

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**DESIGN AND IMPLEMENTATION OF ENERGY
ABSORPTION TEST APPARATUS**

by
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İZMİR

DESIGN AND IMPLEMENTATION OF ENERGY ABSORPTION TEST APPARATUS

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**by
Alif Ngimbi DIAMBU**

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İZMİR**

M.Sc THESIS EXAMINATION RESULT FORM

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DESIGN AND IMPLEMENTATION OF ENERGY ABSORPTION TEST APPARATUS

ABSTRACT

Tests are very important in all disciplines. Any product before being put on the market undergoes a series of tests to ensure its competitiveness against the environment that will host it for the quality, security of persons and goods. In mechanics, the tests allow making a preliminary study on the physical behavior of materials. Machinery parts which are subjected to shocks and dynamic loads during their operation must have good energy absorption and good performance. Therefore, to decide on the type of material to use in those components, testing is very important. Among the test types and devices known in the world of science and technology, the rebound resilience test machine to determine the bounciness (elasticity) of rubber having a Shore-A hardness under impact stress represents a negligible handle. The number of manufacturers is few and the literature does not say much about it. This study focuses on designing a rebound resilience test machine for testing rubber and rubber-like materials using the commercial software SolidWorks. The angular position of the pendulum is acquired using Arduino board via Matlab and a Schob type pendulum according to the standard DIN 53512 and its equivalents (ISO 4662 and ASTM D7121).

Keywords: Rebound resilience, Shore-A hardness, Rubber, Schob pendulum, Arduino

ENERJİ YUTMA TEST APARATININ TASARIMI VE UYGULAMASI

ÖZ

Testler tüm disiplinlerde çok önemlidir. Piyasaya sürülmeden önce herhangi bir ürün, kalite, kişi ve mal güvenliği için kendisini barındıracak çevreye karşı rekabetçiliğini sağlamak için bir seri teste tabi tutulur. Mekanikte, testler malzemelerin fiziksel davranışı hakkında ön çalışma yapılmasına izin verir. Çalışmaları sırasında darbelere ve dinamik yüklemelere maruz kalan makine parçaları, iyi enerji sönmeme ve iyi performansa sahip olmalıdır. Bu nedenle, bu bileşenlerde kullanılacak malzeme türüne karar vermek için test yapmak gerekir. Bilim ve teknoloji dünyasında bilinen test türleri ve cihazlar arasında, “Shore A” sertliğine sahip olan kauçuğun çarpma gerilmesi altında geri sekme kabiliyetini (elastikiyetini) belirlemek için kullanılan geri sekme (geri tepme) test cihazı ihmal edilebilir bir oranda ele alınmıştır. Üretici sayısı azdır ve literatürde bu konuda fazla bilgi bulunmamaktadır. Bu çalışma kauçuk ve kauçuk benzeri malzemelerin geri sekme kabiliyetini test etmek için, bir geri sekme test cihazının ticari bir yazılım olan SolidWorks ile tasarımına odaklanmıştır. Sarkacın açılma konumu Matlab aracılığıyla Arduino kart kullanılarak toplanmıştır ve Schob tipi bir sarkaç DIN 53512 standardına göre ve muadillerine (ISO 4662 ve ASTM D7121) uygun olarak elde edilmiştir.

Anahtar Kelimeler: Geri sekme (tepme) esnekliği, Shore-A sertliği, Kauçuk, Schob sarkaç, Arduino

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CHAPTER ONE

INTRODUCTION

Polymers are among the most widely used materials in different fields and in several products. Its field of use is so vast that the production from natural sources is just not sufficient to meet all our needs, for that reason the industry resort to artificial polymers made in laboratories and petrochemical plants. Among polymers, rubber material has an essential role in many applications due to its properties such as the incompressibility, reversibility, large elongation, high mechanical strength, long-term hardness stability, waterproof, poor heat and electric conductivity, and service life. Specifically, rubber can withstand deformation up to several hundred percents and resume its original shape within a short time following stress release (Luo, Liu & Yin, 2013). In view of all these properties of rubber, it's not surprising to find it used in products like tires, adhesives, pencil erasers, roofing membrane, protective gloves, electrical cables, inflatable boats, balloons, etc. The choice of the right type of rubber will largely depend on the environment of use. This choice decision making will be guided by testing. In applications where rubber is under repeated shocks and dynamic loads in machine elements, for instance, a resilient type of rubber should be used. However, few studies have focused on rubber rebound resilience properties in the literature. Andris, Svetlana, Elvijs & Edgars (2017), conducted a study on Determination Constants of 4-Element Rheological Model with Rebound Resilience Method, where a mathematical model to describe collision is elaborated using an algorithm for the determination of the constants of the chosen model. Maurice (1999) on Rubber Technology described rebound resilience testing and presented some rebound resilience results of various rubbers with the effect of temperature. Roger (2006) on Physical Testing of Rubber described different kind of rubber testing techniques including rebound resilience. This work focuses on the design and implementation of energy absorption test apparatus for rubber and rubber-type materials having a Shore-A or IRHD¹ hardness of between 30 and 85, using a Schob-type pendulum Rebound Resilience testing machine according to DIN 53512, ISO

¹ International Rubber Hardness Degree

4662 and ASTM D7121. Together with the current introduction, we divided this work into six main chapters. Besides the introduction we have:

- In Chapter Two, a theoretical review on rebound resilience testing machines is presented. Here, general concepts on these machines are presented together with standards review.
- In Chapter Three, the design and manufacturing of a prototype of the machine under discussion is presented, alike but not the same with existing machines. Here, we evince the compliance of our design to standards, the components design and characteristics, the components and test specimen manufacturing, the electronic and data acquisition and the budget evaluation are presented.
- In Chapter Four, testing on the machine prototype is performed. Here, we present the test sample preparation, test results, and test report.
- In Chapter Five, test results are discussed. We analyze the link between natural rubber hardness and rebound resilience, the effect of rubber specimen aging on the hardness and rebound resilience, the effect of temperature on the rebound resilience and the natural rubber origin link with the rebound resilience.
- Chapter Six summarizes all the work and presents the prospects for the future.

This study will allow correlating the rebound resilience property of rubber to the Shore-A hardness, the aging influence on rebound resilience, the temperature effect on rebound resilience and a comparison between rubbers from different origins, one from Vietnam and another from the Democratic Republic of Congo. The scientific community will have a more elaborate resource on rebound resilience testing machines having a different data acquisition technique (Arduino and Matlab), a lighter design compared to some existing machines of the same kind for instance, Rebound resilience tester Zwick 5109, 51 kg (Zwick Roell, n.d.), a frictionless system since an inexpensive accelerometer (MPU6050) has been used to capture different motion angles instead of a device that can increase friction (Potentiometer). The industry may use this design to create a new brand of this kind of machines. Ultimately, test results from this study may be used as a basis for future researches in this field.

CHAPTER TWO

THEORETICAL REVIEW ON REBOUND RESILIENCE TESTING MACHINES

2.1 General Concepts on Rebound Resilience Testing Machines

In this section, general concepts on rebound tester are presented.

The world wars boosted the industry, the rubber industry wasn't indifferent to that situation. New challenges kept arising in the absence of relations between countries. At that moment, two researchers Van Itersen and A.Schob developed independently but at the same moment the idea of using the so-called Schob-type pendulum for testing the elasticity of rubber (Memmler, 1935), which is used today in rebound resilience testing machines.

There are three basic types of rebound resilience apparatus, the falling ball type under gravity, the pendulum type with a swinging indenter attached to it and the vertical rebound tester (Qualitest, 2017). Although the falling ball type is simple in concept and free from vibration and friction, the pendulum type is mostly used in the industry providing that a greater range of equivalent frequencies can be easily obtained without changing the indenter size (Roger, 2006). Rebound resilience is used in quality control testing and is defined differently according to several authors. It enters in the category of unforced dynamic motion testing where test pieces are subjected to one-half of deformation. Roger (2006) defines it as a percentage of “the ratio of the energy of the indenter after impact to its energy before impact”, hence, in the case where the indenter falls under gravity, is equal to “the ratio of rebound height to the drop height”. The same author defines it as “the ratio of the square of velocities before and after impact (...).”. Deutsche Norm DIN² 53512 (2000) defines the rebound resilience, R as “the ratio of energy returned to energy applied or as the ratio of the height of rebound of a pendulum by its height of fall” as shown in Figure 2.1.

² Deutsches Institut für Normung.

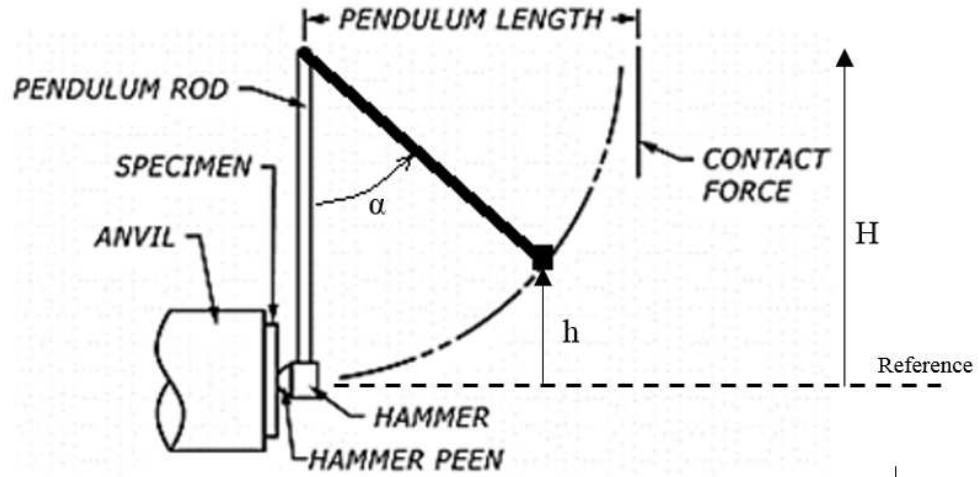


Figure 2.1 Schematic detail of the Schob pendulum (ASTM³ Int., 2018)

Under constant energy-input conditions, rebound tests give a simple estimate of energy loss and have been shown by several authors to correlate with "tangent delta" $\tan \delta$ (Maurice, 1999). The rebound resilience is defined as;

$$R = \frac{E_R}{E_I} = \exp(-\pi \tan \delta) \quad (2.1)$$

$$\frac{E_A}{E_R} = \pi \tan \delta \quad (2.2)$$

Where E_I , E_R and E_A are respectively, the incident energy, reflected energy and absorbed energy ($E_A = E_i - E_R$). However, the relationship between the loss factor $\tan \delta$ and the rebound resilience R is not particularly accurate because loss factor is strain-dependent and in an impact test, the form of applied strain is complex and its magnitude is not controlled (Roger, 2006). For low values of $\tan \delta$, its relationship with rebound resilience may be expressed by (Deutsche Norm DIN53512, 2000):

$$R \approx 1 - \pi \tan \delta \quad (2.3)$$

Roger (2006) presents a variety of pendulums used for rebound test machines including Lupke pendulum, Schob pendulum, Dunlop pendulum, Goodyear-Healey pendulum, Tripsometer, Zerbini torsion pendulum, as shown in Figure 2.2.

³ American Society for Testing and Materials

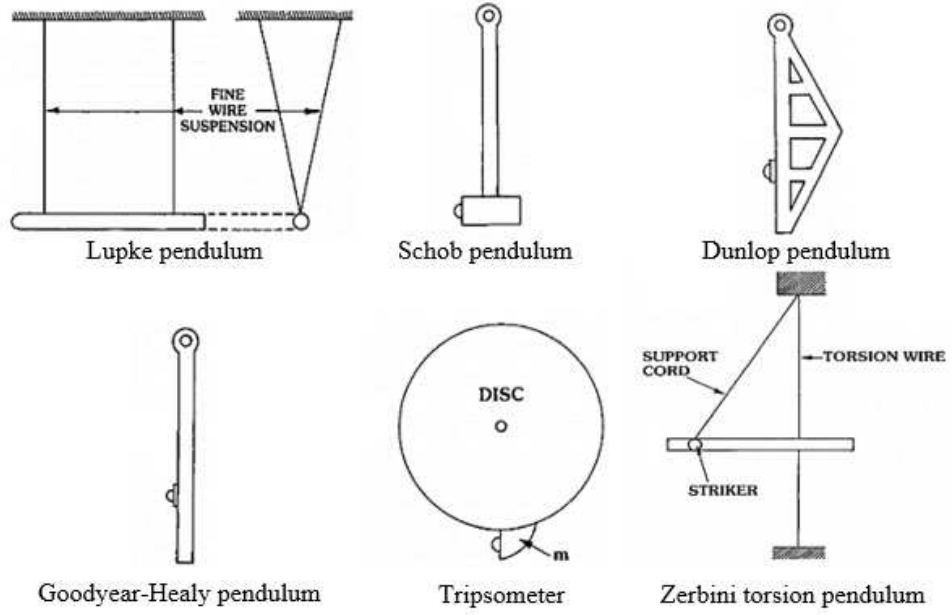


Figure 2.2 Rebound test machines pendulums (Roger, 2006)

The concept of rebound resilience of rubber is somehow related to the concept of coefficient of restitution of the dynamics of bodies subjected to impacts, which was formalized by Vincent & Bernard (2004) as being the square root of the ratio of the work of the normal force F_n during the compression period $[0, t_c]$, over the restitution period $[t_c, t_f]$. Assuming that the impact is split up into two different periods, the one during the contact (the compression) and the one after the contact (the restitution).

$$e^2 = \frac{W_n^r}{W_n^c} = \frac{\int_{t_c}^{t_f} F_n v_n dt}{\int_0^{t_c} F_n v_n dt} \quad (2.4)$$

The rebound resilience is then expressed (Maurice, 1999; Deutsche Norm DIN53512, 2000; ASTM Int., 2018) as:

$$R = \frac{[1 - \cos(\text{angle of rebound})]}{[1 - \cos(\text{angle of fall})]} \cdot 100 \quad (2.5)$$

The angle of rebound α is the angular position of the pendulum after the first strike (Figure 2.1) and the angle of fall is the angle at the striking position. Assuming the reference of the pendulum to be at the horizontal position while held by the pendulum

release device, the angle of fall will be 90°. Therefore, the rebound resilience can be expressed according to the equation 2.5 as:

$$R=(1-\cos\alpha) \cdot 100 \quad (2.6)$$

The relation above may be expressed as a ratio of the initial height H or L (The length of the pendulum) over the apex height of the rebound h (Deutsche Norm DIN53512, 2000; ASTM Int., 2018), Figure 2.1. H is the maximum height of the pendulum after the first strike calculated from the center of the test specimen.

$$R=\frac{h}{H} \cdot 100 \quad (2.7)$$

2.2 Rebound Resilience Tester Standards Review

In this section, general information will be provided in the context of rebound resilience apparatus design, test specimens preparation, test conditions, test procedure, and report. This information is derived from the standards DIN-53512-2000 and ASTM D7121 - 05 (Reapproved 2018).

2.2.1 Test Scope

This test is applied for thermoset rubbers and thermoplastic elastomers with a Shore A hardness lying between 30 and 85 IRHD subjected to impacts. It may also be used for polyester, plastic foam and polyether foam (Deutsche Norm DIN53512, 2000; ASTM Int., 2018).

2.2.2 Apparatus

Rebound resilience shall be carried out by a mechanical device equipped with a pendulum having one degree of freedom, oscillating under the effect of gravity on an axis perpendicular to it. The pendulum shall be a Schob-type pendulum at the end of which shall be fixed a spherical indenter mounted on a hammer (ASTM Int., 2018).

The specimen to be tested shall be placed and immobilized on a fixture in the form of a mechanical clamping without any lateral restraint. The machine must also incorporate a device to read the value of rebound resilience, which may be analog or digital (ASTM Int., 2018).

The machine frame and anvil group shall have a mass at least 100 times greater than the impact mass (Deutsche Norm DIN53512, 2000).

The surface of contact of the test specimen with the machine shall be metallic, flat, smooth and perpendicular to the indenter during impact (ASTM Int., 2018).

2.2.2.1 Apparatus Parameters

- The effective mass “ m_{eff} ” shall be between 0.247 kg and 0.35 kg (Deutsche Norm DIN53512, 2000).
- The diameter of the indenter “ D ” shall be between 12.45 mm and 15.05 mm (Deutsche Norm DIN53512, 2000).
- Impact speed “ v ” shall be between 1.97 m/s and 1.99 m/s (Deutsche Norm DIN53512, 2000) and shall be calculated using the equation:

$$v = \sqrt{2 \cdot g \cdot L_{red}} \quad (2.8)$$

Where g is the gravity constant, L_{red} is presented below. Andris et al. (2017) used the same equation of the velocity to evaluate the speed of the pendulum immediately after the rebound.

- Impact mass “ m ” shall be between 0.252 kg and 0.258 kg (Deutsche Norm DIN53512, 2000).

- The length of the pendulum “L” shall be between 199.5 mm and 200.5 mm (Deutsche Norm DIN53512, 2000).
- Apparent strain energy density shall be in the interval given by the equation 2.9 (Deutsche Norm DIN53512, 2000):

$$A_{SE} = \frac{m \cdot v^2}{D \cdot d^2} = 351^{+112}_{-27} \text{ kJ/m}^3 \quad (2.9)$$

“D” is the indenter diameter and “d” the test piece thickness.

- Force “F” acting on the pendulum at distance L from its pivot point at the horizontal position for the verification of the effective mass shall be between 2.47 N and 2.53 N (Deutsche Norm DIN53512, 2000).
- The reduced length of the pendulum “L_{red}” shall be determined from a period “T” as an average of 50 oscillations with the machine placed at 45°, and the pendulum set in motion with an initial angle of 5°. L_{red} is given by (Deutsche Norm DIN53512, 2000);

$$L_{red} = \frac{g \cdot T^2}{4 \cdot \pi^2} \quad (2.10)$$

“L_{red}” shall be between 198.5 mm and 201.5 mm.

- The energy of the pendulum “A_n” shall be in the interval given by the equation 2.11 (Deutsche Norm DIN53512, 2000).

$$A_n = m \cdot g \cdot L_{red} = m \cdot \frac{v^2}{2} = (500 \pm 9) \text{ mJ}. \quad (2.11)$$

- To check the friction, the pendulum shall have 300 full oscillations when it is released from a 40° angle (Deutsche Norm DIN53512, 2000).

2.2.3 Test Specimen

2.2.3.1 Preparation of Test Specimens

Test specimens shall have a smooth, flat surface with faces parallel to each other. They can be cut or molded. They shall have a diameter of between 29 mm and 53 mm and a thickness between 12 mm and 13 mm. A stack of no more than three layers may be used as a specimen, provided their contact surface is smooth and each layer thickness is identical (Deutsche Norm DIN53512, 2000; ASTM Int., 2018).

2.2.3.2 Test Specimens Conditioning

After vulcanization, the test shall be carried out over a period of 16 hours to one month. In the case of finished products, this period shall not exceed three months. In the case of test under normal conditions, the test specimens shall be held in an ambient environment (23 ± 2) °C at least three hours before the test (Deutsche Norm DIN53512, 2000; ASTM Int., 2018).

2.2.4 Test Temperature

Except for the ambient temperature, tests can be performed at higher temperatures (up to 100°C) or lower temperature (-70°C). For test temperature different from the ambience, the anvil, the test specimen, and the test piece holder shall be brought to the test temperature. For tests at 100°C, the test specimen shall be heated for a period of 30 to 40 minutes (Deutsche Norm DIN53512, 2000; ASTM Int., 2018).

2.2.5 Test Procedure

After mounting the test piece on the machine, a series of at least six rebounds shall be carried out, the median value of the last three rebounds represents the rebound resilience of the tested material. The first three are made for mechanically conditioning the test piece (Deutsche Norm DIN53512, 2000; ASTM Int., 2018).

2.2.6 Test Report

At the end of the tests, a report containing the following elements shall be drawn up (Deutsche Norm DIN53512, 2000; ASTM Int., 2018):

- General description of test samples, their origins, and date of vulcanization.
- Dimensions of test pieces.
- Details on the type of mixture used for the preparation of specimens.
- Type of test samples preparation (Cut or molded).
- Information on the history of test specimens before the test.
- Test ambient temperature.
- Conditioning period in minutes and temperatures in °C.
- Device used for testing and type of test holder.
- Any deviation from the standards
- Test Date.
- Test results including:
 - Number of specimens tested
 - The value of rebound resilience calculated for each test specimen.

CHAPTER THREE

DESIGN AND MANUFACTURING OF THE REBOUND RESILIENCE TESTER

3.1 Machine Components Design and Compliance with Standards

In this section, we will present all the machine components verifying the design compliance with standards, according to the last section of Chapter Two above.

Apart from electronic devices, the machine is designed with 41 components (Considering once each component). The detailed list of components will be presented down in this chapter. Yet, the components concerned by the standards are the piece holder, the frame, the anvil, the hammer set, the indenter, the pendulum rod, ball bearings, and test pieces.

3.1.1 Piece Holder Compliance with Standards

In compliance with section 2.2.2, we designed the piece holder as a clamping device without lateral restraint, just allowing to fix the test piece on the anvil. This design is just appropriate and compliant to the standards. More details are given in the following section presenting the machine technical characteristics.

3.1.2 Device to Read the Rebound Resilience

In compliance with Section 2.2.2, a digital method was used to read the rebound resilience of different tested specimens using data retrieved from Arduino board and transferred to Matlab, by the help of a gyro-accelerometer device “MPU6050”. An algorithm providing the rebound angle and computing the rebound resilience value was used. More details are given in the section on the electronic of the apparatus.

3.1.3 Pendulum Impact Mass Compliance with Standards

The pendulum impact mass is actually the mass of the hammer group including, the hammer, the indenter and the hammer load balance. It's related to the force acting on the pendulum at a distance L from its pivot. The force created by the impact mass at the horizontal position to be between 2.47 N and 2.53 N as required by the standards, the mass of the hammer group should be between 252 g and 258 g in compliance with the Section 2.2.2, with the gravity considered at the sea level 9.807 m/s² (Deutsche Norm DIN53512, 2000).

We considered a medium value of 254.92 g to create 2.5 N of force.

3.1.4 Pendulum Length Compliance with Standards

In compliance with section 2.2.2.1, the pendulum length “L” considered for the machine is 200 mm.

3.1.5 The Frame-Anvil Group Compliance with Standards

In compliance with Section 2.2.2 about the mass, the frame-anvil group shall have a mass at least 100 times greater than the impact mass, the frame-anvil group of the machine as designated in the technical drawings is composed by the bottom body, the middle body, the anvil hole, and the anvil. Without considering light fastener weights, all the group weighs about 27.212 kg. Providing that the impacting mass is composed by the hammer, the indenter and the hammer load balance weighs about 254.92 g, the ratio of the frame-anvil group by the hammer group “r” gives about 107 times, which is higher than 100 times.

$$r = \frac{\text{Frame-Anvil mass}}{\text{Impacting mass}} = \frac{27212}{254.92} = 106.7 \quad (3.1)$$

3.1.6 Anvil Compliance with Standards

In compliance with section 2.2.2 about the anvil surface quality and position, the manufactured anvil surface is smooth, flat and almost without roughness. Contrariwise, on the computer designed component, knurling was added on the surface for reason of better fixation of the rubber specimens.

3.1.7 Determination of the Standard Mass of the Pendulum Rod

Assuming the mass of the pendulum rod to be “ m_r ”. “ m_r ” is related to the pendulum rod diameter to be determined using the bending resistance criteria. The pendulum at the horizontal position can be considered as an end-loaded cantilever beam. The maximum bending stress $\sigma_{\max}$ is given by (Lingaiah,2003; Timoshenko, 1968):

$$\sigma_{\max} = \frac{M_{\max} \cdot C}{I} = \frac{M_{\max}}{Z} \quad (3.2)$$

Where $M_{\max}$ is the maximum bending moment, I denotes the moment of inertia, C denotes the distance from the neutral axis to the farthest point from it and Z denotes the section modulus. For a cylinder:

$$Z = \frac{\pi \cdot d^3}{32} \quad (3.3)$$

The maximum bending moment can be expressed by the yield stress (Lingaiah, 2003):

$$\sigma_{\max} = 0.66 \cdot \sigma_y \quad (3.4)$$

Lingaiah (2003) gives the yield stress for stainless steel 304 used for the pendulum rod as $\sigma_y=207$ MPa. Therefore, the diameter d will be:

$$d \geq \sqrt[3]{\frac{32 M_{\max}}{\pi \cdot 0.66 \cdot \sigma_y}} \quad (3.5)$$

$M_{\max}$ for an end-loaded cantilever beam is:

$$M_{\max} = F \cdot L \quad (3.6)$$

Therefore, $M_{\max} = F \cdot L = 500 \text{ N.mm}$. Thus, $d \geq \sqrt[3]{\frac{32 \cdot 500}{\pi \cdot 0.66 \cdot 207}} = 3.34 \text{ mm}$.

