Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Automatic Machine for Induction Coil Production

Master's Final Degree Project

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Supervisor

Kaunas, 2024

Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Automatic Machine for Induction Coil Production

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Mechanical Engineering (6211EX009)

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Kaunas, 2024

Kaunas University of Technology

Faculty of Mechanical Engineering and Design

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Automatic Machine for Induction Coil Production

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1. Task of the Master's Final Degree Project

Given to the student – Antanas Kepalas

1. **Topic of the project**

Automatic Machine for Induction Coil Production

(In English)

Automatinė mašina indukcinių ričių gamybai

(In Lithuanian)

2. **Aim and tasks of the project**

Aim: to design an automatic machine for induction coil production
Tasks:
1. Review existing technologies
2. Analyse the shape of internal induction coil
3. Create an initial design of machine
4. Conduct an experiment to calculate wire bending moment
5. Design the main components of the machine
6. Prepare main component drawings for manufacturing
7. Estimate costs and draw conclusions.

3. **Main requirements and conditions**

Use relevant sources to review the existing technologies. The main parameters of the project are bending moments for wire coiling and bending. The wire bending operations must create a shape that has all the features of the internal coil. The designed machine must have enough torque for bending the wire with given factor of safety. The main components of the machine must not be subjected to loads that would exceed the given maximum stress and deformation limits.
SolidWorks software to be used for CAD design
SolidWorks Simulation and Ansys Workbench to be used for stress simulations

4. **Additional requirements and conditions for the project, report and appendices**

Requirement to present at least one assembly drawing of the machine and at least one detail drawing of one of the main components of the machine.

Project author	Antanas Kepalas		
	(Name, Surname)	*(Signature)*	*(Date)*
Supervisor	Darius Pauliukaitis		
	(Name, Surname)	*(Signature)*	*(Date)*
Head of study field programs	Kęstutis Pilkauskas		
	(Name, Surname)	*(Signature)*	*(Date)*

Antanas Kepalas. Automatic Machine for Induction Coil Production. Master's Final Project / supervisor Assoc. prof. dr. Darius Pauliukaitis; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Mechanical Engineering, Engineering Sciences

Keywords: machine, induction, coil, inductor, automatic

Kaunas, 2024. 64 p.

Summary

The project explores the new idea of automatically producing induction coils, and designs the equipment, that would be required to achieve it. The project is comprised of five parts: research, conceptual design, experiment, detailed design, economical part. During the research part, the existing technologies are analysed, including their working principle, main components, and production capabilities. Also, the shape of the induction coil inductor is analysed, and order of operations is determined. The conceptual design involves functional design of components based on the wire forming steps: wire feeding, 2D bending, parting-off and coiling. During conceptual design, the fully automatic process is created that starts from a wire workpiece and ends with a finished part. The purpose of experiment is to find the flexure stress-strain relationship of inductor material – annealed copper wire, which is used for calculating wire bending loads. The three-point bending experiment is performed and the stress-strain graph is converted from the results. The detailed design starts with analysing the purpose of the part and creating its shape with CAD software. Next, the maximum loads are calculated, and a simulation is run to find the maximum stresses, which are used in factor of safety calculations. The design and material of the part are selected such that the safety factor is larger than required. The main sub-assemblies of the machine are the spindle mechanism and the guide roller mechanism. The spindle mechanism consists of a rotating mandrel, on which wire is coiled into helical shape. The mandrel is mounted on the spindle head, that is powered by motor and gearbox, via chain and sprocket drive. The guide roller consists of a wheel that participates in wire coiling process. The wheel is moved by two actuators: vertical pneumatic actuator and horizontal screw drive. The other main components of the machine include 2D bending mechanism, wire feeding and straightening mechanism and machine frame. The economical part includes cost calculations of purchased standard parts and unique custom machined parts. It was determined that automatic machine without operator has 81 percent faster pay-back period than operator assisted machine.

