rotation compared to more stiff materials. As for future recommendations, off-center, the "volcano effect" and creating a dynamic model of the bolting sequence should be more thoroughly investigated.

Bibliography

[1] Nils Kinch. Managing Strategic Illusions The Volvo Strategy in Retrospett. http://uu.diva-portal.org/smash/get/diva2:128556/FULLTEXT01.pdf.

[2] Our Company's Core Values | Volvo Cars, 2017-04-28. http://www.volvocars.com/intl/about/our-company/our-company-at-a-glance/core-values.

[3] P.E Ralph S. Shoberg. Engineering fundamentals of threaded fastener design and analysis, 2000. http://www.hexagon.de/rs/engineering fundamentals.pdf.

[4] *3-2-1 Positioning*, Taken from webpage: 2017-05-10. http://www.me.iitb.ac.in/ ramesh/courses/ME338/fixturing.pdf.

[5] *Power Focus 4000-G-HW : Controller for electrical assembly tools*, Taken from webpage: 2017-04-24. http://www.atlascopco.com/lyus/products/assembly-tools/1401262/1432629/.

[6] *ToolsTalk Power Focus : Software*, Taken from webpage: 2017-04-24. http://www.atlascopco.com/ttus/products/assembly-tools/product/1472219/.

[7] *JMP : Software*, Taken from webpage: 2017-04-24. https://www.jmp.com/en_us/home.html.

[8] Ansys Workbench, 2017-02-24. http://www.ansys.com/.

[9] W. Brian Rowe. *Hydrostatic, Aerostatic and Hybrid Bearing Design*, 2012. https://books.google.se/books?id=9EKsLj-nj7UC&pg=PA1&redir_esc=y#v=onepage&q&f=false.

[10] *Tensor ETV DS72-30-10: Electric nutrunner specifications*, Taken from webpage: 2017-04-24. http://www.atlascopco.com/mgus/products/tensor-etv-ds72-30-10/product/1459431/.

[11] *Tensor ETV DS92-370-HAD: Electric nutrunner specifications*, Taken from webpage: 2017-04-24. http://www.atlascopco.com/mgus/products/assembly-tools/product/1459503/.

[12] *Stainless Steel data*, Taken from webpage: 2017-04-27. http://www.valbrunanordic.se/wp-content/uploads/2014/10/EN_1_4404_-1408_Valbruna_Nordic_svenska.pdf.

[13] *Aluminium data*, Taken from webpage: 2017-04-27. http://www.aalco.co.uk/datasheets/Aalco-Metals-Ltd_Aluminium-Alloy-5754-H22-Sheet-and-Plate_153.pdf.ashx.

[14] *Black steel data*, Taken from webpage: 2017-04-27. https://www.ssab.com/products/brands/ssab-domex-structural-steel/products/ssab-domex-355mc.

[15] *Galvanized steel data*, Taken from webpage: 2017-04-27. http://www.emw-stahlservice.de/fileadmin/redakteur/EMW/DOWNLOAD/PDFs_Einzelseiten/Katalog-05-11/Hot-dip-galvanized-sheet.pdf.

A

Appendix

A.1 Technical Specifications: Tensor ETV DS72-30-10 800rpm

- Model type Angle
- Speed 800 r/min
- Weight 1.4 kg
- Torque range 9 - 35 Nm
- Length 412 mm
- CS distance 13.5 mm
- Sound standard ISO15744
- Sound pressure <70 dB(A)
- Vibration standard ISO28927-2
- Vibration value <2.5 m/s^2

Source for this data can be found at Atlas Copcos official webpage[10].

A.2 Technical Specifications: Tensor ETV DS92-370-HAD 170rpm

- Model type Angle
- Speed 170 r/min
- Weight 8.3 kg
- Torque range 95 - 370 Nm
- Length 661 mm
- CS distance 35 mm
- Sound standard ISO15744
- Sound pressure <70 dB(A)
- Vibration standard ISO28927-2
- Vibration value <2.5 m/s^2

Source for this data can be found at Atlas Copcos official webpage[11].

A.3 Material data

The material data are in the next pages presented in the following order, with sources cited next to each metal:

- Stainless steel [12]
- Aluminium [13]
- Black steel [14]
- Galvanized Steel [15]

ValbrunaNordic

Standard Cr-Ni-Mo Austenitic Stainless Steel
EN 1.4404/ 1.4401 - ASTM 316 /316 L
MAXIVAL®

A stainless austenitic steel

Typical analysis %	C	Cr	Ni	Mo
EN 1.4404	0,03	17	11	2,2
Delivery condition	Solution annealed			

Mechanical properties

Values for solution annealed condition acc. to EN 10272
at room temperature

Tensile strength Rm	N/mm^2	520 - 700
Proof strength Rp_{02}	N/mm^2	min 210
Elongation A_5	%	min 45
Impact energy KV	J/cm^2	Min 100
Hardness	HB	Max 215

Cold-worked material:
The maximum HB-values may be raised by 100 HB or the Tensile strength value may be raised by 200 N/mm^2 and the Elongation value lowered to 20 % for bars ≤ 35 mm.