For manufacturing reason and providing safety, a diameter of 7 mm was used. With this consideration, the pendulum rod mass “ m_r ” is about 60.25 g. The maximum deflection at the impact point is evaluated by the equation (Hall, Holowenko & Laughlin, 1961):

$$y_{\max} = -\frac{1}{3} \frac{F \cdot L^3}{E \cdot I} = -\frac{1}{3} \frac{64 \cdot F \cdot L^3}{E \cdot \pi \cdot d^4} \quad (3.7)$$

With the Young modulus $E = 200 \text{ GPa}$ for stainless steel 304 (Lingaiah, 2003), $y_{\max} = -0.28 \text{ mm}$. This deflection will be smaller in reality on the machine since the pendulum release device is used at the front side of the pendulum to hold and release it from its horizontal position.

3.1.8 Effective Mass of the Hammer Group Compliance with Standards

In compliance with Section 2.2.2.1, the hammer group effective mass is within interval. The effective mass can be defined as the mass of the pendulum rod to be added to the mass of the hammer to better predict the behavior of the pendulum so that the compound pendulum can be studied like a simple pendulum (Diambu & Kiral, 2019). The model can be represented as in Figure 3.1.

The velocity at a point “ y ” of the pendulum rod being “ u ”, and the velocity at the position “ L ” being “ v ”. The velocity at “ y ” can be expressed as:

$$u = \frac{v \cdot y}{L} \quad (3.8)$$

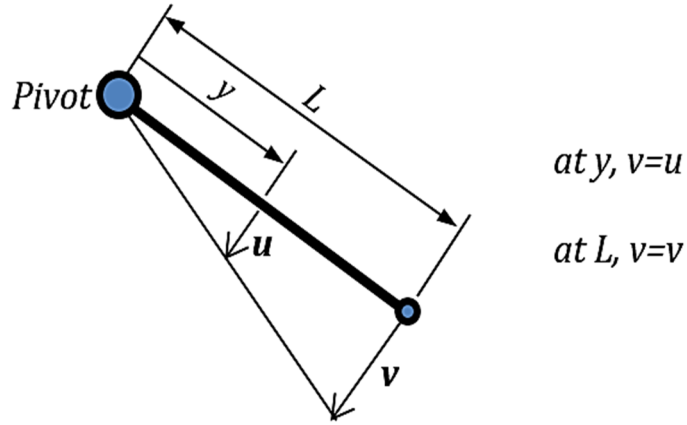


Figure 3.1 Pendulum model (Diambu & Kiral, 2019)

The kinetic energy being:

$$E = \frac{v^2 \cdot m}{2} \quad (3.9)$$

The mass of the pendulum rod to be added to the hammer mass can be evaluated by considering its contribution to the total kinetic energy of the group. It will, therefore, be the integration over the length of the pendulum rod of an element of mass positioned at a point y having a velocity u from 0 to L (Diambu & Kiral, 2019). Assuming “ dm_r ” to be a pendulum rod mass element, “ dm_r ” can be expressed as:

$$dm_r = \frac{dy}{L} \cdot m_r \quad (3.10)$$

The integration over “ y ” of the kinetic energy “ E ” from 0 to L gives:

$$E = \frac{1}{2} \int_0^L u^2 dm_r = \frac{1}{2} \int_0^L \frac{m_r}{L} \frac{v^2}{L^2} y^2 dy = \frac{1}{3} \cdot \frac{m_r v^2}{2} \quad (3.11)$$

The pendulum rod mass “ m_r ” effect to the total energy is 1/3 of the kinetic energy. This comes to say that the mass of the pendulum rod to be added at the point of impact is 1/3 of its total mass. So, the effective impacting mass to consider will be:

$$m_{\text{eff}} = m + \left(\frac{1}{3}\right)m_r \quad (3.12)$$

“ m ” being known (from 3.1.3) equal to 254.92 g and “ m_r ” being 60.25 g, the effective impacting mass $m_{\text{eff}} = 275$ g.

It should be noted that shear stress may occur during the pendulum strike. The impact force should be evaluated to verify the shear criterion on the pendulum rod. However, to determine that force, the pendulum velocity should be evaluated at the impact point. In that condition, the pendulum effective mass should be considered instead of the impact mass. But yet, the pendulum impact velocity is related to the pendulum reduced length.

3.1.9 Pendulum Reduced Length Compliance with Standards

This parameter allows approximating the pendulum impact velocity. In section 2.2.2.1, this parameter is given in equation 2.10, where T is determined experimentally based on an average of 50 oscillations. 50 oscillations were done in 45 sec, the value of T was so found equal to 0.9 sec. However, a precise result is given by Amrani, Paradis & Beaudin (2007), on large-angle period of a simple pendulum, for $\theta = \frac{\pi}{2}$ at impact:

$$T = 2\pi \sqrt{\frac{L}{g} \left(1 + \frac{\theta_0^2}{16} + \frac{11\theta_0^4}{3072}\right)} \cong 1.055 \text{ sec} \quad (3.13)$$

But this value gives a pendulum reduced length far larger than the standard range given in 2.2.2.1. This situation is not quite surprising since the equation in equation 3.13 is better applied for pure simple pendulum while our pendulum case is a

compound pendulum assumed to be a simple one. Thus, using the experimental period “T” and the equation 2.10 for the pendulum reduced length. The gravity being 9.807 m/s², a value considered at sea level, it’s also assumed that due to the low velocity of the pendulum rod, air resistance can be ignored (Nathan, Bor-Kai, Emily & Kwek-Tze, 2016).

$$L_{\text{red}} = \frac{9.807 \cdot 0.9^2}{4 \cdot \pi^2} = 0.201215 \text{ m} = 201.215 \text{ mm} \quad (3.14)$$

Which is in the standard range.

3.1.10 The Indentor Compliance with Standards

In compliance with section 2.2.2.1, the indentor diameter “D” used for this design was 15 mm.

3.1.11 The Pendulum Impact Speed Compliance with Standards

In compliance with section 2.2.2.1.3, the pendulum impact speed is determined from the equation 2.8. Thus,

$$v = \sqrt{2 \cdot g \cdot L_{\text{red}}} = 1.9866 \text{ m/s} \quad (3.15)$$

Based on this velocity, the pendulum diameter shear stress validation can be performed according to considerations in Section 3.1.8. Lingaiah (2003) gives the shear stress condition as:

$$A \geq \frac{4 \cdot V}{3\tau_{\text{max}}} \quad (3.16)$$

Where τ_{max} is the maximum shear stress given by:

$$\tau_{\text{max}} = 0.6 \cdot \sigma_y \quad (3.17)$$

V is the normal effort, so $V=F$, and A is the cross-section area. Providing that the effective mass should be used instead of the so-called impact mass, the current force “F” will be different from the force at the horizontal position used to evaluate the bending stress. Let’s designate this force “ F_{eff} ”, and the acceleration at the impact point “ a_i ”. So, $V=F_{\text{eff}}$ instead.

$$F_{\text{eff}} = m_{\text{eff}} \cdot a_i \quad (3.18)$$

Considering the right impact instant, “v” being the impact velocity and “t” the time between the pendulum reference position (horizontal) and the impact point. Thus, “ a_i ” will be:

$$a_i = \frac{\Delta v}{\Delta t} \quad (3.19)$$

Considering the initial velocity and the time to be 0, “t” will be the quarter of the pendulum period. The pendulum period was found to be equal to 0.9 sec. Thereby,

$$t = \frac{T}{4} = \frac{0.9}{4} = 0.225 \text{ sec} \quad (3.20)$$

“ a_i ” becomes:

$$a_i = \frac{v}{t} = \frac{1.9866}{0.225} = 8.83 \text{ m/s}^2 \quad (3.21)$$

Using equation 3.18,

$$V = F_{\text{eff}} = 0.275 \cdot 8.83 = 2.42825 \text{ N} \quad (3.22)$$

From equations 3.16 and 3.17, for a circular cross-section,

$$d \geq \sqrt{\frac{16 \cdot V}{\pi \cdot 1.8 \cdot \sigma_y}} = \sqrt{\frac{16 \cdot 2.42825}{\pi \cdot 1.8 \cdot 207}} = 0.18218 \text{ mm} \quad (3.23)$$

This result shows that the diameter chosen for the pendulum rod in Section 3.1.7 will resist shear stress as well.

3.1.12 Test Specimen Compliance with Standards

In compliance with Section 2.2.3.1, the test specimen thickness and diameter used for the design were respectively 12.5 mm and 48 mm. But two types were manufactured 12 mm thick - 31 mm of diameter for one type and 13 mm thick – 32 mm of diameter for the other.

3.1.13 Apparent Strain Energy Density Compliance With Standards

In compliance with Section 2.2.2.1, where “D” is the indenter diameter and “d” the test piece thickness.

$$A_{SE} = \frac{m \cdot v^2}{D \cdot d^2} = \frac{0.25492 \cdot 1.9866^2}{0.015 \cdot 0.0125^2} = 429253 \text{ J/m}^3 = 429.253 \text{ kJ/m}^3 \quad (3.24)$$

3.1.14 The Energy of the Pendulum Compliance with Standards

In compliance with Section 2.2.2.1 using Equation 2.11,

$$A_n = m \cdot g \cdot L_{red} = m \frac{v^2}{2} = 0.25492 \cdot 9.807 \cdot 0.201215 = 0.50304 \text{ J} = 503 \text{ mJ} \quad (3.25)$$

3.1.15 Friction Checking

Although the friction checking has not been performed, the pendulum rotation being insured by rolling bearings, friction loss is known to be reduced in these devices. Providing that no other device likely to increase friction was used, friction shouldn't affect negatively the results of tests. In addition, since the pendulum period test has been performed and was successfully compliant to the standards recommendations,

this is one more reason to believe that the friction effect won't affect rebound resilience test results.

3.1.16 Test Performing Compliance with Standards

This section will cover the test piece preparation, test piece conditioning, test environment, test temperature, test procedure, and test report.

3.1.16.1 Standard Test Piece Preparation

Test pieces were molded in two different molds since they were manufactured twice. The first series couldn't be used for tests seeing that the standard specification time to perform the test (From 16 hours to one month) was largely exceeded since the machine was not ready for tests. This first series test pieces are 13 mm thick and have 32 mm of diameter. However, these specimens weren't thrown away since we used it to perform rubber aging effect on hardness and rebound resilience study. The second series test pieces are 12 mm thick and have 31 mm of diameter.

3.1.16.2 Standard Test Piece Conditioning

The two series of test pieces were vulcanized respectively on January 21, 2019 and 19 July 2019. Tests were performed on July 26, 2019, in seven days, less than a month and more than 16 hours for the second series.

3.1.16.3 Standard Test Environment

The environment temperature in the morning of 26 July 2019 in the Machine Dynamics Laboratory of Mechanical Engineering Department of Dokuz Eylül University was 25.3 °C, the temperature measured using an infrared thermometer that we will present in the section on testing. Although the ambient temperature was 0.3 °C higher than required, this very small difference shouldn't affect the rebound resilience results.

3.1.16.4 Standard Test Temperature

Tests were also performed in higher temperatures than the ambience, but not in lower temperatures. The highest test temperature was at 95 °C. Test pieces were in a hot water bath over all the testing process.

3.1.16.5 Standard Test Procedure

For each test piece, a series of six rebounds was carried out, the first three rebounds were carried out to mechanically preparing the test pieces while the median value of the last three rebounds was noted as the rebound resilience of the considered specimen.

3.1.16.6 Standard Test Report

A test report will be presented at the end of Chapter Four in compliance with standards.

3.2 Machine Components Characteristics

The designed machine has 41 components considering once each component. A list of components will be presented in this section together with some basic details. For further technical details, components technical 2D drawings are added in the appendices, excluding ready components like screws, washers, bearings and nuts. The following listing is presented based on the exploded diagram listing. Except for the pendulum release motor, electronic devices used in the machine are not presented in this section.

3.2.1 Motor Holder

This stainless-steel sheet component holds the pendulum release motor, designed to be fixed right on the front top of the machine (Figure 3.2).



Figure 3.2 Pendulum release motor holder

3.2.2 Top Body

This component is like an upper receiver of all components to be fixed on the top of the machine (Figure 3.3). The bearing plates, the pendulum shaft and the electronic box are mounted to this part.

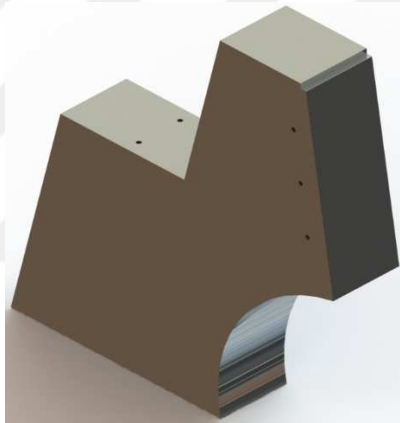


Figure 3.3 Top body

3.2.3 Back Cover - Electronic Box A

This plastic component is the left side of the electronic box where electronic devices are installed (Figure 3.4).



Figure 3.4 Back cover-Electronic box A

3.2.4 Back Cover - Electronic Box

This plastic component is fastened to the middle body (Figure 3.5).

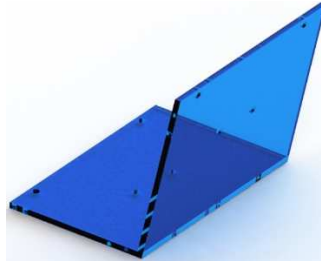


Figure 3.5 Back cover-Electronic box

3.2.5 Back Cover - Electronic Box B

This plastic component is the right side of the electronic box (Figure 3.6).

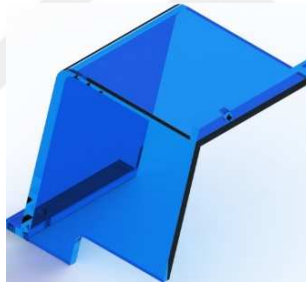


Figure 3.6 Back cover-Electronic box B

3.2.6 Middle Body

This component is an intermediate piece between the top and the bottom body. It was added to ensure a better fixture between both bodies (Figure 3.7).

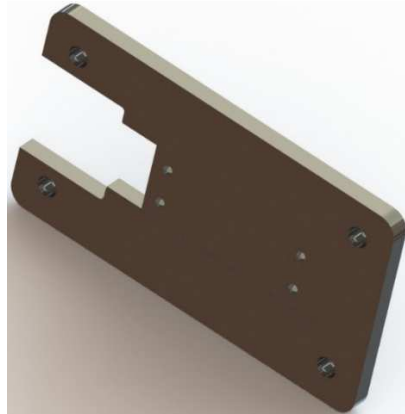


Figure 3.7 Middle body

3.2.7 Machine Stand

The machine stands on these components (Figure 3.8).



Figure 3.8 Machine stand

3.2.8 Bottom Plate

The machines stands are fixed on these plates, they were added for design reasons (Figure 3.9).

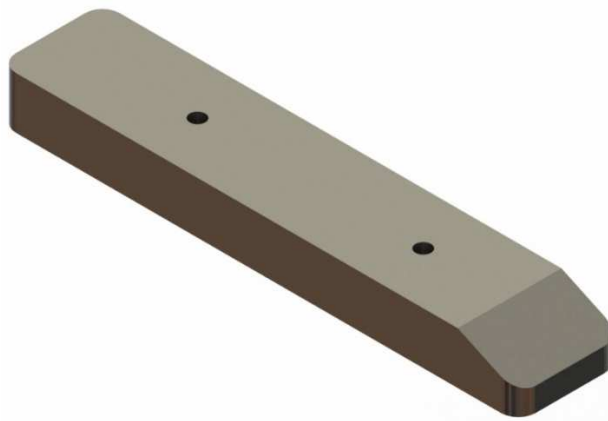


Figure 3.9 Bottom plate

3.2.9 Bottom Body

This component is the lower receiver of all components installed at the bottom of the machine as the anvil, the anvil hole, the dust cover, etc. (Figure 3.10).

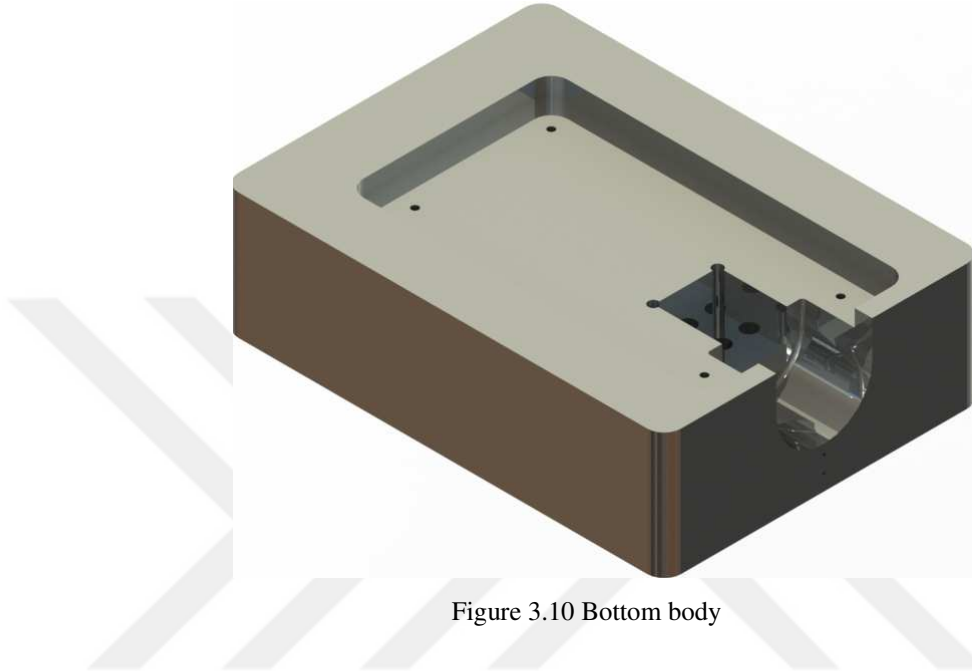


Figure 3.10 Bottom body

3.2.10 Piece Holder

This component allows fixing the test piece to the anvil during tests (Figure 3.11). It's fixed to the bottom body by two screws. The upper screw allows its rotation in order to install the test specimen without removing it all. It's designed with a circular way down to allow the rotation.



Figure 3.11 Piece holder

3.2.11 Anvil Hole

This component is designed with a tapped hole in which the anvil is allowed to move in order to adjust the testing position for different test specimen thickness (Figure 3.12). The moving range of the anvil in the hole is 25 mm, allowing to use test pieces thick up to 25 mm.



Figure 3.12 Anvil hole

3.2.12 MPU6050 Box

This plastic box was designed to immobilize the gyro-accelerometer device in order to avoid noisiness during tests (Figure 3.13). It's mounted on the pendulum shaft.

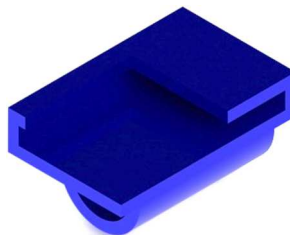


Figure 3.13 MPU6050 box

3.2.13 Anvil

This component is threaded in order to move axially in the so-called anvil hole (Figure 14). Its motion makes the machine flexible to test specimens of different thickness. It has holes on its sides allowing to insert Allen keys, for instance, to rotate it in order to reach the thickness of the test piece to be installed between it and the

piece holder. From its design, it should have graduation marks on it to measure the test piece thickness from the machine. However, those graduation marks weren't added in the finished part.



Figure 3.14 Anvil

3.2.14 Dust Filter

This plastic component was designed to protect the anvil thread from any possible dust that may fall on it (Figure 3.15). This component was designed to be manufactured in transparent glass or plastic in order to observe clearly the graduation marks on the anvil.



Figure 3.15 Dust filter

3.2.15 Test Specimen

Test specimens are rubber and rubber-like materials (Figure 3.16). They were designed to comply with the standards and dimensions were determined accordingly. See the next chapter on tests for more details.



Figure 3.16 Test specimen

3.2.16 Pendulum Release

This component is the key component to hold the pendulum horizontally and release it to perform tests (Figure 3.17). It's mounted on an electric motor with Gearmotor.



Figure 3.17 Pendulum release

3.2.17 Deep Groove Ball Bearing

Ready miniature shielded deep groove ball bearings 627-27 are used. They are fitted into the side plates of the machine. The choice of these bearings was guided using the SKF rolling bearing catalog. The fixture hole diameters into both plates were designed accordingly. The bearings inner diameter should allow the pendulum rotating shaft to

fit perfectly. The choice was made for a standard bearing of 7 mm inner diameter and 22 mm outer diameter (Figure 3.18).



Figure 3.18 Deep groove ball bearing (Svenska Kullagerfabriken [SKF], 2016)

3.2.18 Pendulum Indentor

This component is threaded and is mounted on the hammer of the pendulum (Figure 3.19). The indentor is the pendulum part that strikes the test piece during tests.



Figure 3.19 Pendulum indentor

3.2.19 Pendulum Hammer

This component receives the pendulum rod, the indentor, and the mass balance (Figure 20). All screw mounted. Therefore, the pendulum hammer is equipped with tappers.

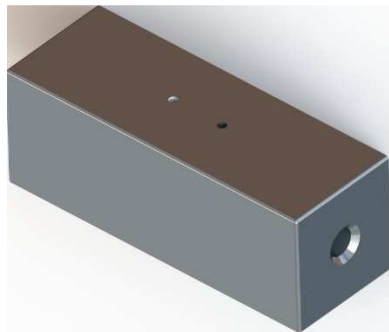


Figure 3.20 Pendulum hammer

3.2.20 Pendulum Hammer Load Balance

This component was added to counterbalance the pendulum since the indenter position might create an unbalanced situation (Figure 3.21).

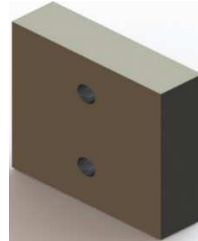


Figure 3.21 Pendulum hammer load balance

3.2.21 Pendulum Rod

This component is actually the pendulum body, it allows the pendulum group to rotate on the rotating shaft. The hammer group is mounted at its end (Figure 3.22).



Figure 3.22 Pendulum rod

3.2.22 Motor

To this device is mounted the pendulum release using two fastening set screws. The motor is a DC motor with gear box. It was chosen since the previous device (Solenoid release) failed to overcome the friction force created by the contact of the pendulum release with the pendulum rod.

3.2.23 Left Plate

The left-side rolling bearing of the pendulum is installed on this plate (Figure 3.23). It's fixed to the top body using 3 screws. It also allows fastening the pendulum release motor holder steel sheet.



Figure 3.23 Left plate

3.2.24 Right Plate

This component is opposite to the previous described above. The right-side rolling bearing is installed. This part is made with kind of chamber allowing the plastic top cover to settle there (Figure 3.24).



Figure 3.24 Right plate

3.2.25 Shaft of the Pendulum Rotary Axis

The pendulum rod using a fixing screw is mounted to this component (Figure 3.25). This shaft is the main component responsible for the rotation of the pendulum since it's the only one in contact with the bearings. It's equipped with a tapped hole at the

center to fix the pendulum rod using a screw, and has a chamber to firmly settle the MPU6050 box.



Figure 3.25 Shaft of the pendulum rotary axis

3.2.26 Top Cover

This plastic component was added for sake of design convenience and to protect bearings from possible dust (Figure 3.26).

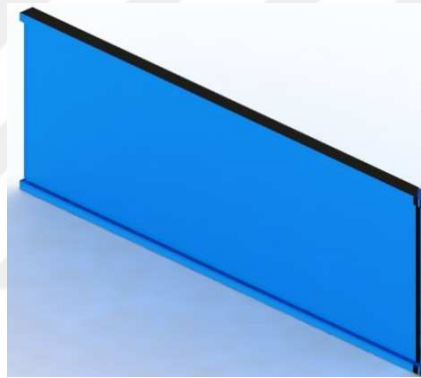


Figure 3.26 Top cover

The machine components are listed in Table 3.1.