Antanas Kepalas. Automatinė mašina indukcinių ričių gamybai. Magistro baigiamasis projektas / vadovas doc. dr. Darius Pauliukaitis; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Mechanikos inžinerija, Inžinerijos moklslai.

Reikšminiai žodžiai: mašina, indukcinė, spiralė, induktorius, automatinė.

Kaunas, 2024. 64 p.

Santrauka

Projekte nagrinėjama nauja idėja automatiškai gaminti spiralinius induktorius bei projektuojama įranga, reikalinga tai įgyvendinti. Šį projektą sudaro penkios dalys: tyrimas, koncepcinis projektavimas, eksperimentas, detalus projektavimas, ekonominė dalis. Tiriamojoje dalyje analizuojamos esamos technologijos, jų veikimo principas, pagrindiniai komponentai, gamybos galimybės. Taip pat analizuojama indukcinės spiralės forma, nustatoma operacijų eiga. Koncepcinis projektas apima funkcinį komponentų projektavimą, pagrįstą vielos formavimo etapais: vielos tiekimu, 2D lenkimu, atskyrimu ir vyniojimu. Koncepcinio projektavimo metu sukuriamas visiškai automatinis procesas, kuris prasideda nuo vielos ruošinio ir baigiasi paruošta detale. Eksperimento tikslas yra nustatyti induktoriaus medžiagos – atkaitintos varinės vielos, kuri naudojama skaičiuojant vielos lenkimo apkrovas, lenkimo įtempių ir deformacijų ryšį. Atliekamas trijų taškų lenkimo eksperimentas ir iš rezultatų konvertuojamas įtempių ir deformacijų grafikas. Detalus dizainas prasideda nuo detalės paskirties analizės ir jos formos sukūrimo su CAD programine įranga. Toliau apskaičiuojamos didžiausios apkrovos ir vykdomas modeliavimas ieškant didžiausių įtempių, kurie naudojami saugos faktoriaus skaičiavimuose. Detalės konstrukcija ir medžiaga parenkama taip, kad saugos koeficientas būtų didesnis nei reikalaujama. Pagrindiniai mašinos mazgai yra suklio mechanizmas ir kreipiamojo ritinėlio mechanizmas. Suklio mechanizmą sudaro besisukantis velenas, ant kurio viela suvyniojama į spiralę. Velenas sumontuotas ant suklio galvutės, kuriai perduoda sukimą variklis ir pavarų dėžė, per grandinės ir žvaigždutės pavarą. Kreipiamąjį skriemulį sudaro ratukas, kuris dalyvauja vielos vyniojimo procese. Ratuką judina dvi pavaros: vertikali pneumatinė pavara ir horizontali sraigtinė pavara. Kiti pagrindiniai mašinos komponentai yra 2D lenkimo mechanizmas, vielos padavimo ir tiesinimo mechanizmas bei mašinos rėmas. Ekonominė dalis apima įsigytų standartinių dalių ir unikalių pagal užsakymą apdirbtų dalių sąnaudų skaičiavimus. Buvo nustatyta, kad automatinė mašina be operatoriaus turi 81 proc. greitesnį atsipirkimo laikotarpį nei mašina su operatoriaus pagalba.

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Introduction

An induction heater is a tool with a conductive coil, that works by passing through high frequency alternating current, that generates heat in the workpiece by induction. High-frequency induction heating equipment has proven to be versatile in many industries. Its purpose is heating metal parts, which is required for hardening, brazing, heat-treating, soldering, stress-relieving, annealing, forging, tempering, or melting operations. The equipment is also used in joining metal assemblies and in applying localized hardening of steel parts. Although the generation of high frequency current is an electrical function, applying and manufacturing this equipment is mostly a mechanical process.