Physical properties acc. to EN 10088

Temperature ° C	20	100	200	300	400	500
Density kg/dm^3	8					
Modulus of elasticity E GPa	200	194	186	179	172	165
Mean coeff. of thermal expansion 20° C –Temp. $x10^{-6} \cdot K^{-1}$	-	16,0	16,5	17,0	17,5	18,0
SpecificThermal Capacity $W/m \cdot K$	15					
Electrical Resistivity $\Omega \cdot mm^2/m$	0,75					
Specific heat $J/kg \cdot K$	500					

EN 1.4404 MAXIVAL® is a molybdenum-containing austenitic stainless steel intended to provide improved corrosion resistance relative to the standard Cr-Ni steel.The addition of molybdenium provides improved resistance to pitting and crevice corrosion in environments containing chlorides or other halides.

It is non-magnetic in the annealed condition but may become slightly magnetic as a result of cold-working or welding.

MAXIVAL® indicates that the steel has been modified in order to obtain good machinability.

Design features

⇒ Enhanced corrosion resistance compared to standard Cr-Ni grades
⇒ Very good machinability
⇒ Excellent formability and weldability
⇒ Excellent impact strength

Corrosion resistance

EN 1.4404 have a versatile corrosion resistance and is suitable for a wide range of applications. The grades with higher molybdenium content (1.4432,1.4436) have somewhat enhanced corrosion resistance compared with grades with lower Molybdenium content (1.4404).
Also the grades have a good resistance to many organic and inorganic chemicals.

Austenitic stainless steels are sensitive to intergranular corrosion due to grain boundary precipitation of chromium carbides, which can occur in the temperature range 550 - 850°C.
It is not a common problem for modern stainless steels since the carbon content is generally kept at a low level. Steels with low carbon content (0,02%) have good resistance to intergranular corrosion.
The resistance to pitting and crevice corrosion can be enhanced by increasing the content of chromium. Molybdenium and nitrogen. These grades have a significantly better resistance to these types of localised corrosion than the standard Cr-Ni grades.
The grade EN 1.4404 and like the standard Cr-Ni steels are susceptible to stress corrosion cracking. Critical service conditions, i. e. applications subjected to combinations of tensile stresses, temperatures above about 50°C and solutions containing chlorides, should be avoided.

Aluminium Alloy
5754 - H22 Sheet and Plate

aalco®

SPECIFICATIONS

Commercial	5754
EN	5754

Aluminium 5754 has excellent corrosion resistance especially to seawater and industrially polluted atmospheres.
It has higher strength than 5251. This high strength makes 5754 highly suited to flooring applications.

Applications
5754 is typically used in:
~ Treadplate
~ Shipbuilding
~ Vehicle bodies
~ Rivets
~ Fishing industry equipment
~ Food processing
~ Welded chemical and nuclear structures

Please note that Mechanical Properties shown are for H22.

CHEMICAL COMPOSITION

BS EN 573-3:2009
Alloy 5754

Element	% Present
Magnesium (Mg)	2.60 - 3.60
Manganese + Chromium (Mn+Cr)	0.10 - 0.60
Manganese (Mn)	0.0 - 0.50
Silicon (Si)	0.0 - 0.40
Iron (Fe)	0.0 - 0.40
Chromium (Cr)	0.0 - 0.30
Zinc (Zn)	0.0 - 0.20
Titanium (Ti)	0.0 - 0.15
Others (Total)	0.0 - 0.15
Copper (Cu)	0.0 - 0.10
Other (Each)	0.0 - 0.05
Aluminium (Al)	Balance

ALLOY DESIGNATIONS

Alloy 5754 also corresponds to the following standard designations and specifications ***but may not be a direct equivalent***:

A95754
Al Mg3
Al 3.1Mg Mn Cr
AW-5754

TEMPER TYPES

The most common tempers for 5754 aluminium are shown below with H114 & H111 being the most common treadplate temper

- O - Soft
- H111 - Some work hardening imparted by shaping processes but less than required for H11 temper
- H22 - Work hardened by rolling then annealed to quarter hard
- H24 - Work hardened by rolling then annealed to half hard
- H26 - Work hardened by rolling then annealed to three-quarter hard