Table 3.1 Machine component characteristics

N°	Designation	Q ^{ty}	Total Weight (g)	Material	Obser.
1	Motor holder	1	106.45	---	Appx 1
2	Washer of middle body	8	3.52	---	
3	Top body	1	7204.45	ST52	Appx 2
4	Back cover-Electronic box A	1	39.56	Power ABS	Appx 3
5	Back cover-Electronic box	1	55.25	Power ABS	Appx 4
6	Back cover-Electronic box B	1	39.56	Power ABS	Appx 5
7	Back cover linking screw	4	3	Screw steel	
8	Screw Elec. Cover-Top body	4	4.96	Screw steel	

Table 3.1 continues

9	Washer of L-R plate screw side	6	0.72	---	
10	Screw of Left-Right plate sides	6	8.34	Screw steel	
11	Screw of the middle body	8	34.64	Screw steel	
12	Middle body	1	1586.79	1.0037 (ST37)	Appx 6
13	Screw Bottom Plate-Bottom body	4	91.24	Screw steel	
14	Machine stand	4	231.2	1.0503 (C45)	Appx 7
15	Bottom plate	2	7989.44	ST52	Appx 8
16	Bottom body	1	25094.83	ST52	Appx 9
17	Screw Bottom Plate-Anvil	2	36.08	Screw steel	
18	Washer of stands	6	9.06	---	
19	Piece holder	1	13.05	1.4301 (304)	Appx 10
20	Anvil hole	1	278.96	1.4301 (304)	Appx 11
21	Screw piece holder guide	2	0.58	Screw steel	
22	MPU6050 Box	1	1.08	Power ABS	Appx 12
23	Anvil	1	211.7	1.4301 (304)	Appx 13
24	Dust filter	1	4.72	Power ABS	Appx 14
25	Test specimen	1	27.71	Rubber	Appx 15
26	Pendulum release	1	8.97	ST47	Appx 16
27	Groove Ball bearing SKF627	2	24.52	Chrome Steel	
28	Pendulum indenter	1	18.13	1.4301 (304)	Appx 17
29	Pendulum hammer	1	220.14	1.4301 (304)	Appx 18
30	Screw pendulum load balance	2	0.6	Screw steel	
31	Pendulum hammer load balance	1	16.73	1.4301 (304)	Appx 19
32	Pendulum rod	1	60.25	1.4301 (304)	Appx 20
33	Motor	1	193.77	---	
34	Left plate	1	626.4	ST52	Appx 21
35	Right plate	1	626.4	ST52	Appx 22
36	Shaft of the pendulum rotary axis	1	31.97	1.4301 (304)	Appx 23
37	Top cover	1	8.67	Power ABS	Appx 24
38	Screw motor cover	8	7.12	Screw steel	
39	Set Screw pendulum release	2	0.24	Screw steel	
40	Nut of back cover linking screw	12	4.08	Screw steel	
41	Screw pendulum rod-shaft	1	0.2	Screw steel	
	Machine Components & Total Weight	106	44925.08		

“Appx” stands for appendix. For further details about the machine components, one should refer to the corresponding technical 2D drawings in the appendices. The

designated total weight column is the total weight taking into consideration the number of components.

The general characteristics of the machine is given in Table 3.2.

Table 3.2 General characteristics of the machine

	Characteristics	Values
1.	Machine length	345.82 mm
2.	Machine overall length	524.49 mm
3.	Machine width	200 mm
4.	Machine height	353.5 mm
5.	Machine weight	44.925 Kg
6.	Apparent strain energy density	429.253 kJ/m ³
7.	Pendulum potential energy	503 mJ
8.	Pendulum indenter diameter	15 mm
9.	Pendulum length	200 mm
10.	Pendulum reduced length	201.215 mm
11.	Pendulum impact mass	254.92 g
12.	Pendulum effective impact mass	275 g
13.	Angle of fall	90°
14.	Impact velocity	1.9866 m/s
15.	Anvil motion	25 mm
16.	Specimen diameter range	30 mm ≤ D ≤ 50 mm

Refer to Appendix 25 for more details about the machine general characteristics.

3.3 Machine Components Manufacturing

In this section, we will present the manufacturing process for different machine components. Except for ready components that were purchased, plastic components were 3D printed, components in steel were laser cut and/or machined. The bottom body, bottom plate, left and right plates, top body, and middle body were laser cut and then machined. Apart from components made from stainless steel (See Table 3.1), all the other components were chrome plated for protection against corrosion.

The manufacturing processes started with laser cutting the components mentioned above by Ales Pres Bursa. Laser-cut components were sent to MİNOS Makina

Otomasyon for machining, chrome plating, and montage process. The machine first state after machining before chrome plating is presented in Figure 3.27.



Figure 3.27 Machine montage after machining (Personal archive, 2019)

After that step, the machine components were chrome plated and two SKF miniature single row deep groove ball bearings were installed. As every human work doesn't lack mistakes, we figured out that the anvil didn't fit right in its hole, a small adjustment was necessary by adding a thin layer of Teflon band on the thread (Figure 3.28). The aim was just to firmly fasten the anvil to avoid losses during tests. That small Teflon band layer shouldn't create any negative effect on the results. Besides that, the pendulum shaft came running idle into the bearings, the shaft diameter was under the tolerance. Some adjustments on the shaft allowed to fix the issue. The machine state after these processes is presented in Figure 3.29.



Figure 3.28 Anvil adjusted (Personal archive, 2019)

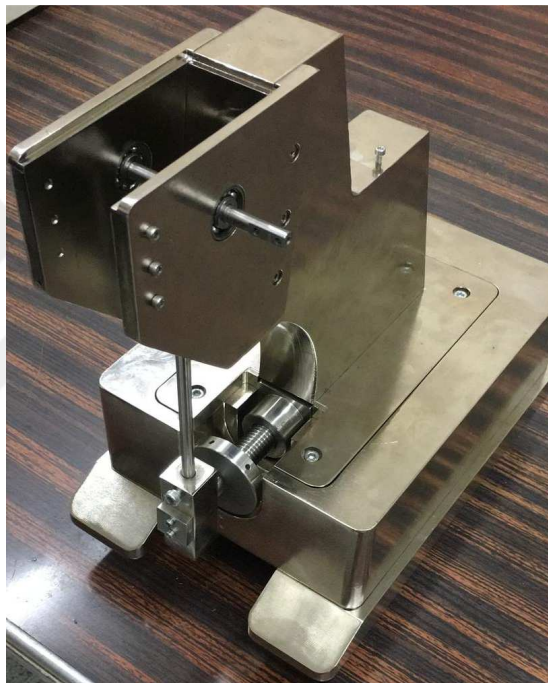


Figure 3. 29 Machine montage after chrome plating (Personal archive, 2019)

In addition, the test piece holder device was missing since the first device wasn't easily machinable. We designed an easy one to be laser cut (Figure 3.30).



Figure 3.30 Piece holder (Personal archive, 2019)

When the solenoid didn't do the pendulum release job, the motor holder steel sheet was designed and sent for laser cutting (Figure 3.31).



Figure 3.31 Motor holder (Personal archive, 2019)

Then after, plastic components 3D drawings of the machine were sent for 3D printing to LİZZAM Tasarım. After the 3D printings, the color of plastic filaments of the 3D printed parts was different. A painting process followed using a blue spray acrylic paint by the help of ERSÜS Arms. Some 3D printed components are presented (Figures 3.32-3.37).



Figure 3.32 Top cover 3D print (Personal archive, 2019)



Figure 3.33 Dust filter 3D print (Personal archive, 2019)

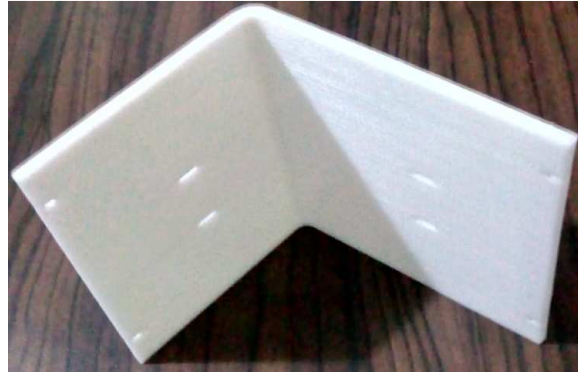


Figure 3.34 Back cover-Electronic box 3D print (Personal archive, 2019)



Figure 3.35 Back cover-Electronic box A 3D print painted (Personal archive, 2019)



Figure 3.36 Back cover-Electronic boxes 3D print painted (Personal archive, 2019)

To the first concept, the pendulum release would be ensured by a solenoid device. But it was not enough powerful to overcome frictions. A housing was designed for the solenoid, even though we didn't use it into the finished machine but it's still worthy to present it for sake of information.



Figure 3.37 Solenoid housing 3D print (Personal archive, 2019)

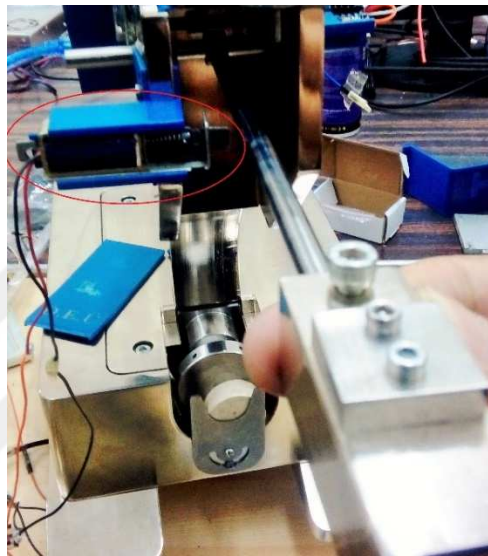


Figure 3.38 Solenoid housing 3D print on the machine (Personal archive, 2019)

Figure 3.39 shows the finished machine. In the figure, different components are shown such as: DC motor with gear box (1), Pendulum release (2), Motor holder (3), MPU6050 (4), MPU6050 housing (5), Left side plate (6), Pendulum rod (7), Hammer (8), Hammer load balance (9), Indentor (10), Test specimen (11), Anvil (12), Dust filter (13), Anvil hole (14), Bottom plate (15), Bottom body (16), Middle body screw (17), Middle body (18), Top body (19), Back cover left and right side (20,21), Top cover (22).

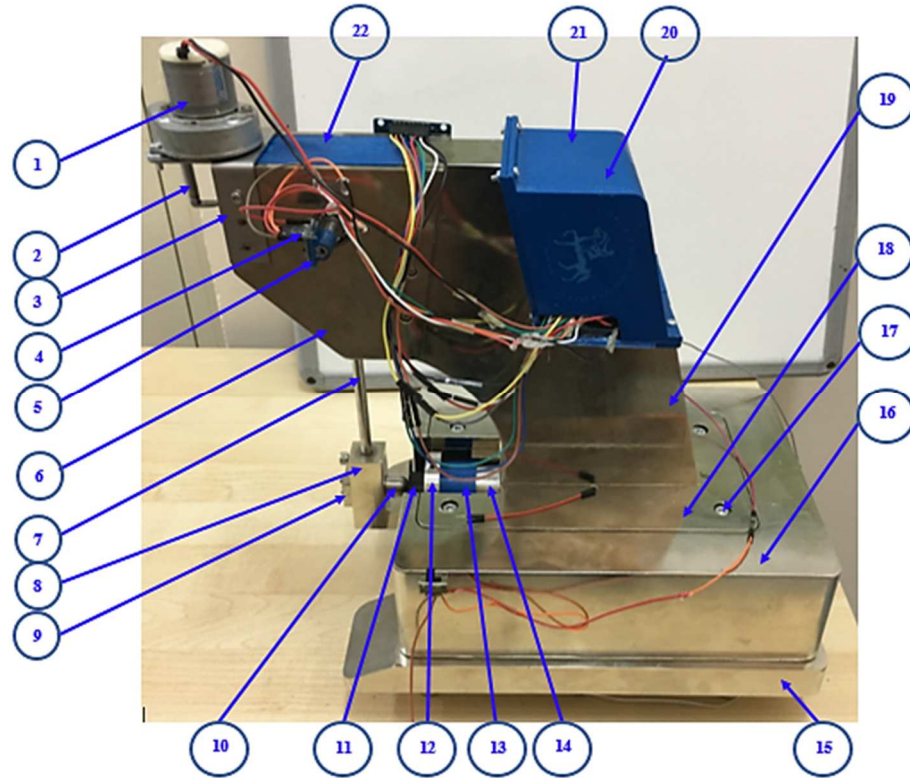


Figure 3.39 Finished rebound resilience tester (Personal archive, 2019)

Some additional pictures of the machine are presented in the appendices.

The preparation of test specimens then followed. We should mention once again that test pieces were manufactured twice as stated in section 3.1.16.1 providing that the first test specimens couldn't be used for tests according to standards. Further details will be presented in the chapter about testing on the machine.

3.4 Electronic of the Apparatus

The present machine aims to evaluate the absorbed energy of rubber and rubber-like materials by rebound resilience. The maximum angle of the pendulum after the first strike is tracked. Therefore, a device to track that angle was investigated. First, the idea was to use a potentiometer mounted on the pendulum shaft. However, even though this device is quite handy, another issue showed up at a glance, the friction issue. A component like a potentiometer mounted on the shaft could likely increase the friction and yet influence negatively the results of the machine. Thus, our choice

was oriented to a frictionless device that could rotate with the shaft without any adverse effect. Finally, we went for a gyro-accelerometer, an MPU6050 (Figure 3.40).

The MPU6050 belongs to the MPU-60X0 series of devices. It's the first integrated 6-axis Motion Tracking device in the world that combines a 3-axis gyroscope and a 3-axis accelerometer (InvenSense Inc, 2013). Table 3.3 presents some basic parameter of the device.

Table 3.3 MPU6050 basic characteristics (InvenSense Inc, 2013)

Parameters	Rating (A.M.R ⁴)	Normal condition
Supply Voltage, VDD	-0.5V to +6V	2.375V-3.46V
Operating Temperature Range	-40°C to +105°C	
Storage Temperature Range	-40°C to +125°C	

From this table, we can see that the MPU6050 can be used even for higher or lower temperature conditions.

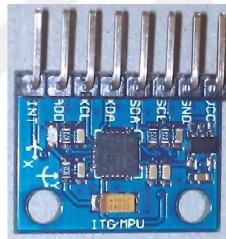


Figure 3.40 MPU6050 gyro-accelerometer (Instructables circuits, 2019)

The MPU6050 was used with the Arduino UNO microcontroller board (Figure 3.41).

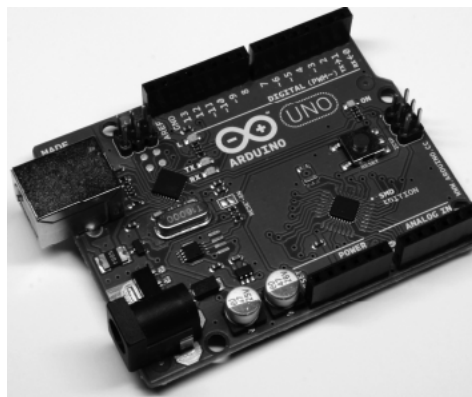


Figure 3.41 Arduino UNO board (Evans, 2011)

⁴ Absolute Maximum Rating: Stress above that may cause permanent damage to the device

Below is presented the circuit of the Arduino UNO with the MPU6050. The MPU6050 communicate with the Arduino through the I2C protocol (Figure 3.42).

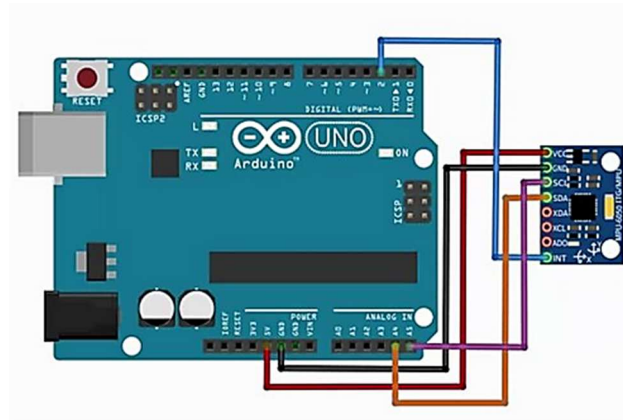


Figure 3.42 MPU6050 connection diagram to the Arduino UNO (Instructables circuits, 2019)

After connecting these components using jumpers, the MPU6050 is settled into its housing mounted on the pendulum shaft. The MPU6050 requires some special libraries and calibration before use. Once the libraries are added and the device is calibrated, the program is ready to be downloaded in the Arduino board via a USB cable connecting the Arduino to the computer. The open-source Arduino software contains some code samples for multiple basic tasks. The angle measurement algorithm using the MPU6050 is one of them. The algorithm was improved by adding some additional feature such as filtering routines for better results.

Pendulum angular motion data were saved and transferred to Matlab. A Matlab code was written to find the rebound resilience from the maximum angle of the pendulum after the first strike. The code sample is presented below.

```
clear; clc;

data=load ('file_name.txt'); % Change data file name
L=length(data); z=1; max_angle=90; min_angle=0;
for i=1 : L-6
    if max_angle ==0 || min_angle ==0
        temp1=data(i+1,1)-data(i,1);
        temp2=data(i+2,1)-data(i+1,1);
        temp3=data(i+3,1)-data(i+2,1);
        temp4=data(i+4,1)-data(i+3,1);
        temp5=data(i+5,1)-data(i+4,1);
```

```

temp6=data(i+6,1)-data(i+5,1);
if temp1<0 && temp2<0 && temp3<0 && temp4>0 &&
temp5>0 && temp6>0
    min_angle(z)=data(i+3)
    z=z+1;
end
end
end

d_angle=max_angle-min_angle;
R= (1-cosd (d_angle))

```

This algorithm checks three values from both sides to ensure the real minimum value since data saved from Arduino were noisy for angles around the reference position. An example of data will be provided in the section on testing.

3.5 Machine Manufacturing Budget

The machine manufacturing total budget is evaluated and presented in Table 3.4. The V.A.T⁵ is included in the price.

Table 3.4 Machine manufacturing budget

Item designation	Item N°	Supplier	Price
Machine main body steel /laser cutting	5	Ales Pres	300.00 TL
Components machining		Minos Mak.	1 500.00 TL
Arduino Mini Set	1	Hobidevre	41.29 TL
Single row deep groove ball bearings	2		33.55 TL
Specimen holder	1	LİZZAM T.	60.00 TL
MPU6050-GY521	1	Hobidevre	18.94 TL
Jumper sets (Male-Female)	5	Hobidevre	26.56 TL
Mini Breadboard	1	Hobidevre	2.75 TL
3D printings	6	LİZZAM T.	150.00 TL
Arduino Nokia LCD 5110	1	Hobidevre	24.19 TL
Total budget			2 157.28 TL

According to the currency on August 03, 2019, the manufacturing cost of the machine is about \$ 388.

⁵ Value Added Tax

CHAPTER FOUR

TESTING ON THE APPARATUS

In this chapter, we will present the test results obtained using the manufactured apparatus. The chapter is divided into three sections, test samples preparation, test results, and test report.

4.1 Test Sample Preparation

Test specimens are prepared according to the related standards. In this section, we present the general concepts on rubber technology, to end up with the procedure we used to prepare the specimens.

4.1.1 General Concepts on Rubber Technology

This section aims to give basic information about rubber technology and processes, and the manufacturing process.

Rubber manufacturing process is based on some key operations that can be summarized into three main stages: Mixing, shaping and vulcanizing (Freakley, 1985). The finished product quality depends straightly on these operations.

4.1.1.1 Rubber Mixing

This process depends on both rubber form and the scale of operations. The internal mixer is used for medium and large scale while two-roll-mill are used for small scale. This operation is complex due to the viscoelastic behavior of rubber and the nature of additives (Freakley, 1985). For our specimens, the two-roll-mill mixer was used.

Mixing with two-roll-mill is realized following a cycle presented in Table 4.1 (Maurice, 1999).

Table 4.1 Two-roll-mill mixing cycle

	Roll-Mill
Temperature, °C	70 ± 5°C
Mixing speed, slow roll	24 rpm
Roll ratio (slow to fast roll)	1 to 1.4 (slow to fast)

Once the mill is opened and the temperature is adjusted, rubber is added on the front roll, different additives of the natural rubber recipe are added consequently according to the needed final product, including zinc oxide, sulfur, stearic acid, benzothiazyl disulfide, and carbon black.

4.1.1.2 Rubber Shaping

Rubber shaping refers directly to giving to the product the needed shape. Molding is a shaping method included in the vulcanization process.

4.1.1.3 Rubber Vulcanization

Rubber in its original form from the rubber tree is not useful since it's runny, smelly and squashy until it's vulcanized, that is to say, cooked with some chemicals such as sulfur to make it strong, hard and long-lasting for daily life use. Vulcanization allows creating extra bonds (Cross-link) between rubber molecules chains. Thus, after vulcanization natural rubber becomes cross-linked, insoluble in solvents and more resistant to heat and aging (Maurice, 1999). And then follows the molding process.

The molding process used for our specimen preparation was compression molding. In this molding process, the rubber blank (slug) is placed in the mold closure (open flash mold) and a hydraulic press compresses the blank to shape it.

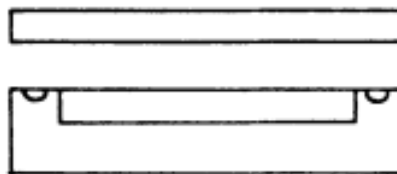


Figure 4.1 Open flash mold (Freakley, 1985)

4.1.2 Test Specimen Manufacturing Process

Two rubber types were used twice (On January 21, 2019 and July 26, 2019) for the test specimens as we mentioned in the chapters above. The rubber from Vietnam was ready for molding (Figure 4.2) while the rubber from Congo was still in a natural state (Figure 4.3).



Figure 4.2 Mixed rubber from Vietnam (Personal archive, 2019)



Figure 4.3 Rubber raw from Congo (Personal archive, 2019)

But it was observed that the rubber raw from the Congolese Mayombe forest was stickier than the Vietnamese. So, it was difficult to mix and remove it from the roll-mixer alone (Figure 4.4).



Figure 4.4 Sticky Congolese rubber on the roll-mill (Personal archive, 2019)

To fix that issue, an equal amount (500g) of Vietnamese rubber was added to the Congolese rubber to boost the mixing process (Figure 4.5).



Figure 4.5 Sticky Congolese rubber mixed with Vietnamese rubber on the roll-mill (Personal archive, 2019)

Then after, the necessary chemicals for vulcanization were added to the mixture gradually (Figure 4.6). After that process, five blanks were cut for both rubber types and put into the mold under the hydraulic press for the vulcanization process (Figure 4.7 - 4.8).



Figure 4.6 Sticky Congolese rubber mixed (Personal archive, 2019)



Figure 4.7 Rubber sample in the mold on January 21, 2019 (Personal archive, 2019)

For our samples, the molds were heated to 160 °C in six minutes. For the test realized on July 26, 2019, mixed raw rubber prepared on January 21, 2019 (from Congo) was jealously kept in the cold (Figure 4.8) under 0°C to maintain its properties. On July 26, 2019, the same molding process done in January was repeated but using a smaller mold (12 mm thick and 31 mm of diameter) shown in Figure 4.9. The control unit of the molding process is shown in Figure 4.10.



Figure 4.8 Cold guarded Congolese rubber raw (Personal archive, 2019)



Figure 4.9 Rubber sample in the mold on July 26, 2019 (Personal archive, 2019)



Figure 4.10 Mold temperature and time command unit (Personal archive, 2019)

On January 21, 10 specimens, five from Congolese natural rubber and five from Vietnamese natural rubber were prepared. On July 26, 10 other specimens were prepared, five from Congolese natural rubber and five from Vietnamese having a different composition. Tables 4.2 and 4.3 summarize respectively the rubber samples characteristics and the chemical used to vulcanize the Congolese natural rubber.

Table 4.2 Rubber samples characteristics

N°	Designation (Co ⁶ , V ⁷ , New ⁸ , Old ⁹)	Dimension (Diameter-Thickness)	Observation
1	1 new Co	31 mm - 12 mm	Black colored
2	2 new Co	31 mm - 12 mm	Black colored
3	3 new Co	31 mm - 12 mm	Black colored
4	4 new Co	31 mm - 12 mm	Black colored
5	5 new Co	31 mm - 12 mm	Black colored
6	1 new V	31 mm - 12 mm	Friction resistant (Grey)
7	2 new V	31 mm - 12 mm	Silicon-Heat resistant (Orange)
8	3 new V	31 mm - 12 mm	Black colored
9	4 new V	31 mm - 12 mm	Oil resistant (Black)
10	5 new V	31 mm - 12 mm	Oil resistant (Black)
11	1 old Co	32 mm - 13 mm	Black colored
12	4 old Co	32 mm - 13 mm	White colored (Friction resistant)
13	5 old Co	32 mm - 13 mm	White colored (Friction resistant)
14	6 old Co	32 mm - 13 mm	Black colored
15	7 old Co	32 mm - 13 mm	Black colored
16	9 old V	32 mm - 13 mm	Black colored
17	10 old V	32 mm - 13 mm	Black colored
18	11 old V	32 mm - 13 mm	Black colored
19	12 old V	32 mm - 13 mm	Black colored
20	13 old V	32 mm - 13 mm	Black colored

Table 4.3 Chemicals used for Congolese rubber vulcanization (In 1 kg of natural rubber)

	Designation	Quantity in 1 kg of natural rubber
1	Zinc Oxide	50 g
2	Sulfur	25 g
3	Dibenzothiazyl disulfide(DM Accelerator)	20 g
4	Diphenil guanine (DPG Accelerator)	10 g

⁶ Refers to Congolese rubber

⁷ Refers to Vietnamese rubber

⁸ Refers to sample manufactured on July 26, 2019

⁹ Refers to sample manufactured on January 21, 2019

Some rubber samples are shown in Figure 4.11.



Figure 4.11 Manufactured rubber samples (Personal archive, 2019)

After specimens cooled down, we tested their hardness to comply with standards. Test results will be presented in the results section.