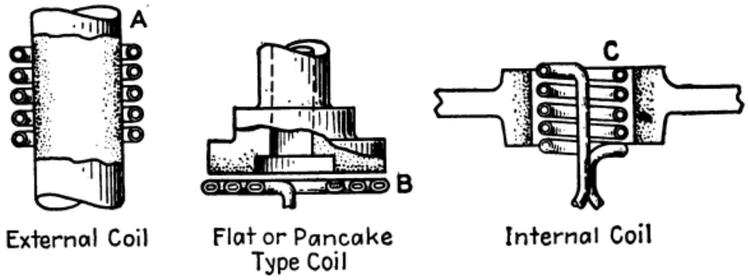

Fig. 1. Induction heater shapes [1]

There are three most popular induction heater inductor (work coil) designs: external coil, flat coil, and internal coil [1]. These three shapes (Fig. 1.) are used for heating the most common surfaces found in machinery. The flat or "pancake" type coil is made from a wire bent into a spiral on a two-dimensional plane. Because it is flat, it can be placed as close to the workpiece as required, making it more versatile than internal and external coils, which need a precise diameter for each individual workpiece. The external coil has a cylindrical interior, which purpose is to let coils closely wrap around a cylindrical workpiece. It is most suitable for heating cylindrical parts, such as shafts and axles. Due to high heating losses, the coil surface must be close to the walls of the workpiece to ensure effective heat transfer. Also, it must be evenly spaced from the surface that it is heating, to ensure even heat distribution. Any localized heating could cause internal thermal stresses inside the part, which could cause cracking, damage, or deformation of the part. The external coil cannot be used for heating internal surfaces. External coil has a lead on the outside of the coil, which is located furthest from the centre of the coil, thus it would cause uneven heating of the component. The internal coil is similar to the external coil, but one of the leads goes through the centre of the coil, which ensures that the outside boundaries of the coil are spaced evenly from the centre. The internal coil inductor is used to heat workpieces that have large openings or bore holes, such as piston housings, tubes, nozzles.

Fig. 2. Internal coil inductor [2]

The focus of this project is to design an automatic machine for manufacturing the internal coil inductors (Fig. 2.). The internal coil has the most complex shape of the three main coil designs. The external coil closely matches the shape of the spring and can be automated by universal CNC coiling machine. The flat coil can be twisted into a spiral shape with a modified 2D bending tool, making the automation process relatively straightforward. The spiral shape of the internal coil inductor is more complicated than a straight coil because both bending and coiling operations may be required to position one of the leads inside the coil. The inductor spiral shaped body is made of a copper tube, which will be referred as “wire” and considered to be a workpiece for both spring and inductor manufacturing.

To design an automated process for internal coil production, two tasks are required. The first task is to analyse existing technologies and machines used for manufacturing inductors and other coiled parts. The second task is to analyse the shape of the internal coil, find out the sequence of operations required for manufacturing it. After both analyses are completed, the data can be compared to find the most suitable methods to form the internal coil inductor and conceptualize automated machine setup.

Aim:

To design an automatic machine for induction coil production

Tasks:

1. Review existing technologies
2. Analyse the shape of internal coil inductor
3. Create an initial design of machine
4. Conduct an experiment to calculate wire bending stress
5. Design the main components of the machine
6. Prepare assembly drawings of designed mechanisms
7. Perform economical calculations of the machine

1. Analysis of coiling machines in industry

First, the industrial machines that produce coiled parts are reviewed and their technologies are analysed. There are three technologies of interest: universal CNC spring coiling machines, lathe type spring coiling machines and internal coil heater production machines.

1.1. Universal CNC spring coiling machines

Spring coiling machines manufacture springs with high precision and produce a broad variety of springs, that have different shapes, sizes, and wire diameters. They are operated by computer numerical controls and are fully automatic. The machines are highly versatile in forming wire in various shapes and are not limited to only springs. They have interchangeable tools and can have up to 12-14 axis of motion [2] that correspond to each of the tool movement. Because the machines are numerically controlled, the spring parameters can be adjusted by changing tool movement parameters, without changing the tool itself.