SUPPLIED FORMS

Alloy 5754 is typically supplied as treadplate

- Plate
- Sheet

GENERIC PHYSICAL PROPERTIES

Property	Value
Density	2.66 g/cm³
Melting Point	600 °C
Thermal Expansion	24 x10^{-6} /K
Modulus of Elasticity	68 GPa
Thermal Conductivity	147 W/m.K
Electrical Resistivity	0.049 x10^{-6} Ω .m

[1 OF 2] CONTINUED

SSAB Domex®

SSAB Domex 355MC

General Product Description

SSAB Domex 355MC meets or exceeds the requirements of S355MC in EN 10149-2. Upon agreement, it can be delivered as double certified. This double certification will enable producers of steel structures, in accordance with EN 1090, to use SSAB Domex 355MC in their CE-marked final component or structure.

Dimension Range

SSAB Domex 355MC is available in thicknesses of 1.80-16.00 mm and widths up to 1860 mm as coils, slit coils and as cut to length in lengths up to 16 meters.

Mechanical Properties

Thickness (mm)	Yield strength R_{eH} (min MPa)	Tensile strength R_m (MPa)	Elongation A_{80} [1] (min %)	Elongation A_5 [2] (min %)	Min .inner bending radius for a 90° bend
1.80- 3	355	430- 550	19	23	0.2 xt
3.01- 6	355	430- 550		23	0.3 xt
6.01- 16	355	430- 550		23	0.5 xt

The mechanical properties are valid in the longitudinal direction.
Bending properties for both longitudinal and transversal direction
1) A80 value applies for thicknesses < 3.00 mm
2) A_5 value applies for thicknesses ≥ 3.00 mm

Impact Properties

Designation	Test temperature	Min. impact energy for longitudinal Charpy V- notch test
B	-	-
D	-20 °C	40 J
E	-40 °C	27 J

Impact testing according to ISO 148-1 is performed on thicknesses ≥ 6mm. The specified minimum value corresponds to a full-size specimen.

Chemical Composition (Ladle analysis)

C (max %)	Si (max %)	Mn (max %)	P (max %)	S (max %)	Al_{tot} (min %)	Nb (max %)	V (max %)	Ti (max %)
0.10	0.03[1)]	1.50	0.025	0.010	0.015	0.09[2)]	0.20[2)]	0.15[2)]

1) SSAB Domex 355MC meets the requirements of category A (thin coatings) for hot-dip zinc-coating in EN 10149-2. Category B for thick coatings is available on request (Si 0.15-0.21%).
2) The sum of Nb, V and Ti is max 0.22%.
The steel is grain refined.

Carbon Equivalent Values

Thickness (mm)	1.80 - 16
CEV Typical	0.17
CET Typical	0.13

$$CET = C + \frac{Mn + Mo}{10} + \frac{Cr + Cu}{20} + \frac{Ni}{40}$$

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

SSAB

X. Hot-dip galvanized sheet

EMW delivery range	Coils	Slit strip	Cut-to-size sheet	
Thicknesses	from 0.30 – 4.50 mm	from 0.30 – 4.50 mm	from 0.40 – 3.00 mm	
Widths	up to 1,850 mm	up to 1,850 mm	up to 1,530 mm	up to 1,850 mm
Lengths	---	---	up to 8,000 mm	up to 3,000 mm
Tolerances	Acc. to DIN EN 10143; finer tolerances available by arrangement.			

Soft grades – hot-dip coated steel strip and sheet made of soft steels acc. to DIN EN 10346 : 2009

Mechanical properties (lat.)

Steel grade/type		Symbol for the type of surface finishing	Elongation limit R_e [1] MPa	Tensile strength R_m MPa	Fracture elongation A_{80} [2] %	Vertical anisotropy r_{90}	Work hardening exponent n_{90}
Code	Material no.				min.	min.	min.
DX51D	1.0226	+Z, +ZF, +ZA, +AZ, +AS	–	270 – 500	22	–	–
DX52D	1.0350	+Z, +ZF, +ZA, +AZ, +AS	140 – 300 [3]	270 – 420	26	–	–
DX53D	1.0355	+Z, +ZF, +ZA, +AZ, +AS	140 – 260	270 – 380	30	–	–
DX54D	1.0306	+Z, +ZA	120 – 220	260 – 350	36	1.6 [4]	0.18
DX54D	1.0306	+ZF	120 – 220	260 – 350	34	1.4 [4]	0.18
DX54D	1.0306	+AZ	120 – 220	260 – 350	36	–	–
DX54D	1.0306	+AS	120 – 220	260 – 350	34	1.4 [4,5]	0.18 [5]
DX55D [6]	1.0309	+AS	140 – 240	270 – 370	30	–	–
DX56D	1.0322	+Z, +ZA	120 – 180	260 – 350	39	1.9 [4]	0.21
DX56D	1.0322	+ZF	120 – 180	260 – 350	37	1.7 [4,5]	0.20 [5]
DX56D	1.0322	+AS	120 – 180	260 – 350	39	1.7 [4,5]	0.20 [5]
DX57D	1.0853	+Z, +ZA	120 – 170	260 – 350	41	2.1 [4]	0.22
DX57D	1.0853	+ZF	120 – 170	260 – 350	39	1.9 [4,5]	0.21 [4]
DX57D	1.0853	+AS	120 – 170	260 – 350	41	1.9 [4,5]	0.21 [4]