A Shore A durometer was used for the hardness testing (Figure 4.12). Tests were performed according to the Deutsche Norm DIN53505-A.



Figure 4.12 Testing the manufactured rubber sample hardness (Personal archive, 2019)

The Shore hardness is defined by DIN-53505 (2000) as “the resistance to indentation by a body of defined shape and under a specified load”. It’s ranged from 0 (Soft rubber) to 100 (Hard rubber) (Figure 4.13).

Shore A
as in DIN 53505

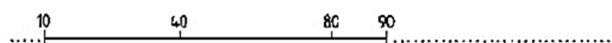


Figure 4.13 Ranges of application for Shore A hardness testing (Deutsche Norm DIN-53505, 2000)

4.2 Test Results

In this section, we present test results for the specimens. Tests were performed for in the Machine Dynamics Laboratory of Mechanical Engineering Department of Dokuz Eylül University at ambient temperature and at different temperatures. The results will include the hardness and the rebound resilience for each test specimen. The designations used in Table 4.2 still remain the same.

To heat test specimens, they were packed in a plastic bag and plunged into a hot water bath heated to over 100°C in an electric kettle. Test pieces were removed from the hot water bath only for test. The temperature was constantly measured using an infrared thermometer (Fluke 576 in Figure 4.14). For the piece holder and the anvil heating, a package of hot water plastic bag was applied around the anvil-piece holder region for some minutes until they reach a temperature close to the test piece temperature.



Figure 4.14 Specimen temperature measure (Personal archive, 2019)

Tables 4.4, 4.5 and 4.6 present the hardness and rebound resilience for different specimens.

Table 4.4 Hardness values for rubber specimens of January 21, 2019, tested on the same day (Ambiance)

N°	Designation	Hardness (Shore A)
1	1 old Co	70
2	4 old Co	52
3	5 old Co	57
4	6 old Co	66
5	7 old Co	55
6	9 old V	70
7	10 old V	70
8	11 old V	74
9	12 old V	70
10	13 old V	70

Table 4.5 Hardness values for rubber specimens of January 21, 2019, tested on July 19, 2019 (Ambiance)

N°	Designation	Hardness (Shore A)
1	1 old Co	71
2	4 old Co	67
3	5 old Co	62
4	6 old Co	67.5
5	7 old Co	66
6	9 old V	78
7	10 old V	78
8	11 old V	81
9	12 old V	79
10	13 old V	78

Table 4.6 Hardness values for rubber specimens of July 19, 2019, tested on the same day (Ambiance)

N°	Designation	Hardness (Shore A)
1	1 new Co	70
2	2 new Co	67.5
3	3 new Co	72
4	4 new Co	72.5
5	5 new Co	72
6	1 new V	57
7	2 new V	57
8	3 new V	68
9	4 new V	47
10	5 new V	45

Now we present the rebound resilience for specimens tested on July 26, 2019. At normal temperature, the median value of rebound resilience was used as the rebound resilience as specified by the standards. The rebound resilience values are given in Table 4.7 and Table 4.8.

The rebound resilience values for old rubber specimens are given in Table 4.7.

Table 4.7 Rebound resilience values for old rubber specimens at 25.3°C (Lab temperature)

Designation	Rebound angle (α)	Rebound resilience	Rebound Median
1 old Co	66.17°	59.598%	55.30%
	63.45°	55.302%	
	61.72°	52.622%	
4 old Co	59.39°	49.081%	49.08%
	60.68°	51.031%	
	58.23°	47.349%	
5 old Co	56.83°	45.287%	47.62%
	58.41°	47.616%	
	59.44°	49.156%	
6 old Co	56.95°	45.463%	47.82%
	58.55°	47.825%	
	60.90°	51.366%	
7 old Co	59.72°	49.570%	47.87%
	58.58°	47.869%	
	58.10°	47.156%	
9 old V	65.81°	59.024%	57.11%
	61.45°	52.207%	
	64.60°	57.106%	
10 old V	64.59°	57.091%	58.31%
	66.17°	59.598%	
	65.36°	58.308%	
11 old V	68.30°	63.025%	59.76%
	66.27°	59.757%	
	63.00°	54.601%	
12 old V	63.50°	55.380%	55.38%
	64.47°	56.902%	
	62.98°	54.570%	
13 old V	63.08°	54.725%	54.73%
	64.43°	56.839%	
	67.16°	61.184%	

The rebound resilience values for new rubber specimens are given in Table 4.8.

Table 4.8 Rebound resilience values for new rubber specimens at 25.3°C (Lab temperature)

Designation	Rebound angle(α)	Rebound resilience	Rebound Median
1 New Co	63.24°	54.975%	54.97%
	64.01°	56.179%	
	69.58°	65.110%	
2 New Co	62.51°	53.841%	53.84%
	65.26°	58.150%	
	60.59°	50.894%	
3 New Co	69.37°	64.767%	56.07%
	60.90°	51.366%	
	63.94°	56.069%	
4 New Co	64.19°	56.461%	57.56%
	64.89°	57.564%	
	67.07°	61.039%	
5 New Co	61.00°	51.519%	59.85%
	66.33°	59.853%	
	69.36°	64.750%	
1 New V	64.46°	56.886%	53.08%
	61.37°	52.085%	
	62.02°	53.084%	
2 New V	63.43°	55.271%	56.07%
	63.94°	56.069%	
	68.22°	62.896%	
3 New V	60.51°	50.773%	51.21%
	62.22°	53.392%	
	60.80°	51.214%	
4 New V	61.23°	51.871%	44.98%
	56.62°	44.981%	
	54.06°	41.306%	
5 New V	57.98°	46.978%	46.77%
	54.75°	42.285%	
	57.84°	46.771%	

Figure 4.15 allows reading easily the distribution of the rebound resilience values of the last 10 new specimens.

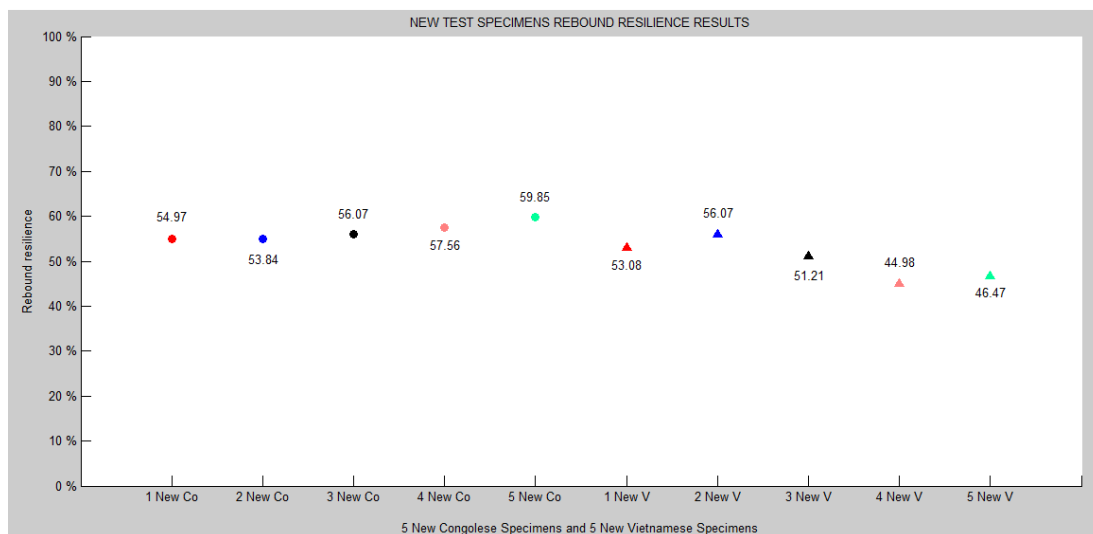


Figure 4.15 Rebound resilience test results for new Congolese and Vietnamese specimens

Table 4.9 Rebound angular motion test data on 4 New V specimen at 55°C

0	0.01	0.01	0.02	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.02
0.02	0.01	0.01	0.02	0.03	0.03	0.03	0.02	0.01	0	0.01	0.02
0.01	0.02	0.03	0.03	0.04	0.04	0.03	0.04	0.06	0.07	0.07	0.08
0.1	0.11	0.13	0.14	0.13	0.21	0.29	0.32	0.34	0.39	0.46	0.54
0.61	0.67	0.73	0.81	0.94	1.07	1.22	1.37	1.55	1.79	2.1	2.56
3.12	3.95	4.72	5.81	6.88	8.14	9.58	11.35	13.3	15.43	17.7	20.44
23.31	26.03	28.95	32.12	35.45	39.38	43.01	47.26	51.11	55.08	59.18	63.97
68.37	72.83	77.4	82.55	87.57	90.88	88.11	84.56	81.1	77.36	74.06	70.78
67.94	65.29	62.26	59.54	56.9	54.04	51.41	48.23	46.11	44.14	42.28	40.62
38.8	37.08	35.47	33.92	32.82	31.81	31.27	30.86	30.6	30.29	30.14	30.16
30.34	30.74	31.45	32.32	33.45	34.53	35.73	37.22	38.64	40.44	42.31	44.34
46.52	48.81	51.51	54.23	56.76	59.42	62.26	65.57	68.61	71.8	75.03	78.62
82.26	85.52	88.8	90.96	88.21	85.83	83.27	81.15	78.96	76.28	74.08	71.83
69.64	67.66	65.53	64.02	62.5	60.93	59.39	57.64	55.88	54.41	53.33	52.51
51.82	51.17	50.67	49.98	49.43	49.07	48.96	49.06	49.3	49.8	50.38	50.93
51.53	52.24	53.21	54.24	55.71	57.16	58.68	60.19	61.77	63.66	65.58	67.39
69.45	71.6	74.07	76.32	78.59	80.88	83.44	86.05	88.47	90.83	90.15	87.91
85.85	84.33	82.7	81.16	79.86	78.58	77.07	75.25	73.58	72.06	70.78	69.63
68.88	68.08	67.22	66.31	65.49	64.59	63.82	63.57	63.44	63.41	63.46	63.5
63.62	63.59	63.7	64.12	64.74	65.4	66.19	67.11	67.99	68.86	69.73	70.78
71.92	73.17	74.59	76.36	77.74	79.17	80.63	82.13	83.89	85.53	87.28	89.23
90.91	89.62	88.42	87.34	86.23	85	83.87	82.82	81.59	80.43	79.55	78.91
78.29	77.65	77	76.03	75.3	74.57	74.22	73.96	73.75	73.64	73.57	73.4
73.27	73.26	73.41	73.68	74.03	74.49	75.01	75.48	75.97	76.57	77.21	77.93
78.83	79.75	80.71	81.66	82.6	83.83	84.83	85.89	87.07	88.27	89.62	90.81
90.58	89.77	89.03	88.31	87.51	86.76	86.09	85.46	85.01	84.47	84.02	

Values from Table 4.9 are considered for the zero-reference taken from the horizontal position of the pendulum. Thus, the rebound angular motion values are found by subtracting 90° from each of these values.

In Figure 4.16, a sample of data of Table 4.9 copied from Arduino and uploaded in Matlab to find the rebound angular motion is represented.

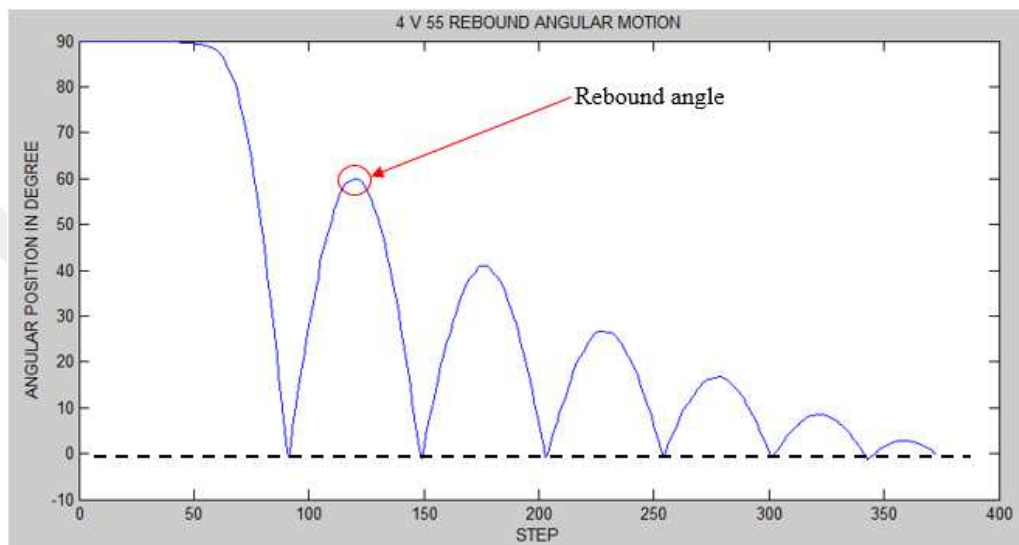


Figure 4.16 Rebound angular motion on 4 New V specimen at 55°C

For high temperature testing, two specimens from each category (Co and V) were chosen (four specimens in total). The so-called 1 New Co, 5 New Co, 2 New V (Silicon) and 4 New V (Oil-resistant). The temperature dependence curves of the rebound resilience of these samples are shown in Figures 4.17-4.20.

Table 4.10 Rebound resilience for 1 New Co specimen at 5 different temperatures (70 Shore A)

N°	Temperature $^\circ\text{C}$	Rebound Resilience
1	41	51.29%
2	46	57.36%
3	51	62.17%
4	56	65.75%
5	67	61.54%

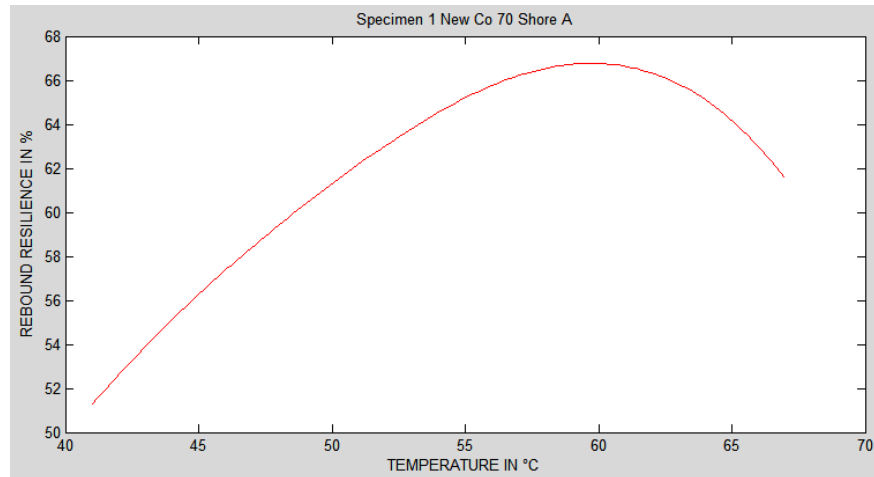


Figure 4.17 Temperature-dependent rebound resilience for 1 New Co Specimen

Table 4.11 Rebound resilience for 5 New Co specimen at 5 different temperatures (72 Shore A)

N°	Temperature °C	Rebound Resilience
1	46	55.08%
2	56	58.63%
3	68	61.72%
4	81	59.90%
5	90	57.61%

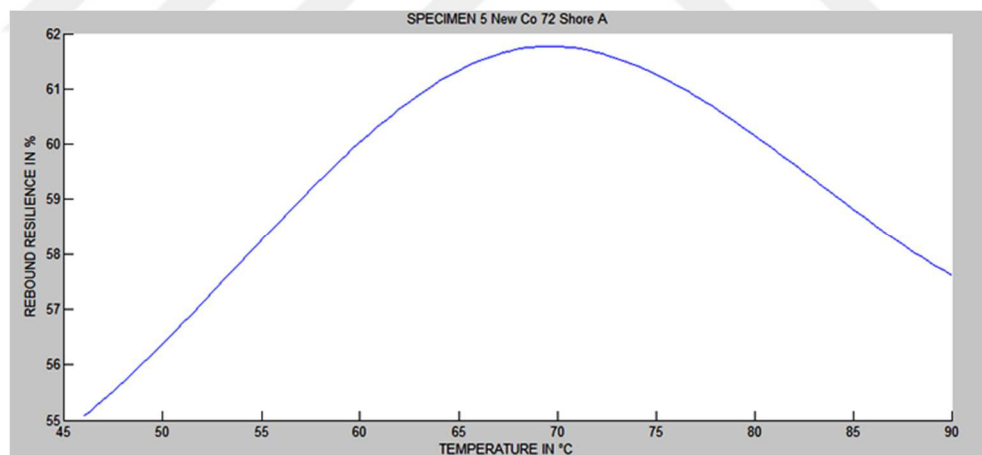


Figure 4.18 Temperature-dependent rebound resilience for 5 New Co Specimen

Table 4.12 Rebound resilience for 2 New V specimens at 5 different temperature (57 Shore A)

N°	Temperature °C	Rebound Resilience
1	42	54.99%
2	49	56.13%
3	61	59.17%
4	65	57.79%
5	70	55.82%

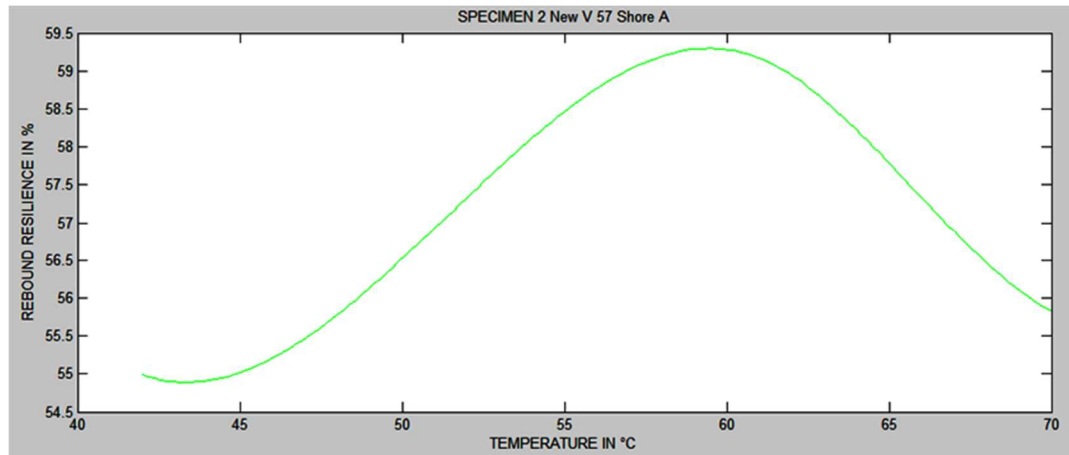


Figure 4.19 Temperature-dependent Rebound resilience for 2 New V Specimen

Table 4.13 Rebound resilience for 4 New V specimen at 5 different temperature (47 Shore A)

N°	Temperature °C	Rebound Resilience
1	55	49.79%
2	63	47.53%
3	70	49.40%
4	75	53.45%
5	80	52.70%

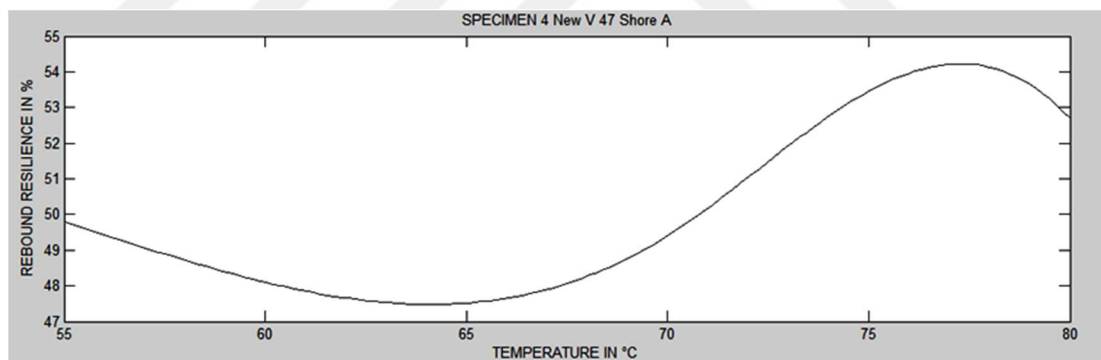


Figure 4.20 Temperature-dependent Rebound resilience for 4 New V Specimen

Superposing all the curves gives the situation shown in Figure 4.21.

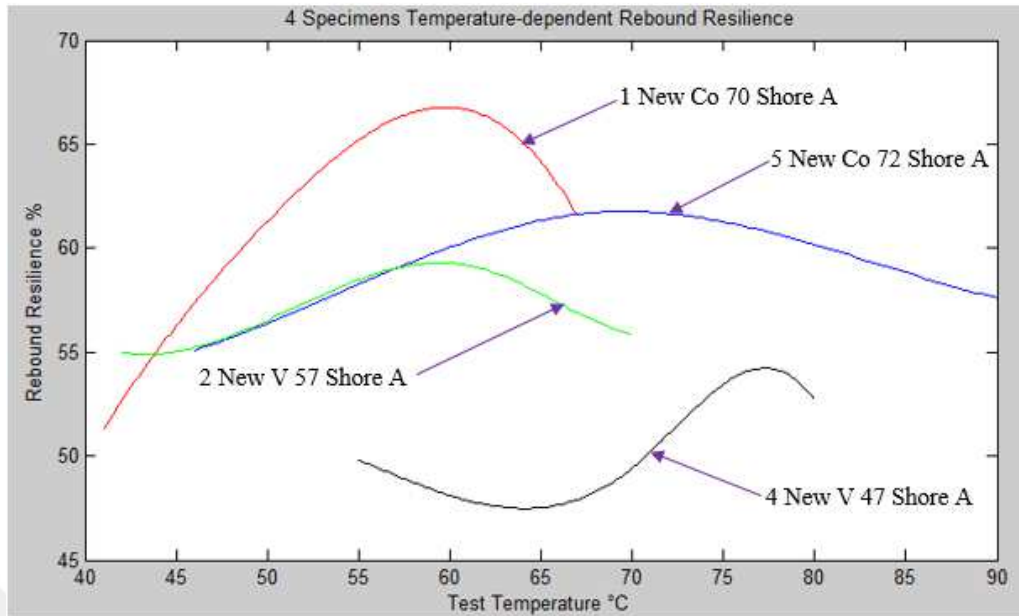


Figure 4.21 Superposition of temperature-dependent rebound resilience curves of 4 specimens

The temperature effect on Rebound resilience for various rubber from the literature is presented in Figure 4.22.

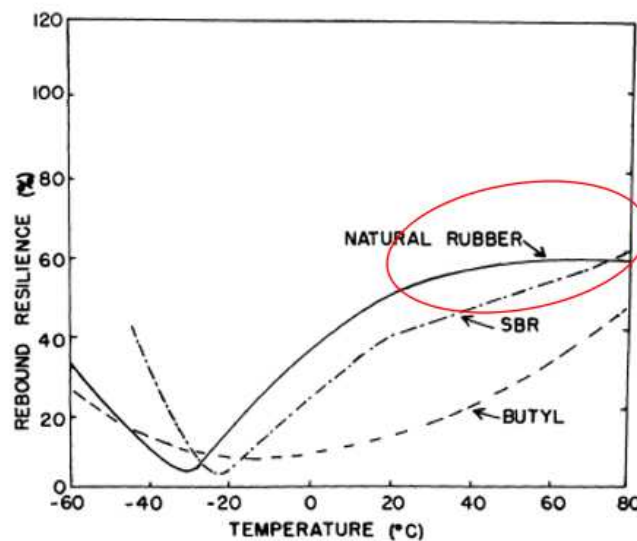


Figure 4.22 Temperature effect on rebound resilience of different rubbers (Maurice,1999)

From the natural rubber curve of Figure 4.22, we can see a similarity with the majority of curves we obtained from our tests using the the manufactured machine, considering the temperature region concerned (from around 40 °C to 80 °C). The curves have downward-facing concavity.

4.3 Test Report

The test report is presented in this section in compliance with standards as stated in Section 2.2.6.

As already stated in previous sections, in total, 20 specimens were prepared in two different processes (Period): 10 specimens on January 21, 2019 and 10 other specimens on July 19, 2019. The first manufactured specimens were out of time since the machine wasn't ready for tests at that time. That's why other specimens were prepared to meet the requirements of the standards. Natural rubber used for specimen preparation came from the Democratic Republic of Congo Mayombe forest Hevea trees (Rubber trees). The other rubber raw comes from Vietnam.

Two different specimen dimensions were used. A 13 mm thick – 32 mm in diameter (from the mold used on January 21, 2019) and a 12 mm thick – 31 mm in diameter (from the mold used on July 19, 2019). Details on the mixture used for test piece from Vietnam weren't provided however, details on test pieces from the D.R. of Congo rubber were already presented in Table 4.3 in Section 4.1.2. Test pieces were produced by molding.

Rubber from Vietnam was mixed before the date of molding. The vulcanization process started some days before mixing while test pieces from the D.R. of Congo were collected from the tree in March 2018 and came in its natural state and were vulcanized on January 21, 2019.