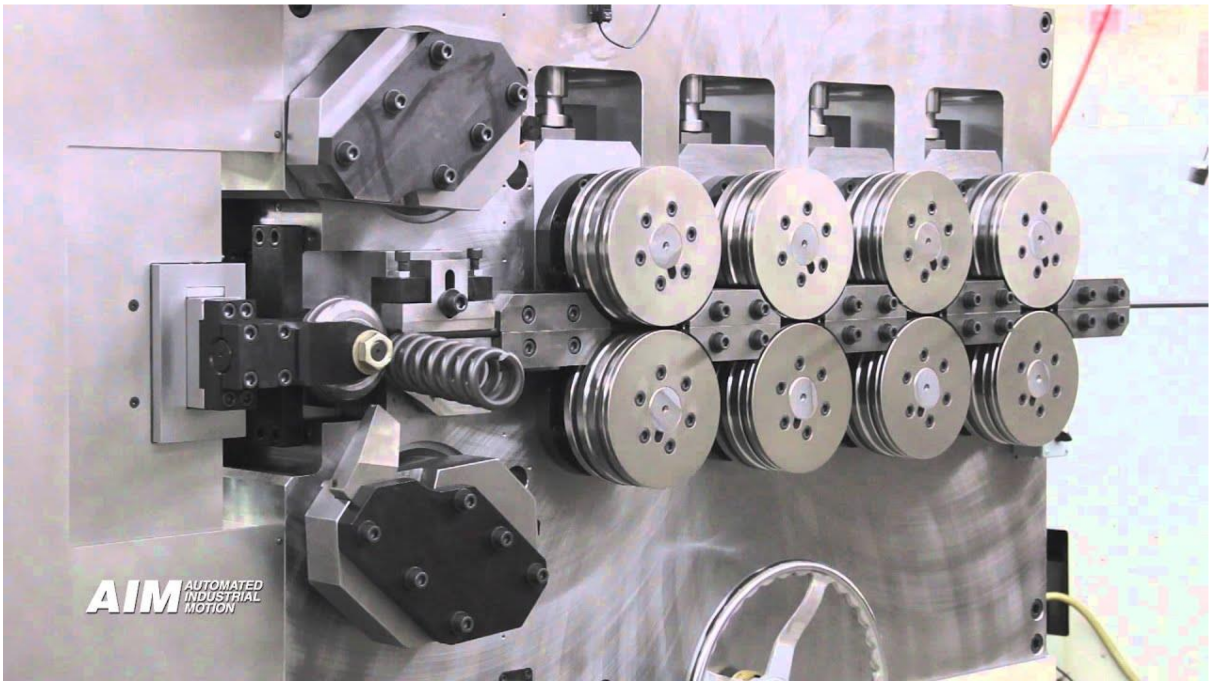

Fig. 3. AIM spring coiling machine [3]

Most of the spring coiling machines have components with similar functional characteristics. Consider a single point spring making machine, made by *Automated Industrial Motion* (AIM) [3]. This machine consists of multiple parts, that are common in almost all spring manufacturing machines.