Chemical composition (melt analysis) of soft steels for cold forming

Steel grade/type		Symbol for the type of surface finishing	Chemical composition Percentage by mass %					
			C	Si	Mn	P	S	Ti
Code	Material no.		max.	max.	max.	max.	max.	max.
DX51D	1.0226	+Z, +ZF, +ZA, +AZ, +AS	0.18	0.5	1.20	0.12	0.045	0.30
DX52D	1.0350	+Z, +ZF, +ZA, +AZ, +AS	0.12	0.5	0.60	0.10	0.045	0.30
DX53D	1.0355	+Z, +ZF, +ZA, +AZ, +AS	0.12	0.5	0.60	0.10	0.045	0.30
DX54D	1.0306	+Z, +ZF, +ZA, +AZ, +AS	0.12	0.5	0.60	0.10	0.045	0.30
DX55D	1.0309	+AS	0.12	0.5	0.60	0.10	0.045	0.30
DX56D	1.0322	+Z, +ZF, +ZA, +AS	0.12	0.5	0.60	0.10	0.045	0.30
DX57D	1.0853	+Z, +ZF, +ZA, +AS	0.12	0.5	0.60	0.10	0.045	0.30

Z = Hot-dip galvanized **ZF** = Galvannealed **ZA** = Galfan **AZ** = Galvalume **AS** = Hot-dip aluminised

[1] If the yield point is not pronounced, the values for the 0.2 % elongation limit ($R_{p0.2}$), apply. If pronounced, the values for the lower yield point (R_{eL})apply.
[2] Reduced minimum values for fracture elongation apply for product thicknesses of t > 0.50 mm (4 units less) and for 0.50 mm < t ≤ 0.70 mm (2 units less).
[3] This value only applies for cold re-rolled products (surface groups B and C).
[4] For t > 1.5 mm, the r_{90} value is reduced by 0.2.
[5] For t ≤ 0.70 mm, the r_{90} value is reduced by 0.2 and the n_{90} value by 0.01.
[6] Please note the minimum fracture elongation value for DX55D + AS products, which does not follow the usual system.
DX55D + AS products are marked according to the best heat resistance.

Construction steels – continuously hot-dip coated steel strip and sheet made of construction steels acc. to DIN EN 10346 : 2006

Mechanical properties (long.)						Chemical composition (Melt analysis)				
Steel grade/type		Symbol for the type of surface finishing	Elongation limit $R_{p0.2}$ [1] MPa	Tensile strength R_m [2] MPa	Fracture elongation A_{80} [3] %	Percentage by mass %				
						C	Si	Mn	P	S
Code	Material no.		min.	min.	min.	max.	max.	max.	max.	max.
S220GD	1.0241	+Z, +ZF, +ZA, +AZ	220	300	20	0.20	0.60	1.70	0.10	0.045
S250GD	1.0242	+Z, +ZF, +ZA, +AZ, +AS	250	330	19	0.20	0.60	1.70	0.10	0.045
S280GD	1.0244	+Z, +ZF, +ZA, +AZ, +AS	280	360	18	0.20	0.60	1.70	0.10	0.045
S320GD	1.0250	+Z, +ZF, +ZA, +AZ, +AS	320	390	17	0.20	0.60	1.70	0.10	0.045
S350GD	1.0529	+Z, +ZF, +ZA, +AZ, +AS	350	420	16	0.20	0.60	1.70	0.10	0.045
S550GD	1.0531	+Z, +ZF, +ZA, +AZ	550	560	–	0.20	0.60	1.70	0.10	0.045

[1] If the yield point is pronounced, the values for the upper yield point (R_{eH}) apply.
[2] For all steel grades, with the exception of S55OGD, a range of 140 MPa can be expected for tensile strength.
[3] Reduced minimum values for fracture elongation apply for product thicknesses of t > 0.50 mm (4 units less) and for 0.50 mm < t ≤ 0.70 mm (2 units less).