The test day was sunny, the temperature in the laboratory was 25.3°C measured using an infrared thermometer. For high temperature test specimens were heated over 100°C. A period of around minutes was observed before turning on the kettle. Tests started once this process of turning on and off was performed four times, in order to ensure that the rubber temperature was evenly distributed. This process was performed throughout the test. The specimens stayed in the hot bath as long as they weren't used yet for the test.

Our manufactured rebound resilience tester was used for tests, a mechanical clamp system was used as a test holder. Details on the machine components are presented in the previous chapters.

This machine design and test operations were carried out in accordance with standards. However, we should mention that, as we stated in Section 3.1.15, the 300 full oscillations friction checking has not been performed providing that the pendulum period test was successfully compliant with the standards. In addition, in high temperature testing, the rebound resilience was measured only once instead of the median value of three rebound values as the standards state. The hot water bath being separated (heating point) from the machine, the temperature difference occurred after each rebound testing, it was not evident to measure three rebound values at one specific temperature.

Tests compliant with standards were carried out on July 19, 2019, and the results are presented in the section given above.

CHAPTER FIVE

DISCUSSION OF RESULTS

In this chapter, the comments are made based on the results obtained from the tests. Here we analyze the link between natural rubber hardness and rebound resilience, the effect of rubber specimen aging on the hardness and rebound resilience, the effect of temperature on the rebound resilience and the natural rubber origin link with the rebound resilience.

5.1 Rubber Aging Effect on the Hardness

By analyzing the results presented in Table 4.4 and Table 4.5 of the test results section, where hardness tests were carried out in January 2019 and July 2019 on the same specimens, we find out that in a period of six months, the specimens have hardened on an average increase of around 10%.

5.2 Mixed Rubber Aging Effect on the Hardness

Natural rubber prepared for the last step of vulcanization (molding) was kept cold under 0°C for six months (from January to July). Without chemically alternating the composition of rubber by adding chemicals in the mixture, we observed from results given in Table 4.5 and Table 4.6 (only the first five samples are concerned) that the finished product of the molding made in July showed a greater hardness than the molded products in January, even though it was well preserved in the cold.

5.3 Relation between Rebound Resilience and Hardness

By observing different rebound resilience test results, we may say that it is difficult to link the hardness of rubber to the rebound resilience since many parameters are involved in influencing rubber properties. But if we look at the first five results (Natural rubber from the D.R. of Congo) of Tables 4.7 and 4.8, given that they refer to the same rubber mixture but hardened by aging (six months in the cold), we can clearly see that an increase in hardness leads to an increase in the rebound resilience.

5.4 Connection between Rubber Origin and the Rebound Resilience

Based on the results obtained from the tests, we observe that there is no apparent link between the rebound resilience and the origin of natural rubber. Furthermore, it should be recalled that natural rubber from the D.R. of Congo had a hyper sticky characteristic, different from rubber from Vietnam so that it was very difficult to mix it alone in the drum (roll-mill) without adding some Vietnamese rubber. Based on this observation, natural rubber from Congo would be better suited for applications where the sticky character is a necessary asset. Finally, it should be noted that the rubber rebound resilience depends on other factors such as vulcanization, additives, etc., rather than the origin.

5.5 The Effect of Temperature on the Rebound Resilience

Referring to the test results presented in Figures 4.17- 4.21, we can conclude that the temperature increase leads to an increase in rubber (natural) rebound resilience. The curve has a downward-oriented concavity. 75 % of the tested specimens have a similar curvature. The rebound resilience reaches a maximum value and then decreases. The maximum point of each specimen differs. This depends on the type of rubber and vulcanization conditions. Comparing the results of our tests with the results in the literature (Figure 4.22), we observe a similarity of the natural rubber curve in the domain of temperature of our tests (between 40 °C and 80 °C).

CHAPTER SIX

CONCLUSIONS

In this thesis study entitled as “Design And Implementation of Energy Absorption Test Apparatus”. A test apparatus was designed and manufactured for rubber testing. A Schob type pendulum was used to measure the rebound resilience of rubber and rubber-like (Silicon) materials having a Shore A hardness between 30 and 85 according to DIN 53512, ISO 4662 or ASTM D7121 standard.

After the theoretical review on rebound resilience testers, the design and manufacturing of the machine components was carried out, then followed the tests on the manufactured machine, the discussion of the test results, to end up with the present conclusion.

This work is closely involved in the process of developing new products to improve the living conditions of human society and the enrichment of scientific literature. A number of basic engineering applications have entered into action for this project, starting with computer-aided design, electronics, laser-cut manufacturing, plastic 3D printing, machining, mounting, fitting, mold, testing, etc. At the end of the manufacturing process, a basic electronic circuit was made to collect data from the dynamic angular positions of the pendulum in real-time, using Arduino and the gyro-accelerator device MPU6050. Tracked data were transferred to Matlab to find the value of rebound resilience. Two software were used for this purpose, Arduino and Matlab.

Using a unique design based on international standards and a unique test data collection technique, this machine will be used to evaluate the energy absorption capacity of rubber materials subjected to repeated dynamic shocks. The apparatus weighs approximately 45 kg, measuring 345.82 mm long when the pendulum is in the vertical position and reaches 524.49 mm with the pendulum positioned horizontally. It is 200 mm wide and 353.5 mm high. The pendulum measures 200 mm with an impact mass of 254.92 g.

To perform the tests on the apparatus, a total of 20 specimens were molded. In reality, the goal was to make 10 natural rubber-based specimens divided into two categories (five specimens for each category). One category from Vietnam and another category from the Hevea trees (Rubber trees) of the Mayombe rainforest in the Democratic Republic of Congo. The first set of specimens was manufactured in January 2019. But the machine wasn't yet available (finished) for testing before the time required for testing by the standards after the vulcanization process. So the first specimens were declassified. The second series of specimens were manufactured in July 2019 when the machine was finished and the tests were carried out seven days after the vulcanization. After completing the tests on the machine, the results can be summarized as follows:

- We find out that in a period of six months, the specimens have hardened on an average increase of around 10%.
- It is difficult to link the hardness of rubber to the rebound resilience since many parameters are involved in influencing rubber properties. However, by observing the results of hardness testing on the natural rubber from the D.R. of Congo, we can clearly see that an increase in hardness leads to an increase in rebound resilience.
- Natural rubber was mixed and made ready for the last step of vulcanization (molding) and kept cold for six months (Until July), produced harder finished product than rubber produced just after the mixing process (in January).
- We observed that there is no apparent link between the rebound resilience and the origin of natural rubber. However, natural rubber from the D.R. of Congo was found to be stickier and could be better suited for applications where stickiness is an asset.
- The temperature increase leads to an increase in the rubber (natural) rebound resilience in some range, in a curve showing a downward-oriented concavity. The rebound resilience reaches a maximum value and starts to decrease. We observed the similarity of the natural rubber curve in the temperature domain of tests (between 40 °C and 80 °C) with the results available in the literature.

Like any project, we also faced a few challenges in the realization of this project such as, some components were manufactured with some mistakes that we were forced to fix (anvil hole came a little bit bigger than the anvil thread and the pendulum shaft came running idle into the bearings), the test time exceeded for the first rubber specimens, changing the design of the pendulum release system when the solenoid could not release the pendulum, testing at different temperatures from room temperature according to standard rules, etc.

Some future prospects for improving this apparatus, for instance, reading test data faster through an LCD screen, including heating and cooling on the machine for more effective testing and use a faster release device, can be advised.

We hope that this master thesis contributes to the creation of a new brand for our industries and brings unveiled knowledge to the university.

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APPENDICES

Appendix 1: Motor Holder 2D Drawing

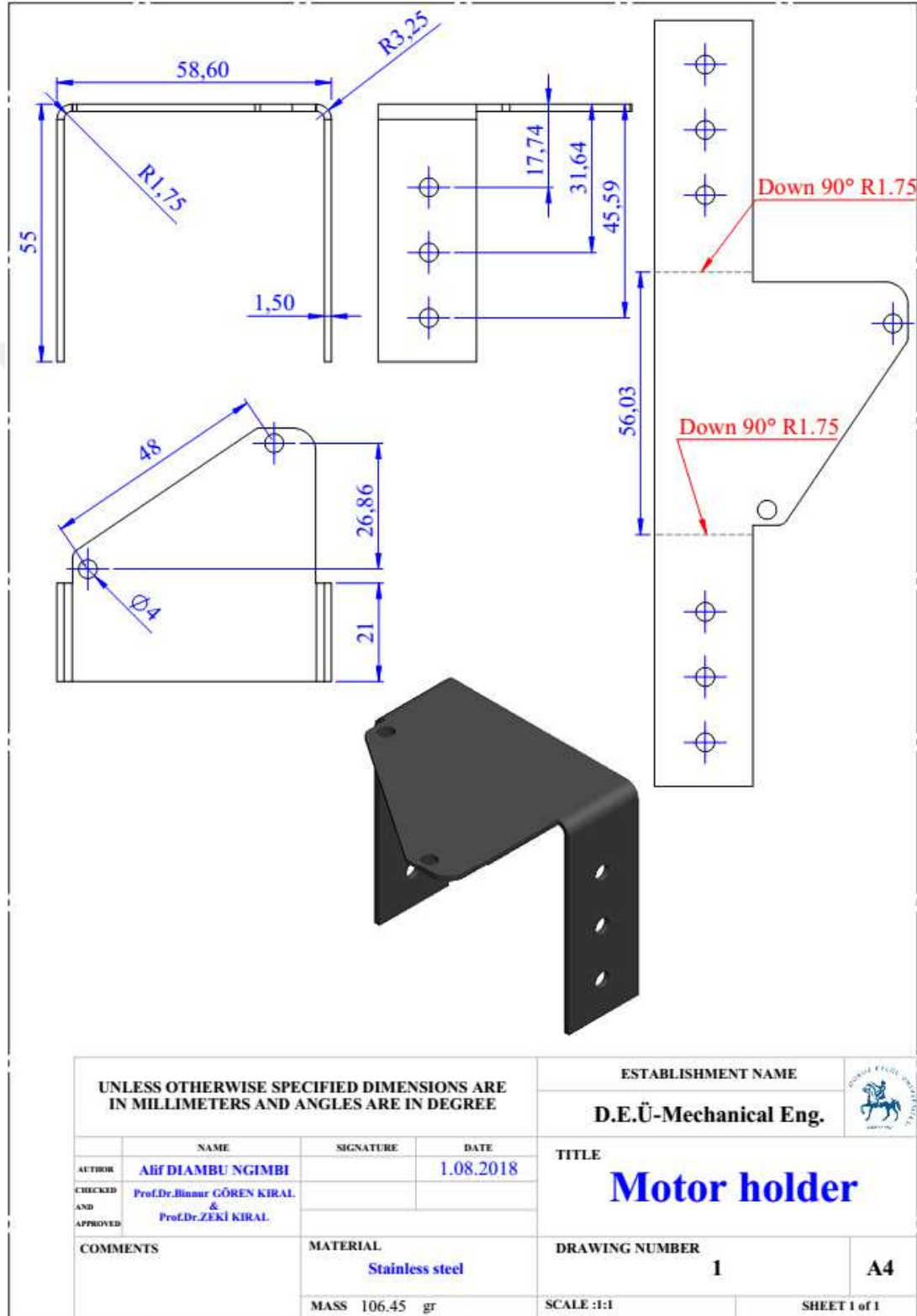


Figure A.1 Motor holder

Appendix 2 : Top Body 2D Drawing

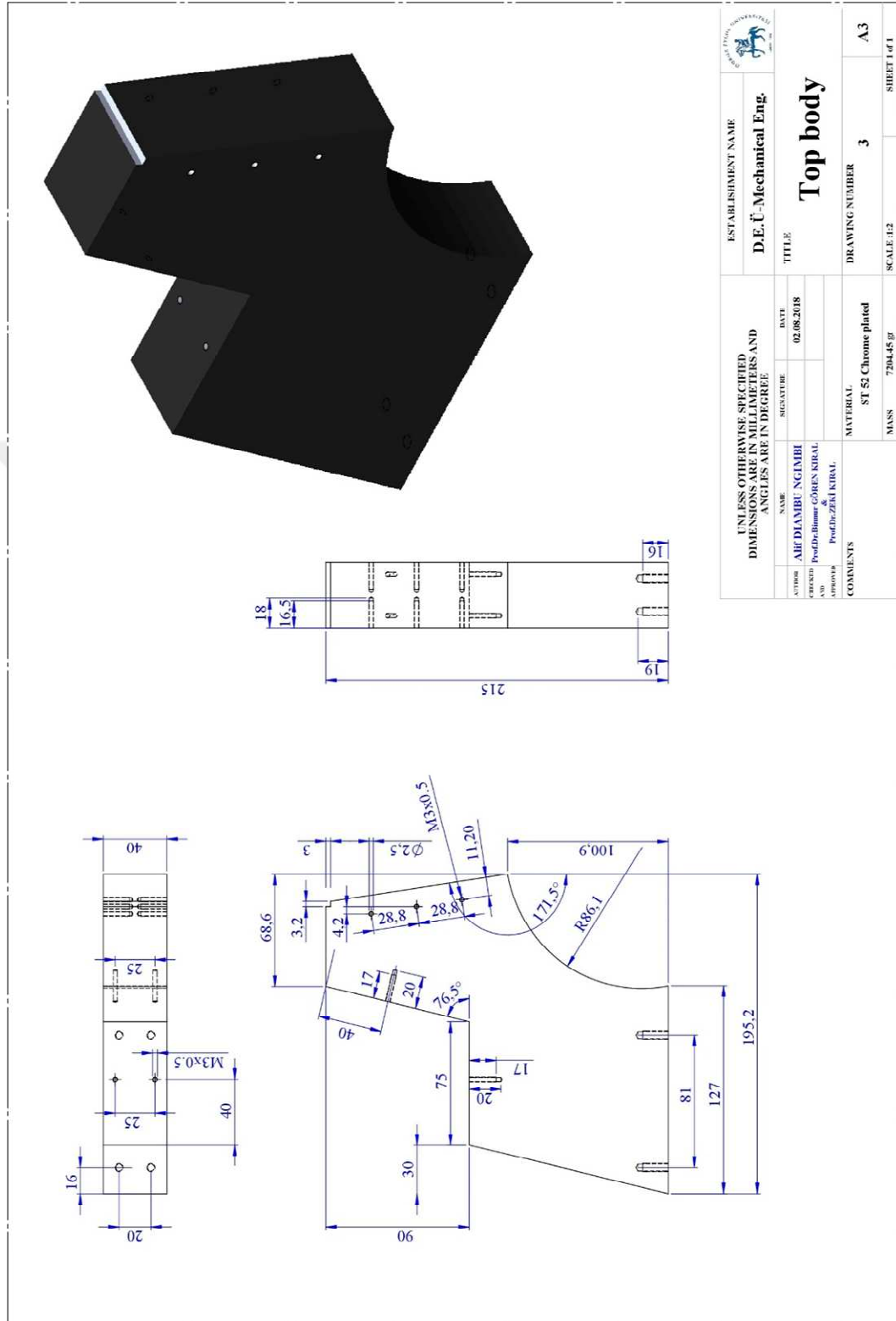


Figure A.2 Top body

Appendix 3: Back Cover-Electronic Box A 2D Drawing

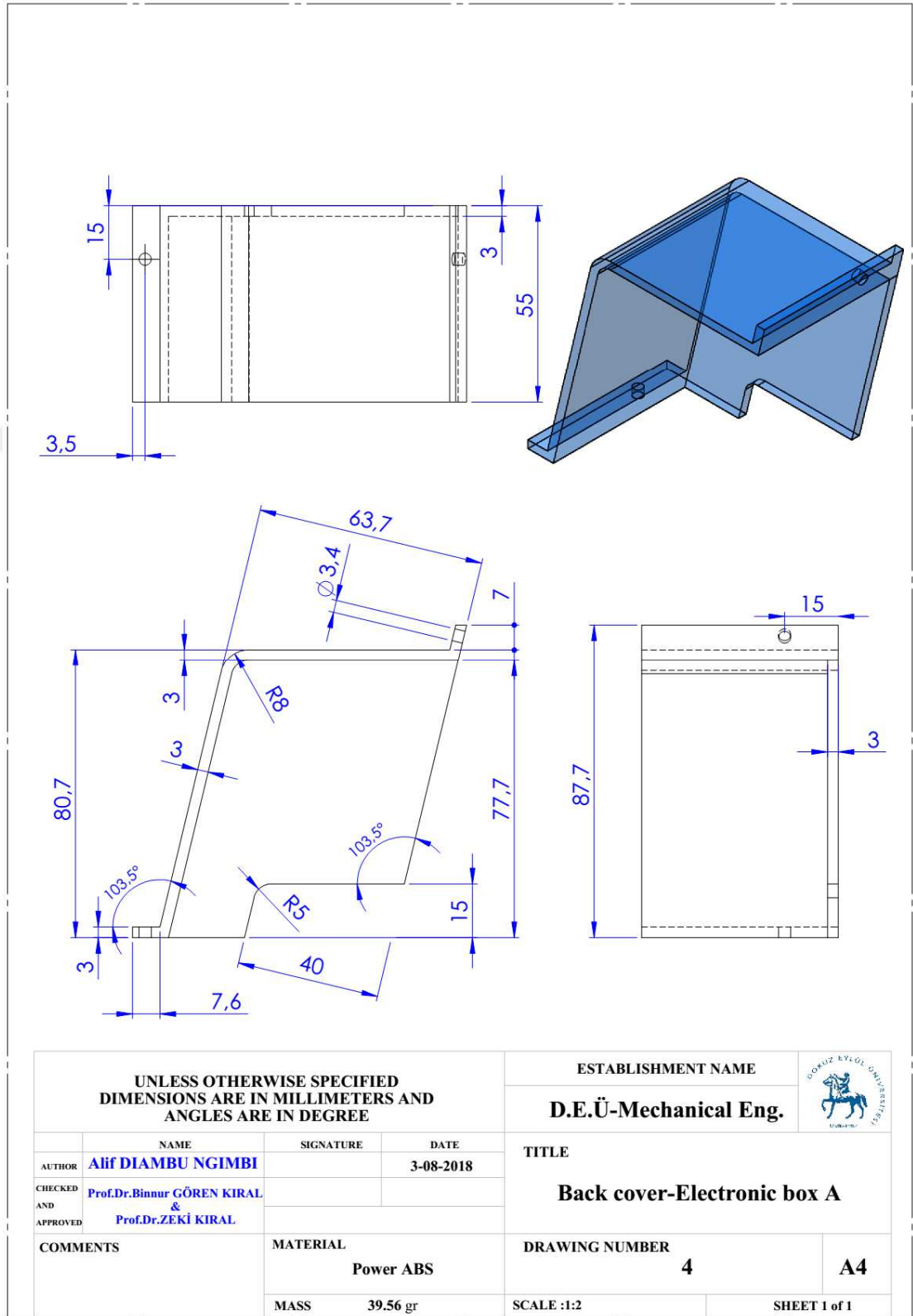


Figure A.3 Back cover-Electronic box A

Appendix 4: Back Cover-Electronic Box 2D Drawing

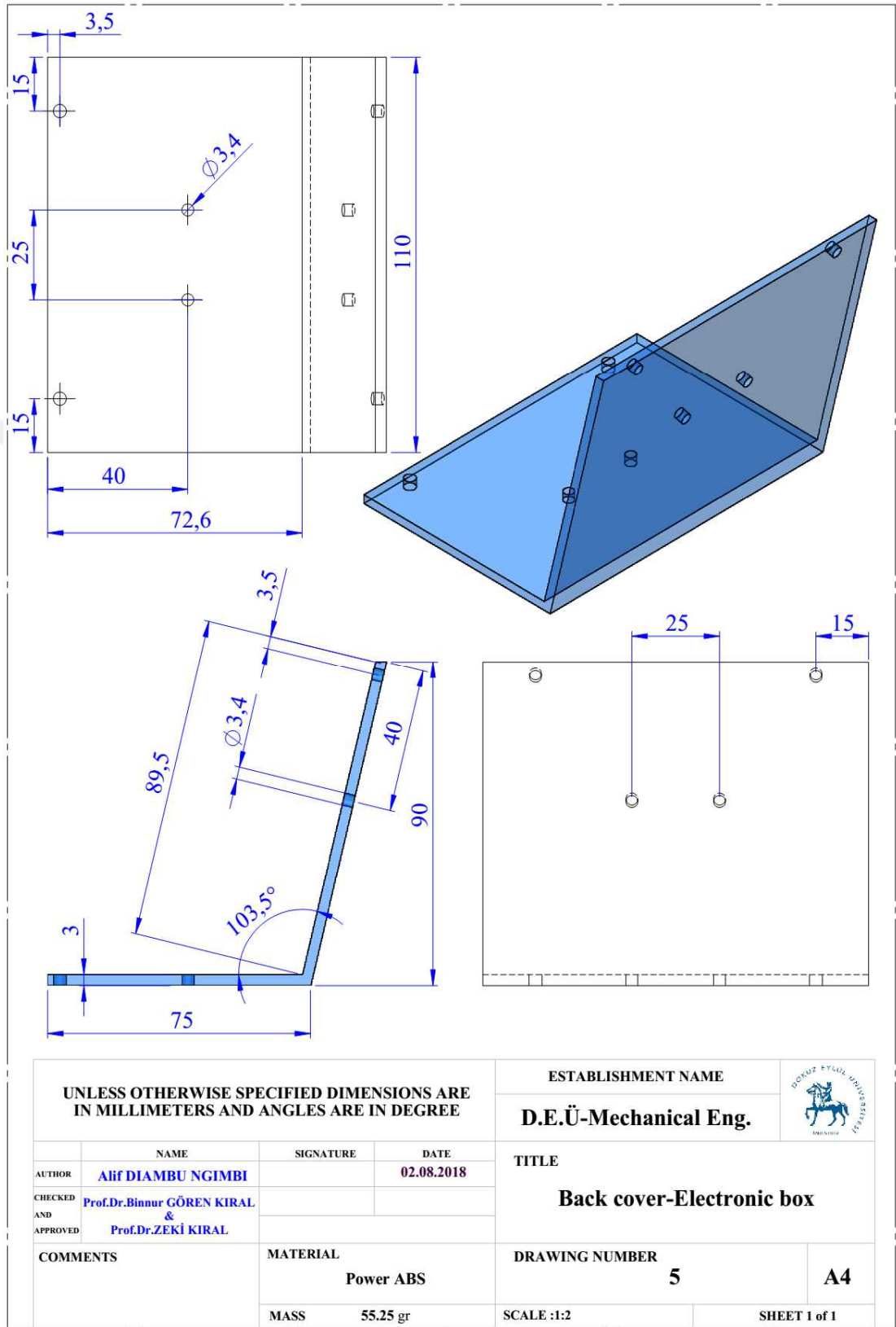


Figure A.4 Back cover-Electronic box

Appendix 5: Back Cover-Electronic Box B 2D Drawing

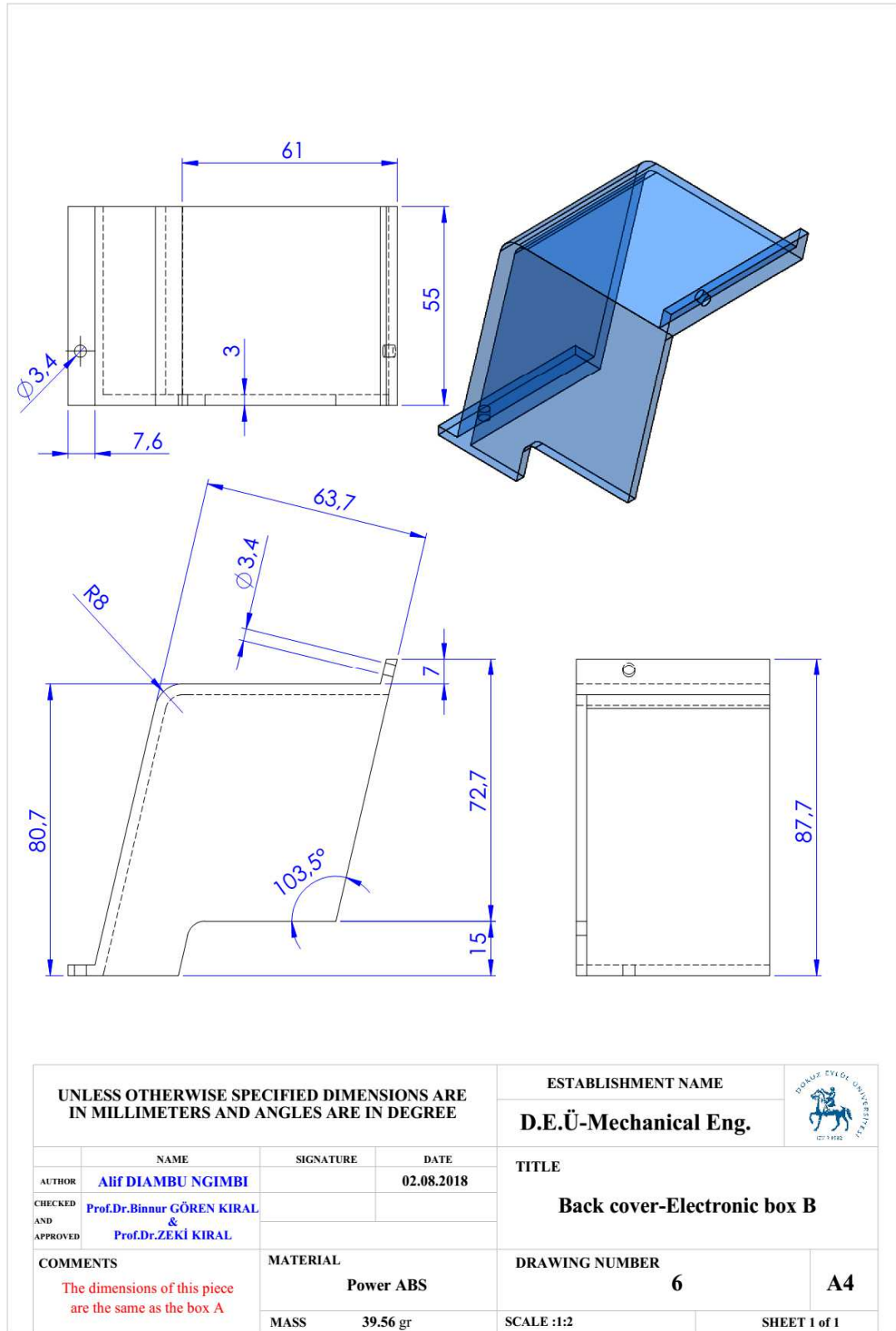


Figure A.5 Back cover-Electronic box B

SECTION A-A
SCALE 3 : 5

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS AND ANGLES ARE IN DEGREE

ESTABLISHMENT NAME	D.E.Ü-Mechanical Eng.		
TITLE	Middle body		
DRAWING NUMBER	12	A3	
DATE	02.08.2018		
SIGNATURE			
NAME	Prof.Dr. Zeki KURAL		
APPROVED	Prof.Dr. Bülent GÖREN KURAL		
APPROVED	Prof.Dr. Zeki KURAL		
MATERIAL	ST 52 Chrome plated		
MASS	1586.79 gr		
COMMENTS			

1

Appendix 7: Machine Stand 2D Drawing

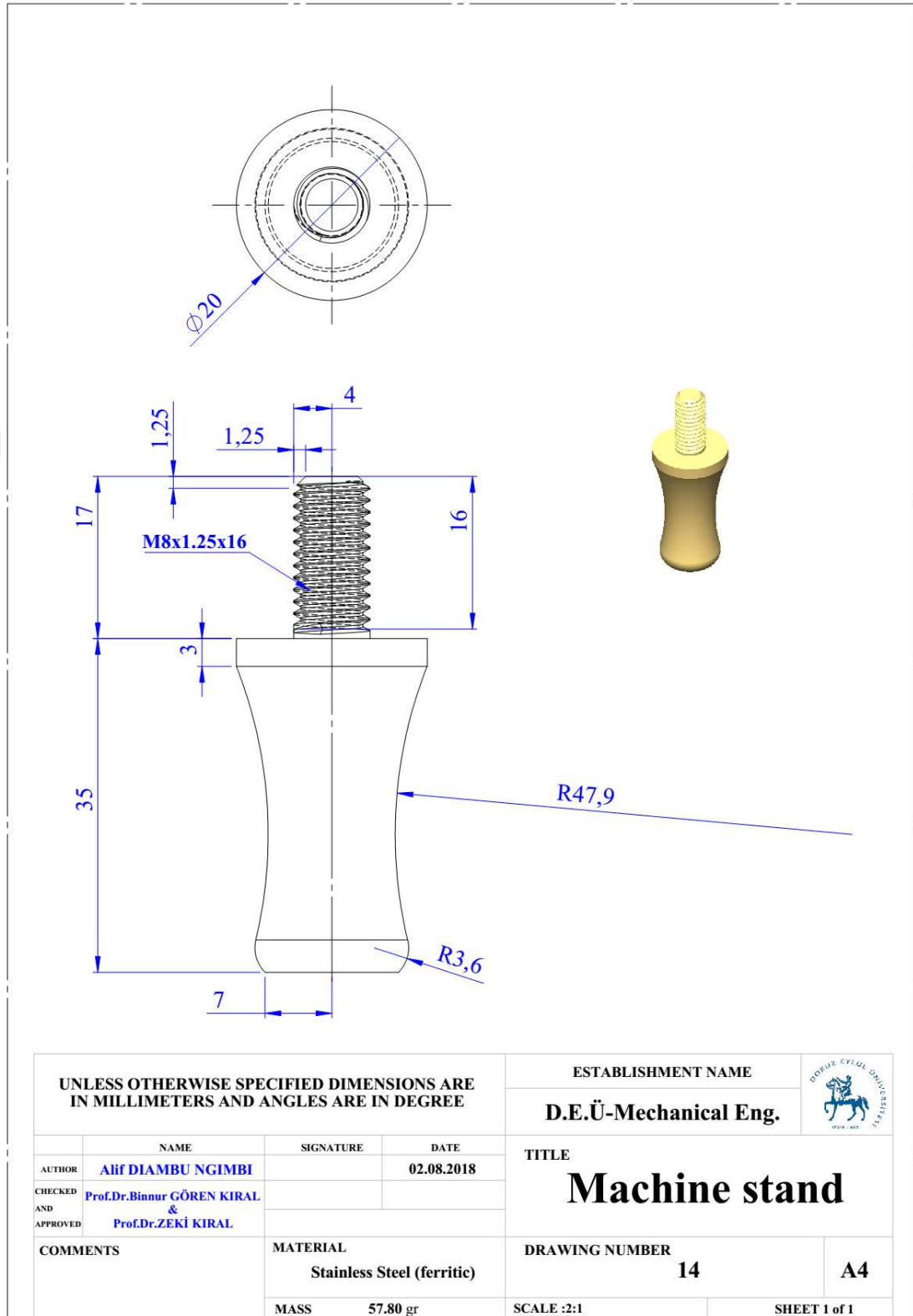


Figure A.7 Machine stand

Appendix 8: Bottom Plate 2D Drawing

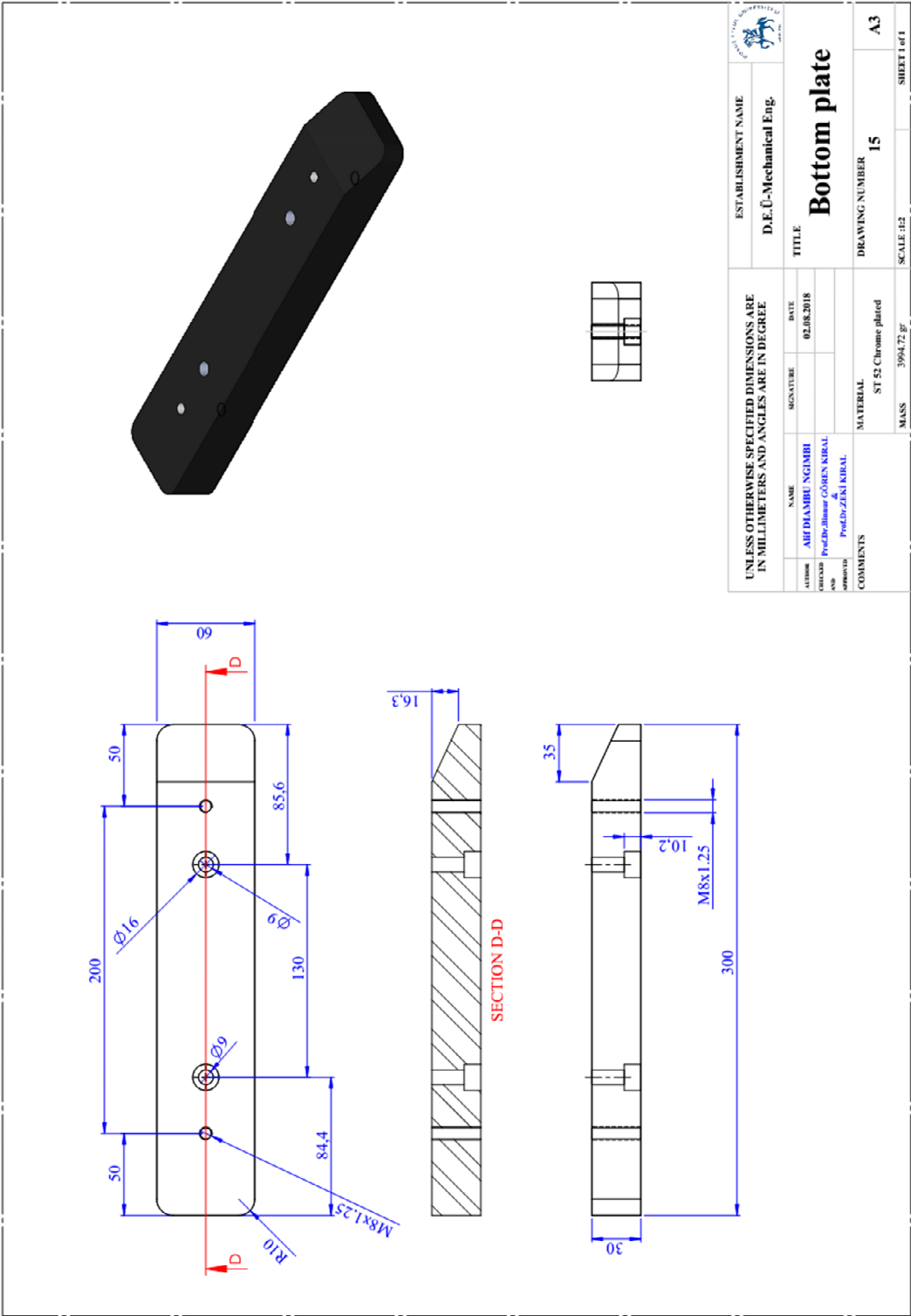


Figure A.8 Bottom plate

[illegible]

Figure A.9 Bottom body

Appendix 10: Piece Holder 2D Drawing

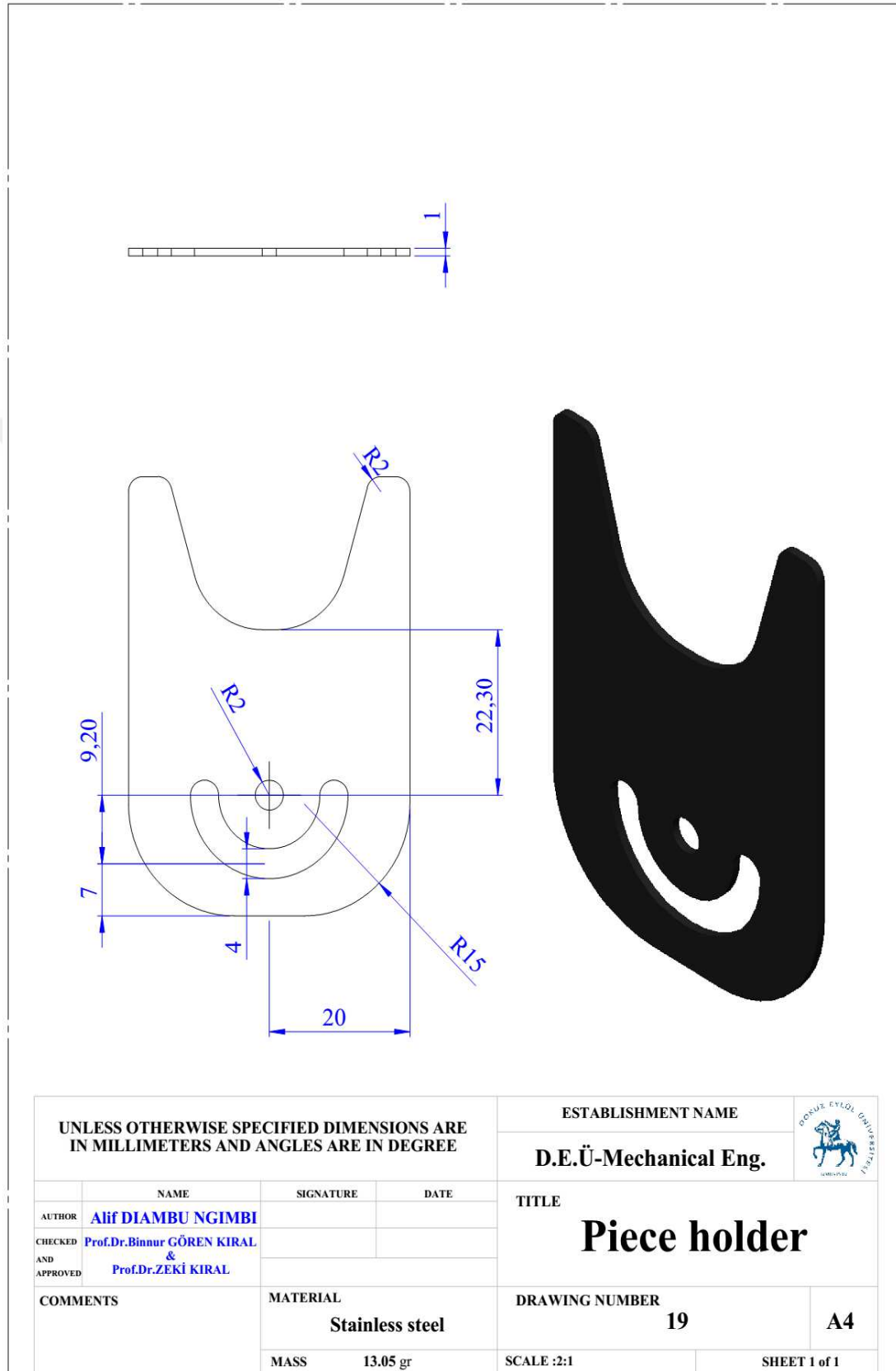


Figure A.10 Piece holder

Appendix 11: Anvil Hole 2D Drawing

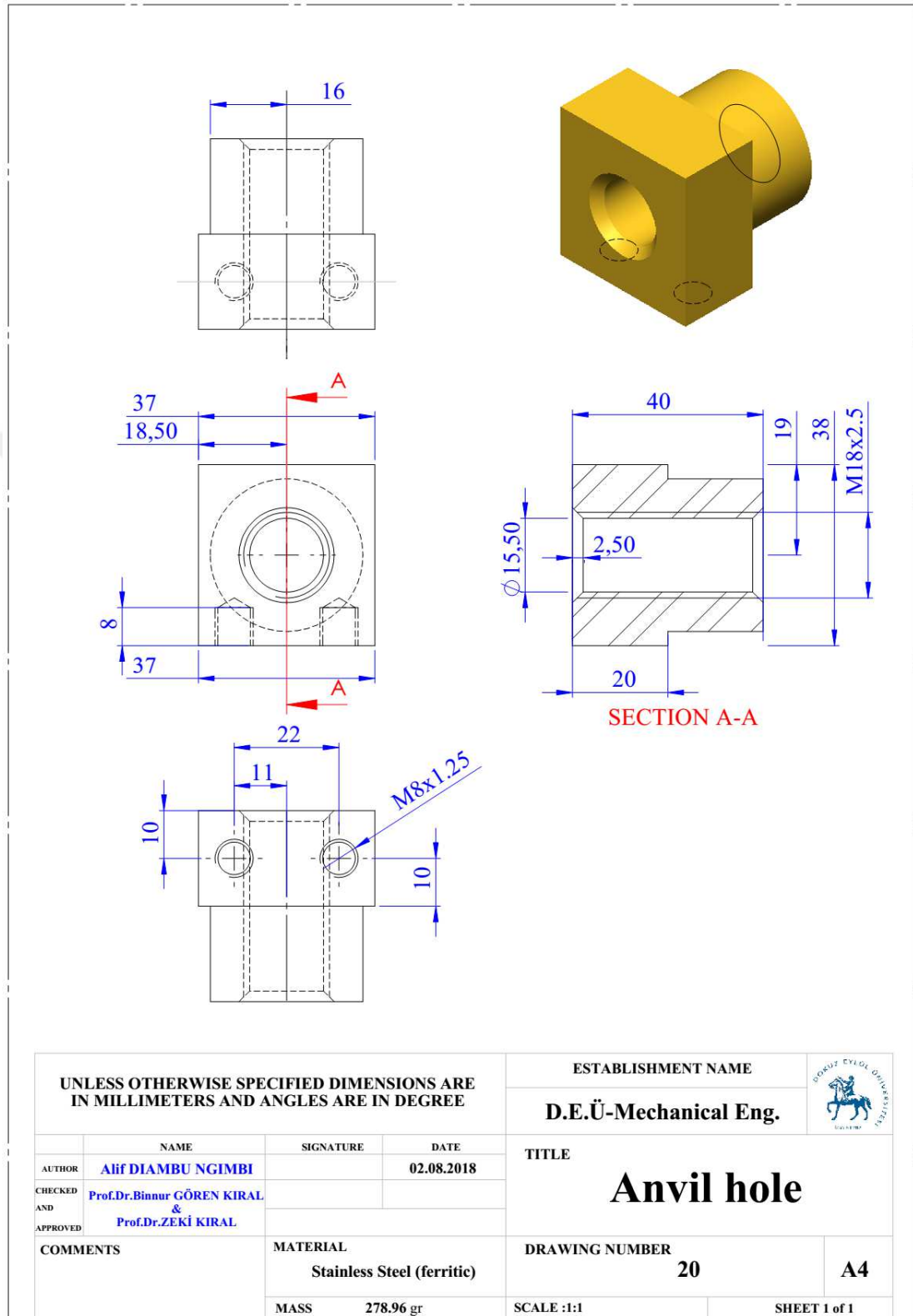


Figure A.11 Anvil hole

Appendix 12: MPU6050 Box 2D Drawing

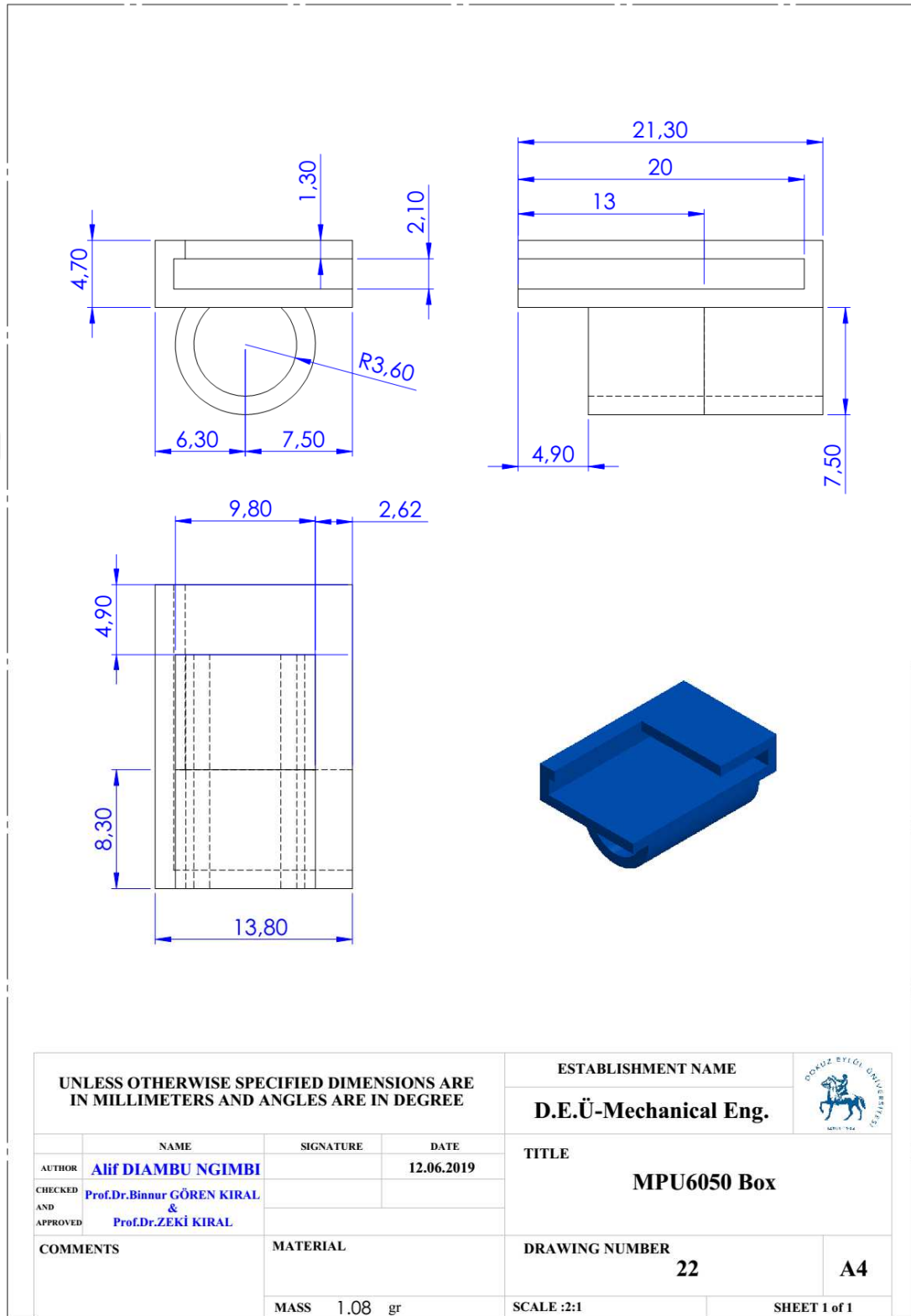


Figure A.12 MPU6050 box

Appendix 13: Anvil 2D Drawing

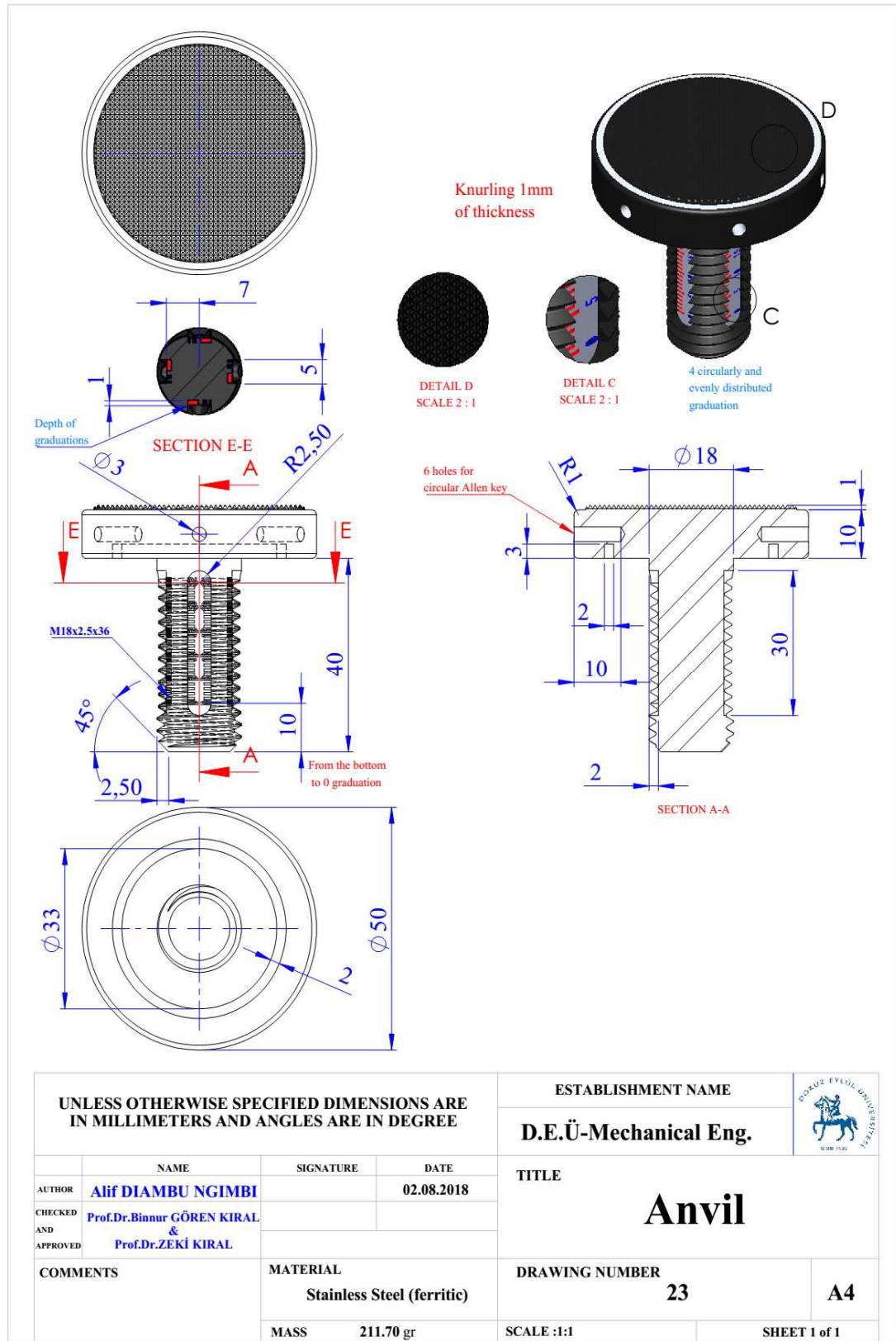
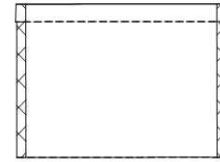
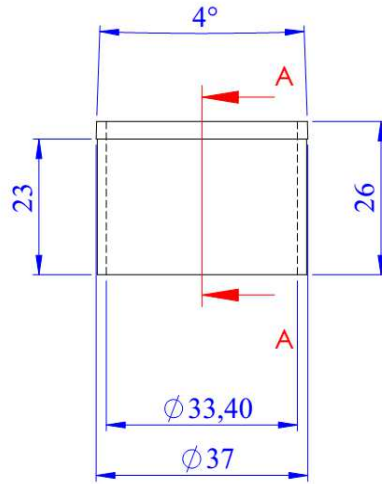
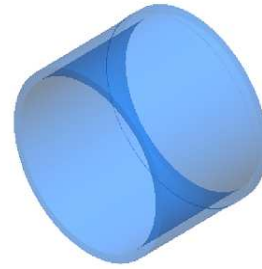
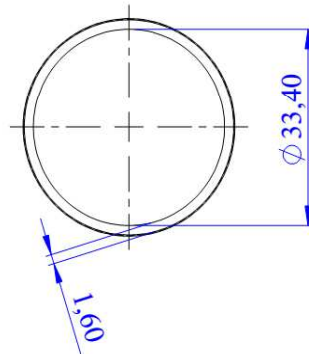


Figure A.13 Anvil

Appendix 14: Dust Filter 2D Drawing



SECTION A-A



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS AND ANGLES ARE IN DEGREE				ESTABLISHMENT NAME		
				D.E.Ü-Mechanical Eng.		
	NAME	SIGNATURE	DATE	TITLE Dust filter		
AUTHOR	Aliif DIAMBU NGIMBI		12.06.2019			
CHECKED AND APPROVED	Prof.Dr.Binnur GÖREN KIRAL & Prof.Dr.ZEKİ KIRAL					
COMMENTS		MATERIAL Power ABS		DRAWING NUMBER 24		A4
		MASS	4.72 gr	SCALE :1:1	SHEET 1 of 1	

Figure A.14 Dust filter

Appendix 15: Test Specimen 2D Drawing

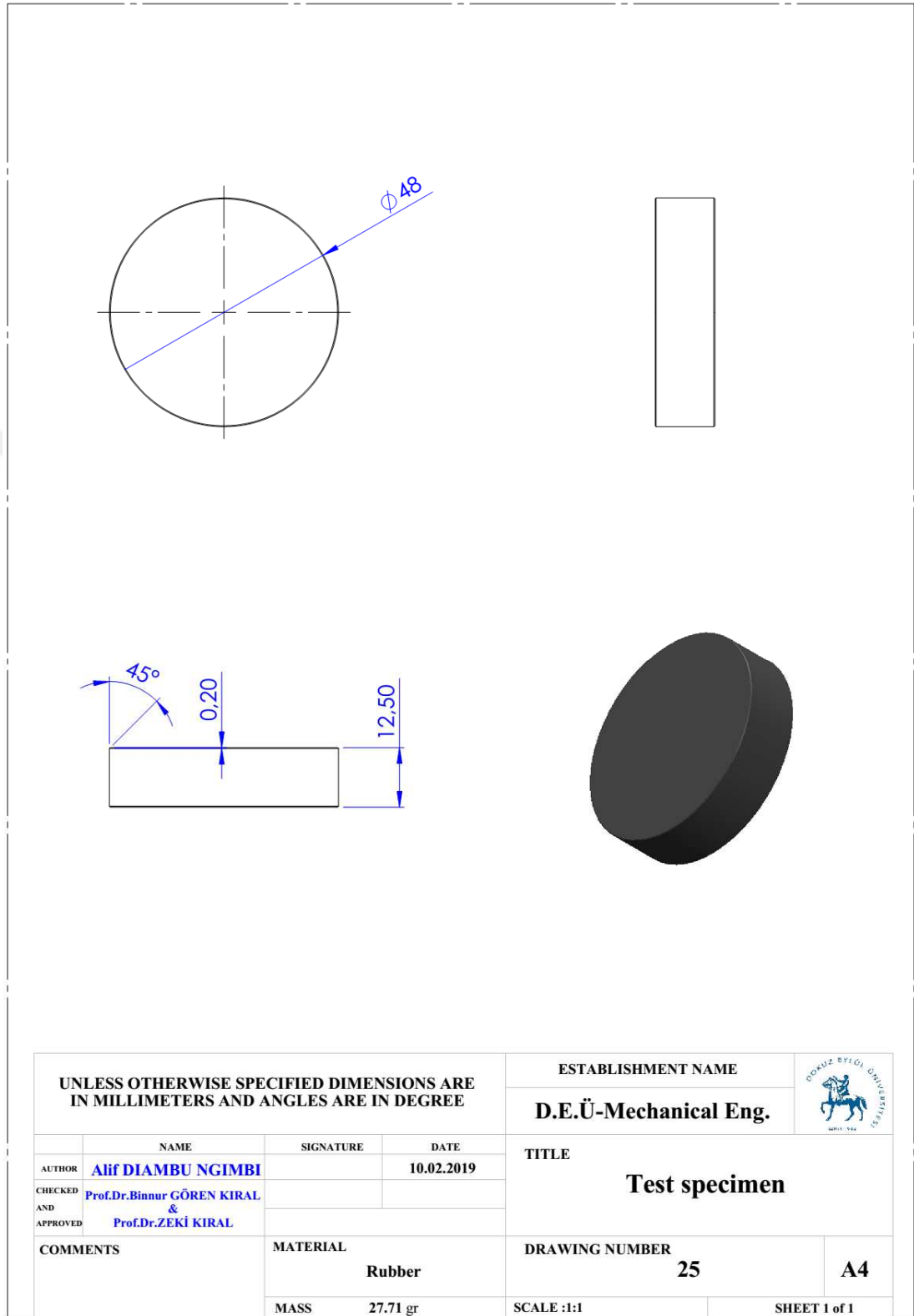


Figure A.15 Test specimen

Appendix 16: Pendulum Release 2D Drawing

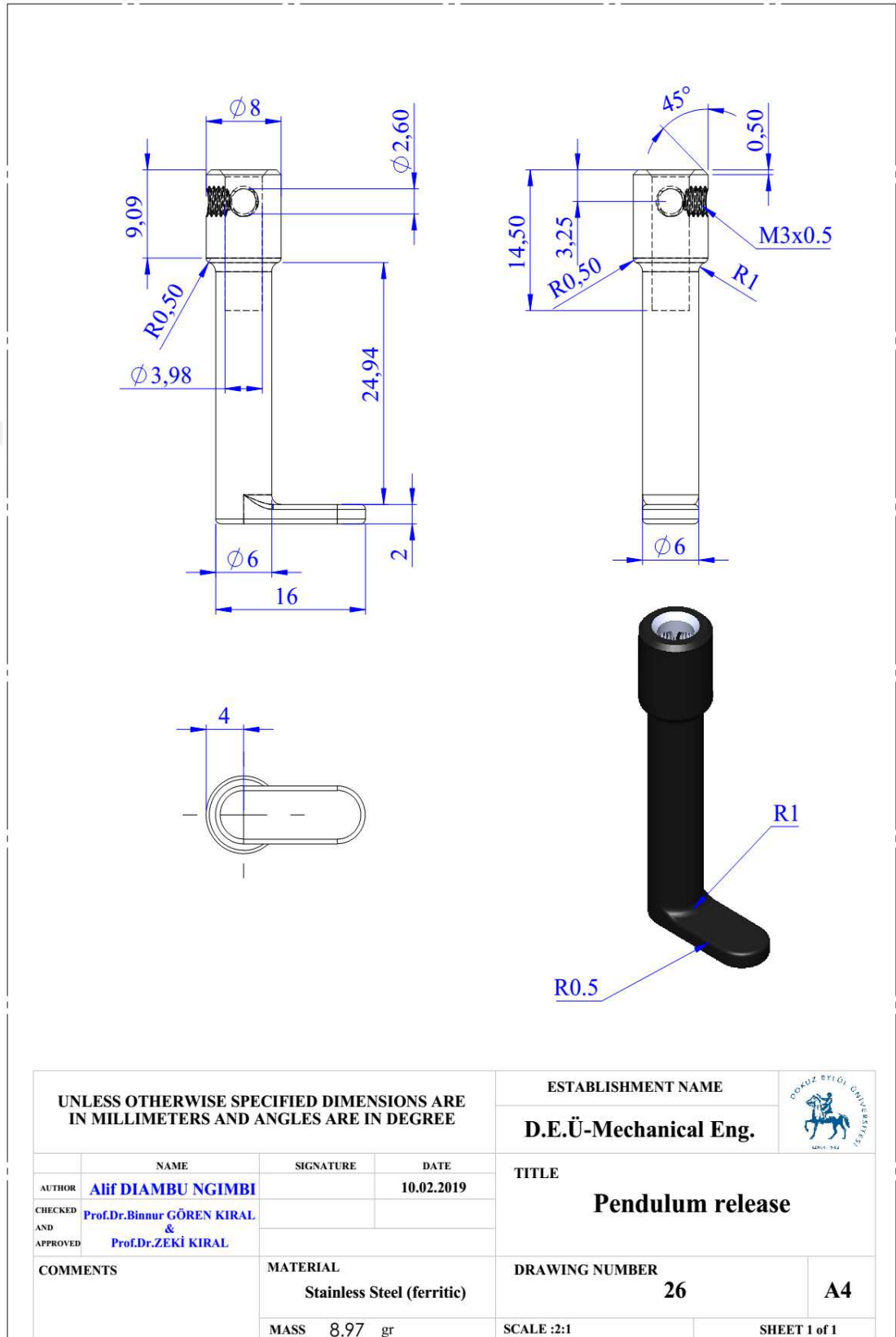
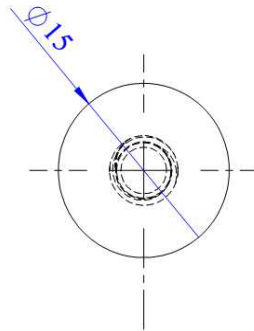
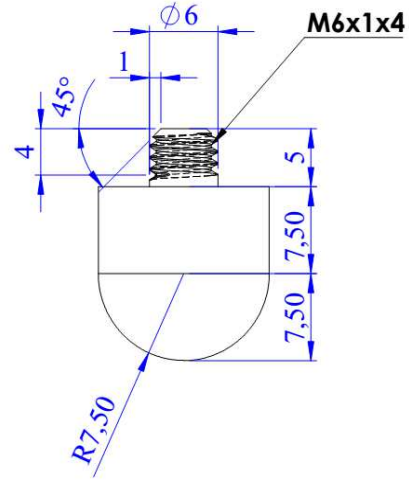


Figure A.16 Pendulum release

Appendix 17: Pendulum Indentor 2D Drawing



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS AND ANGLES ARE IN DEGREE				ESTABLISHMENT NAME		
				D.E.Ü-Mechanical Eng.		
	NAME	SIGNATURE	DATE	TITLE Pendulum indentor		
AUTHOR	Alif DIAMBU NGIMBI		02.08.2018			
CHECKED AND APPROVED	Prof.Dr.Binnur GÖREN KIRAL & Prof.Dr.ZEKİ KIRAL					
COMMENTS		MATERIAL		DRAWING NUMBER		A4
		Stainless Steel (ferritic)		28		
		MASS	18.13 gr	SCALE :2:1		SHEET 1 of 1

Figure A.17 Pendulum indentor

Appendix 18: Pendulum Hammer 2D Drawing

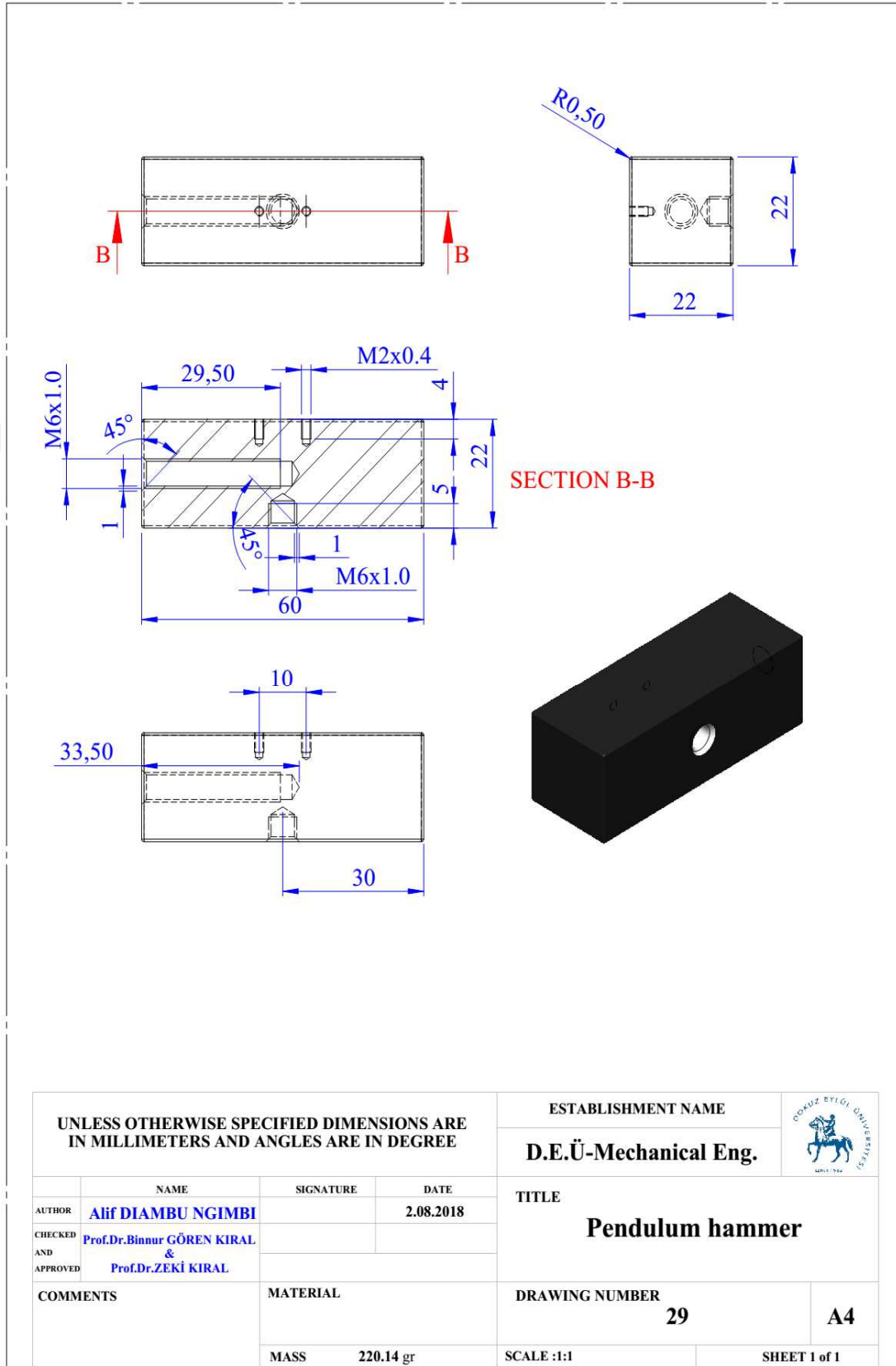


Figure A.18 Pendulum hammer

Appendix 19: Pendulum Hammer Load Balance 2D Drawing

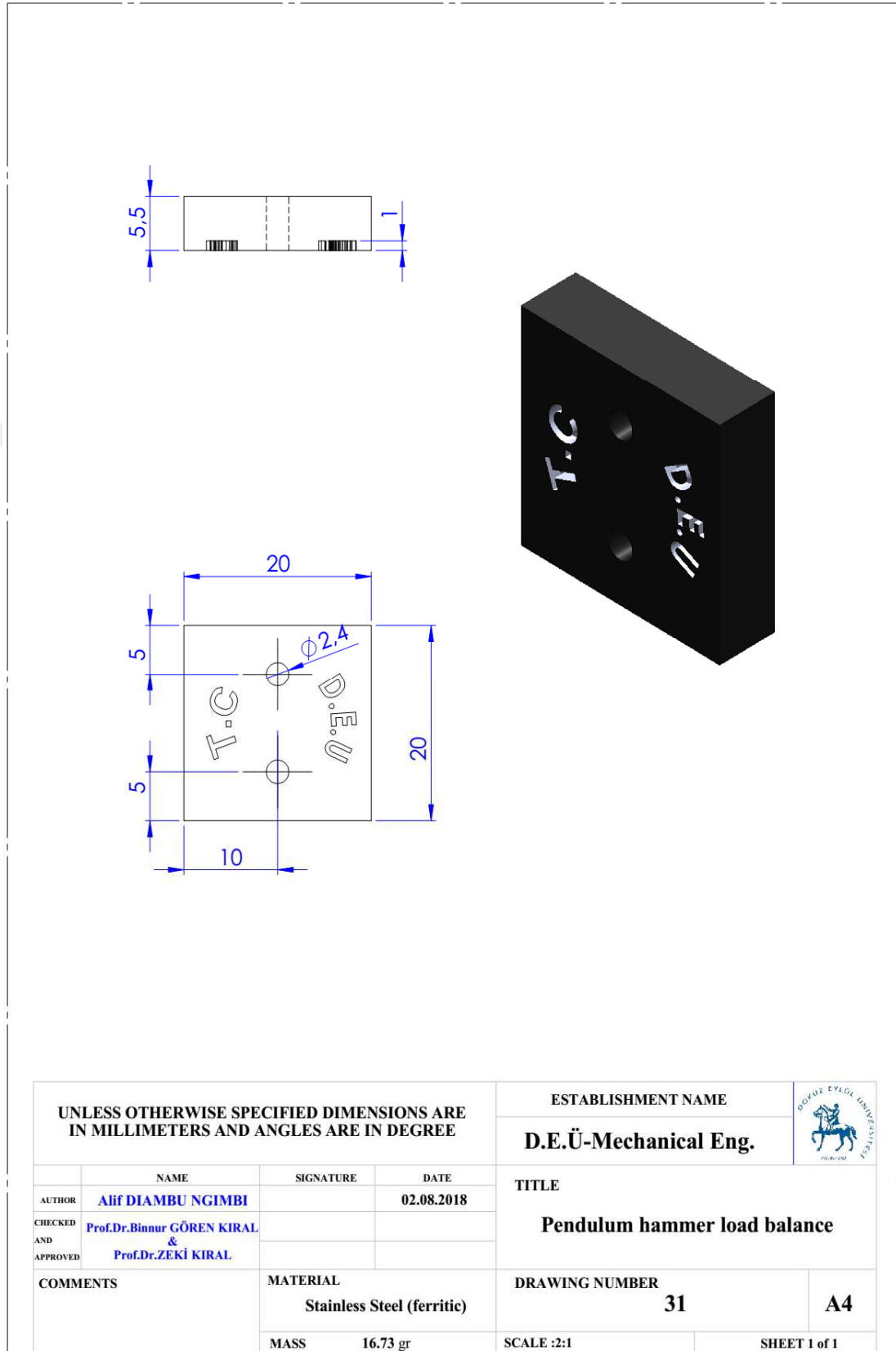


Figure A.19 Pendulum hammer load balance

Appendix 20: Pendulum Rod 2D Drawing

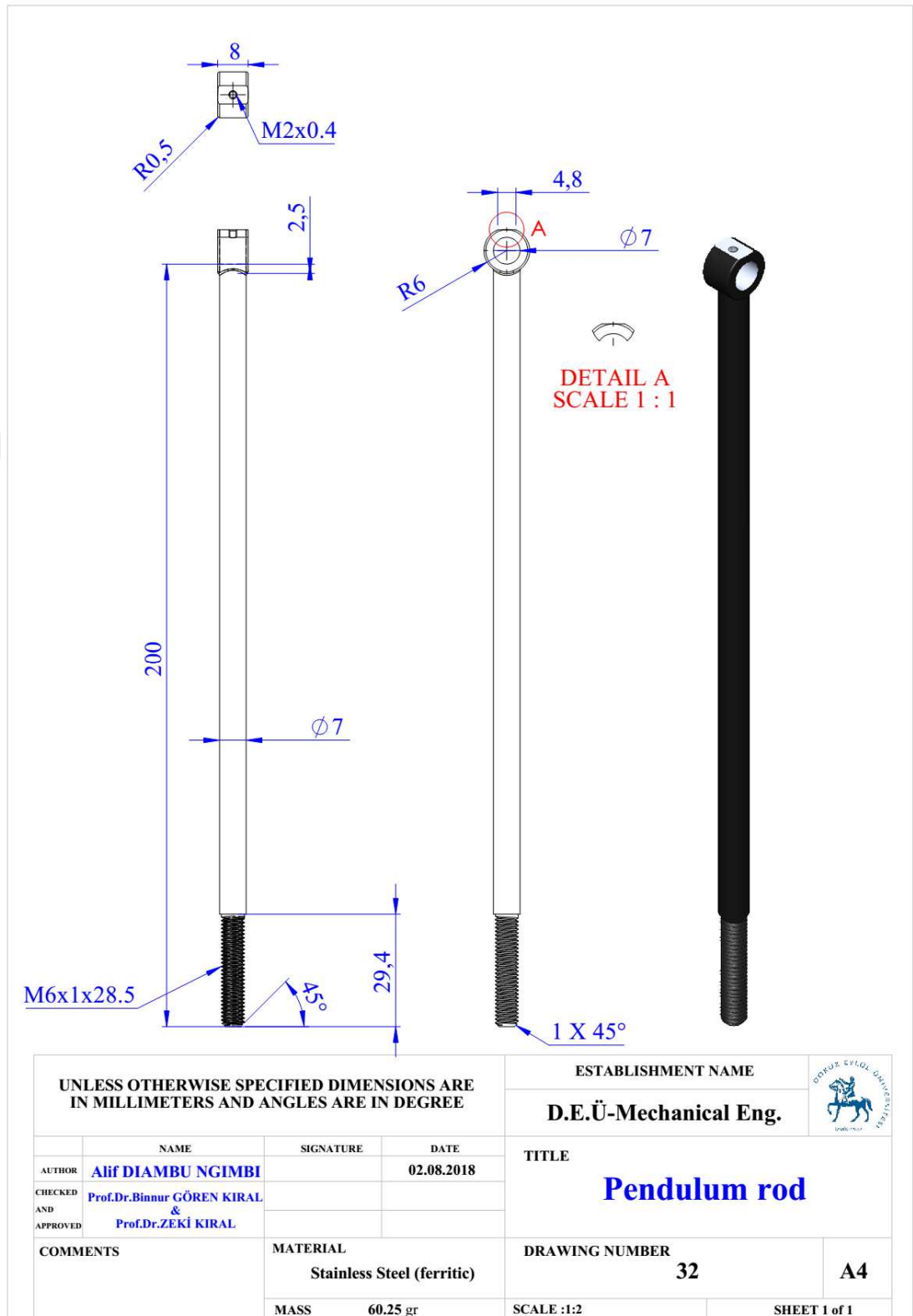


Figure A.20 Pendulum rod

Appendix 21: Left Plate 2D Drawing

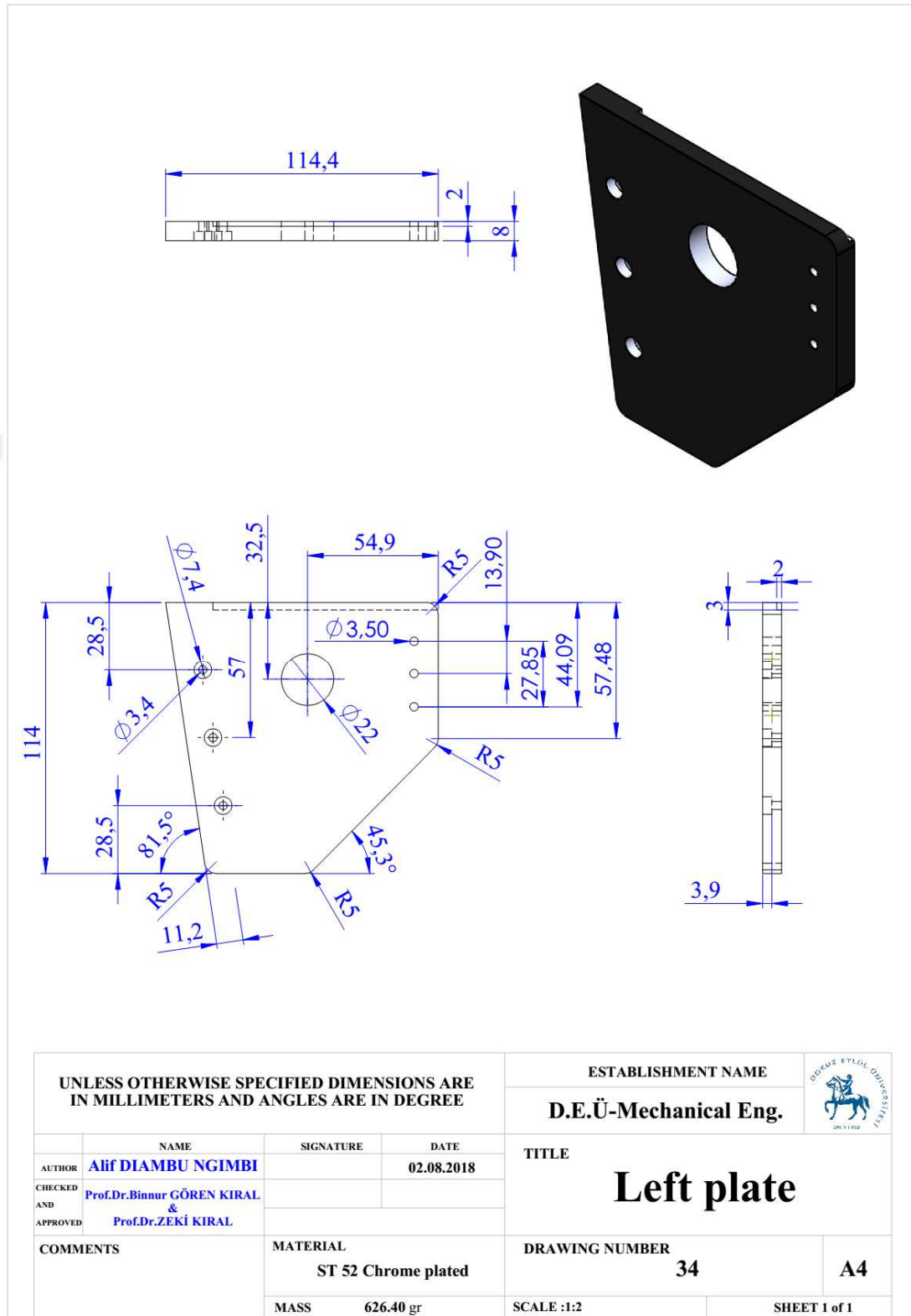


Figure A.21 Left plate

Appendix 22: Right Plate 2D Drawing

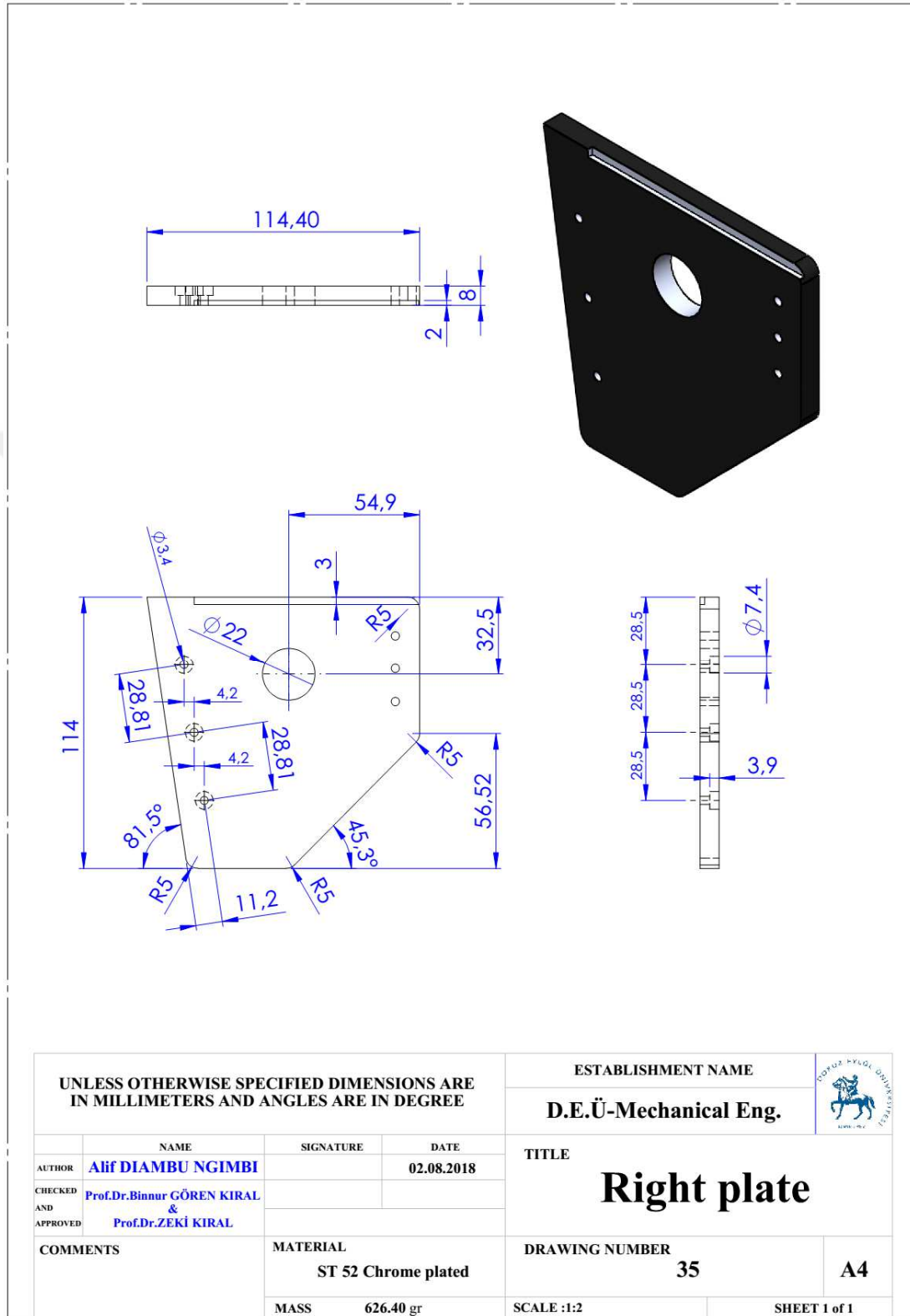


Figure A.22 Right plate

Appendix 23: Shaft of the Pendulum Rotary Axis 2D Drawing

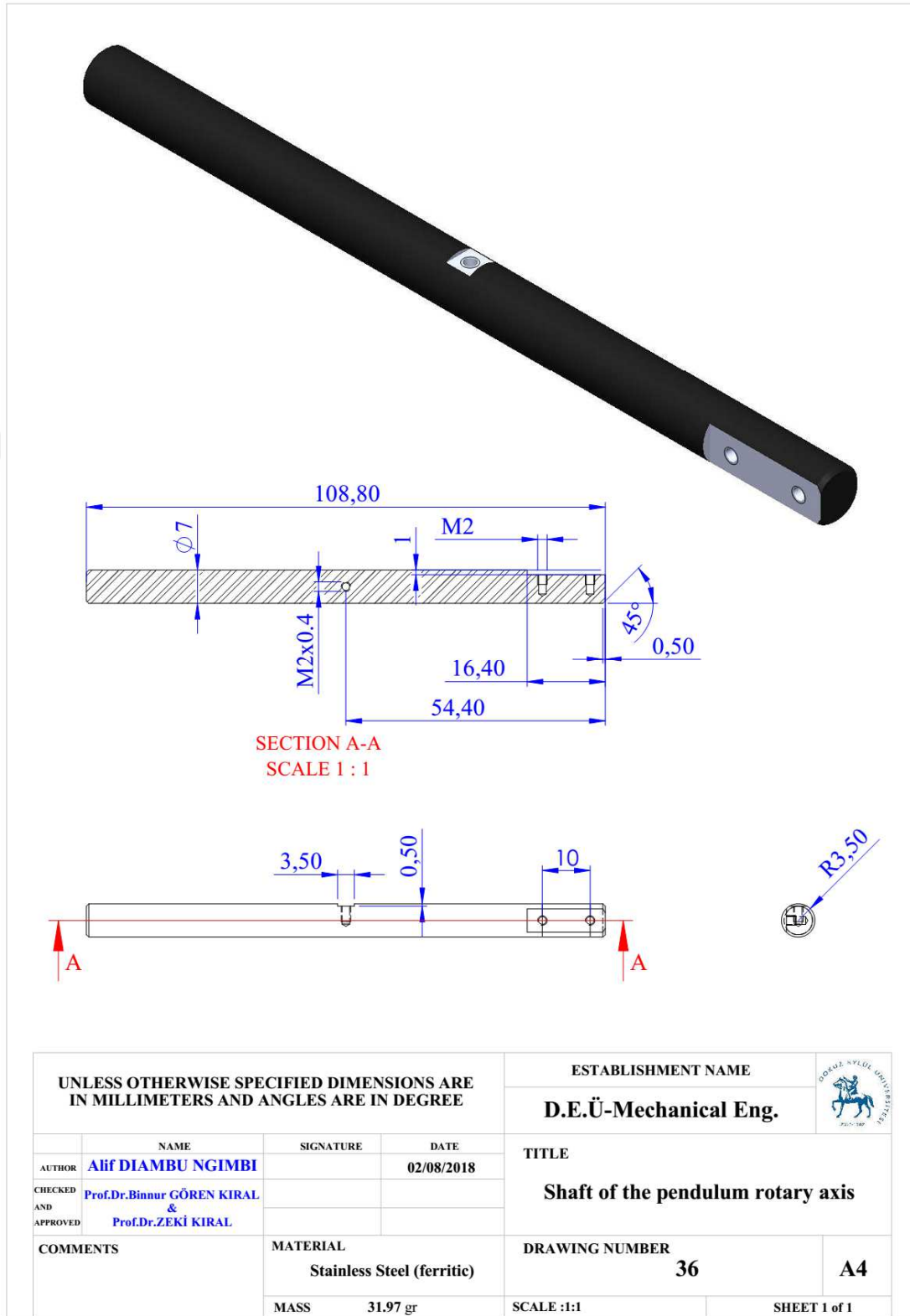


Figure A.23 Shaft of the pendulum rotary axis

Appendix 24: Top Cover 2D Drawing

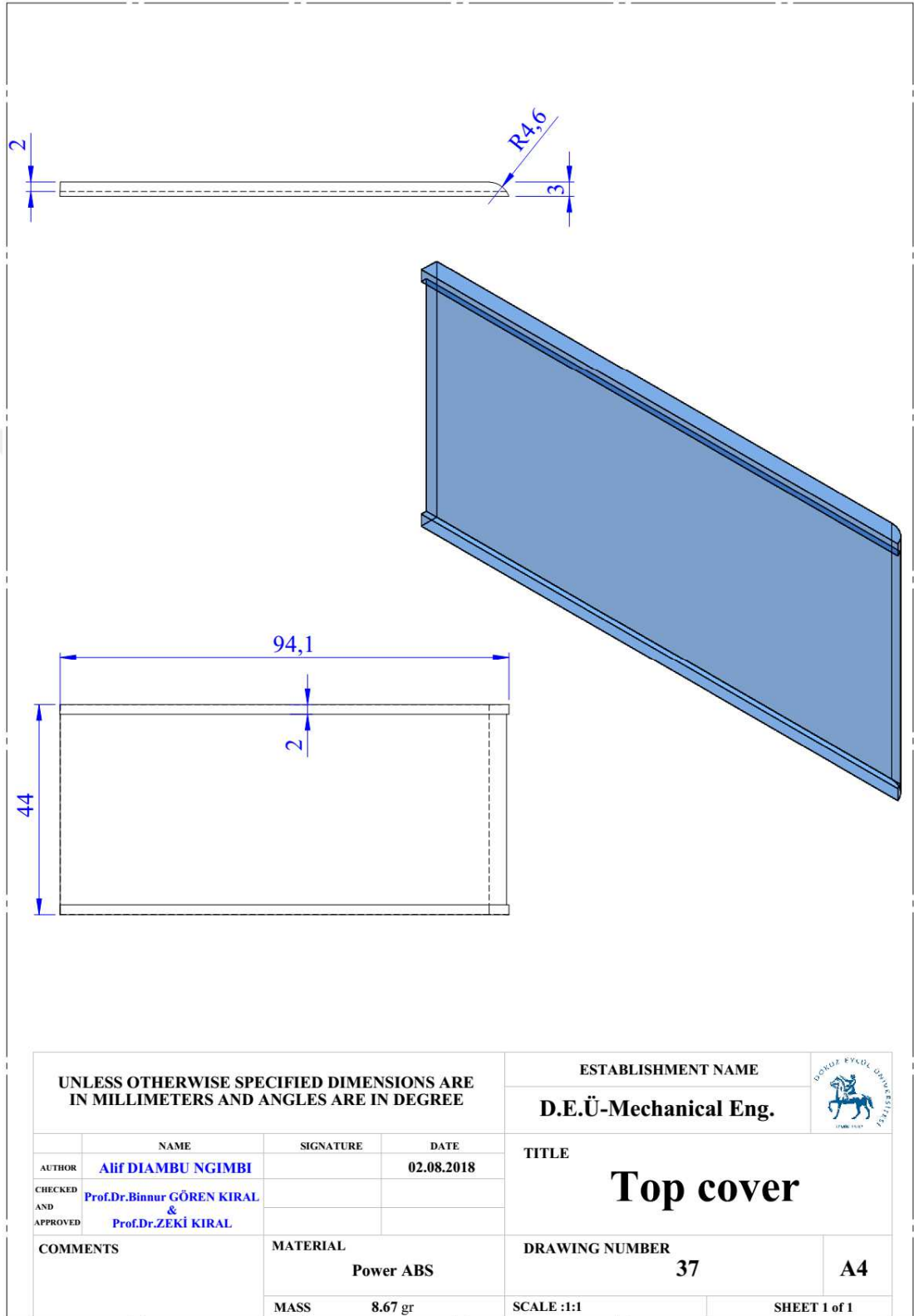


Figure A.24 Top cover

Technical drawing of a mechanical assembly, likely a pendulum or testing machine, showing dimensions and a title block.

Dimensions:

- Overall length: $524,49 \pm 0,51$
- Height: $353,50$
- Width: 200
- Pendulum length: 200mm
- Overall width: $318,50$
- Base width: $214,50$
- Base height: $345,82 \pm 0,02$
- Base width (inner): 139
- Base width (outer): 80

Title Block:

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS AND ANGLES ARE IN DEGREE		ESTABLISHMENT NAME D.E.U-Mechanical Eng.	
NO. IN SET	NAME	DATE	TITLE
01	AIH DIANBU NGIMBI	04-07-2019	The machine measures
DESIGNED BY	AIH DIANBU NGIMBI		
CHECKED BY	Prof.Dr.Bhimu COHEN KIRAL		
APPROVED BY	Prof.Dr.Zeki KIRAL		
COMMENTS		MATERIAL	
		DRAWING NUMBER	00
		SCALE	A3

Appendix 26: Machine Exploded Diagram 2D Drawing

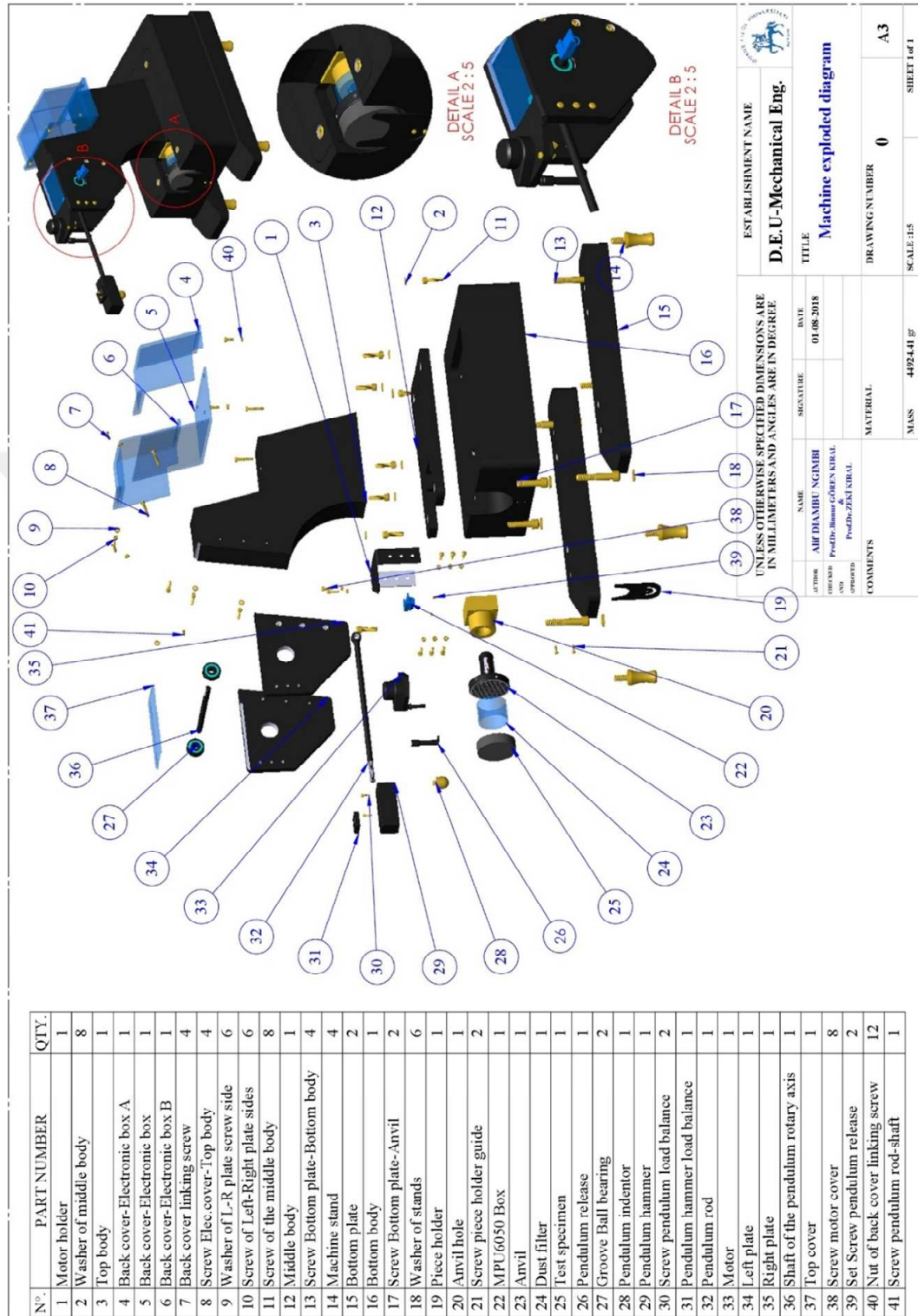


Figure A.26 Machine exploded diagram

Appendix 27: Picture of the Finished Machine

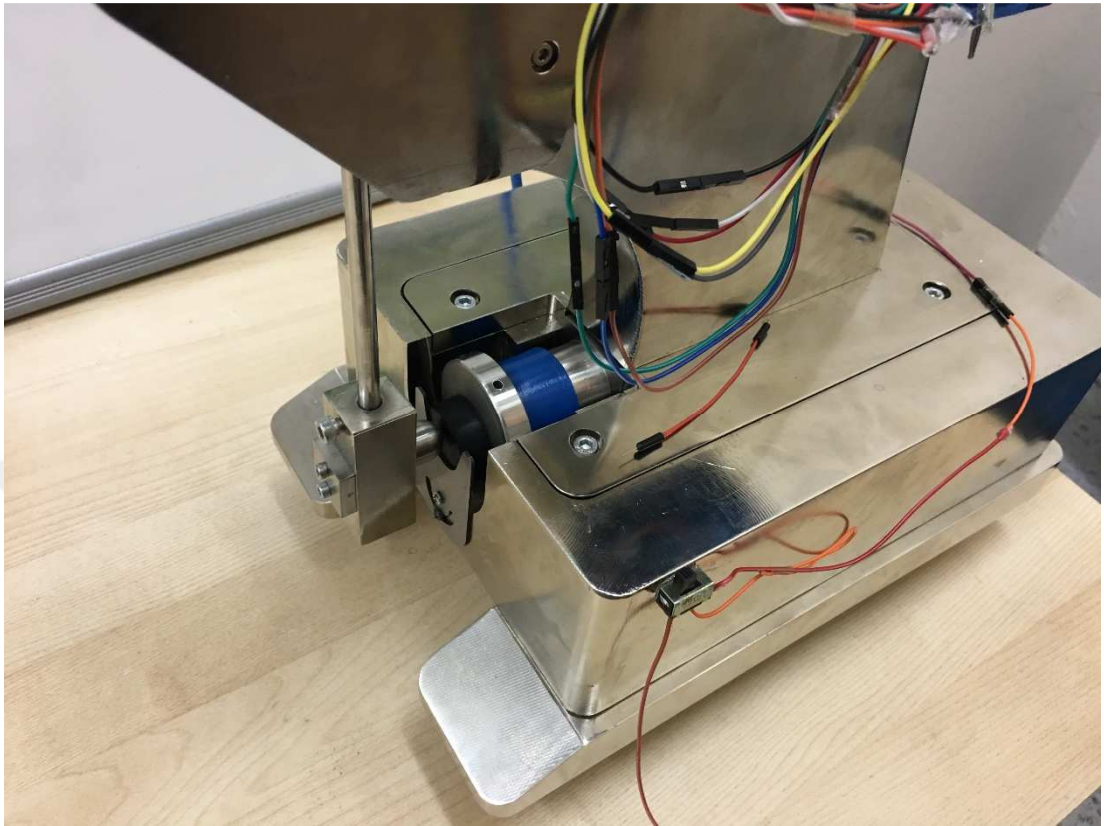


Figure A.27 Finished machine 1 (Personal archive, 2019)

Appendix 28: Another picture of the finished machine

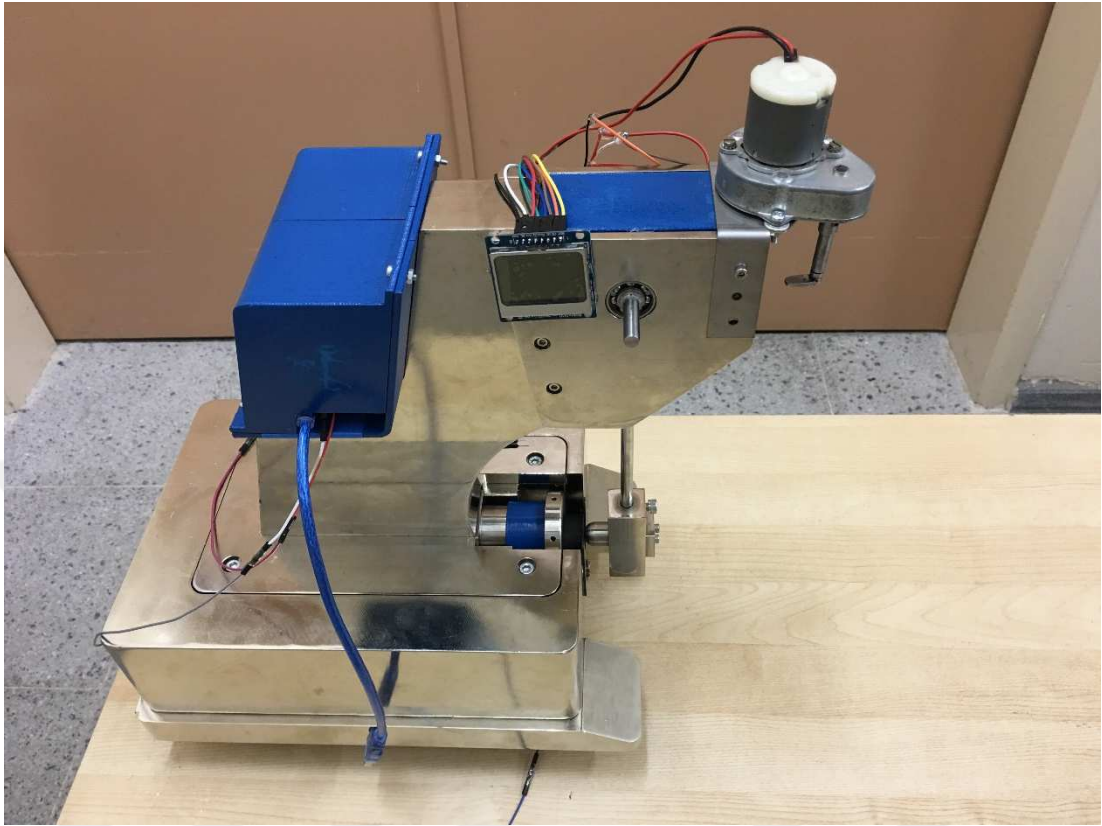


Figure A.28 Finished machine 2 (Personal archive, 2019)