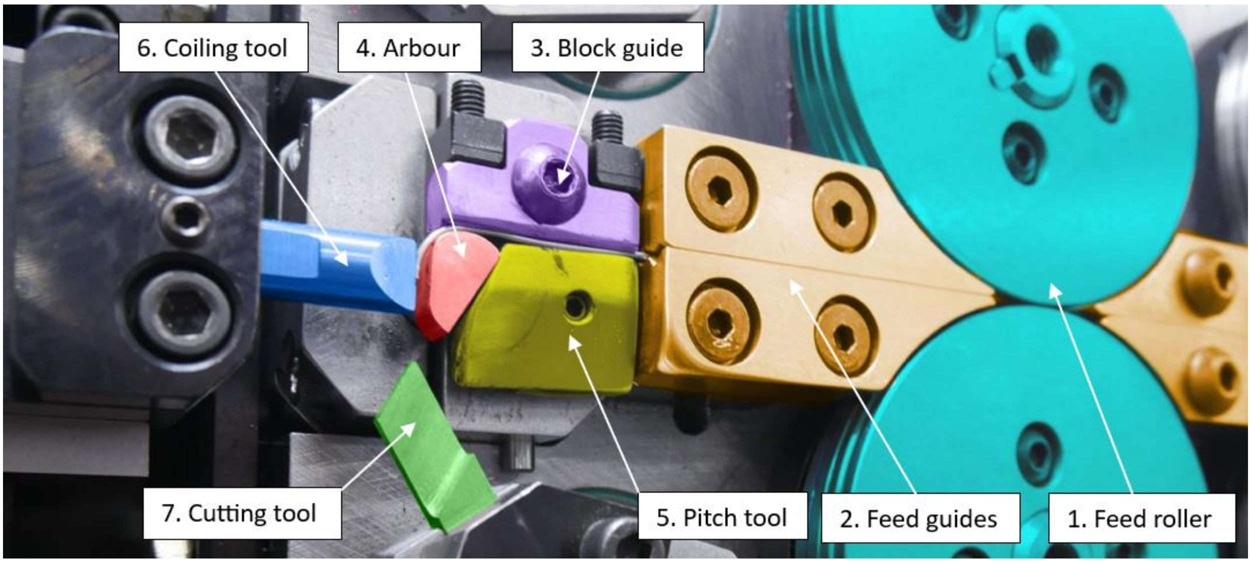

Fig. 4. Components of spring coiling machine

1. Feed roller – pulley shaped circular components that consist of two or more rolls, that draw or feed the wire into the machine. The feeding force provided by the rollers is the main force that forms the wire into a coil.
2. Feed guides – flat components that direct the wire in a straight path. The guides contain grooves of closely similar size to the feed rollers, within an allowed range. The wire moves through the guides until it reaches the components, that participate in bending or forming the wire.
3. Block guide – a block with a bottom groove that ensures the wire moves on a correct path from the feed guides to the coiling point. The groove must match the wire diameter with high accuracy.
4. Arbor – a block with a curved surface on which the wire passes over, after going through the block guide. In this single-point machine, the arbour is a third point of contact. As wire bending physics dictates, at least three points are required to bend the wire. The same is true with coiling the wire. In dual-point coiling machines, the arbour is obsolete during coiling, but it is needed for cutoff operation.
5. Pitch tool – a plate that slides forward and backward and moves the wire on a sloped surface, controlling the pitch of the spring. Both arbour and pitch tool are specifically machined to fit each job.
6. Coiling tool – a tool that contacts the wire and deflects its trajectory, forming the wire into a coiled shape. The parameters of this component determine the angle of wire deflection, which determines the diameter and shape of the spring. Different machines can have different amounts of coiling tools.
7. Cutting tool – a tool that separates the the finished coil from the wire, after the required length has been reached. The wire separation is achieved by shear cutting force. The cutter is positioned below the arbour, because of the direction of the wire coiling. In case of opposite coiling direction, the cutter may be installed above arbour, to ensure the surfaces for shear cutting motion.

The process of wire coiling starts with a spool of wire that is unwound and drawn by the feed rollers (1) and directed through the feed guides (2). Then the wire is guided by a block guide (3) towards the coiling tool (6) where it is deformed into circular shape around the arbour (4). As the wire is coiled, the pitch tool (5) moves continuously to offset each winding of the spring to avoid wire overlapping over itself and creating the shape of the spring. After the product is formed, the cutting tool (7) separates the part, and the process is restarted.

CNC spring coiling machines can be divided into two categories: single point and dual point coilers. As briefly mentioned, the difference between these machines is the tool setup. A single point coiler has only one coiling tool, whereas the dual point setup has two coiling tools, that are in contact with the wire. The single point setup is more versatile and can produce a larger variety of springs. Also, it is more easily integrated with cassette tooling, which allows workers to change setups faster, by quickly changing individual tools. The advantage of dual-point setup is the ability to reduce the friction between coiling surfaces, achieving smoother coil surfaces. Also, two coiling tools allow to achieve greater precision, because the second tool adds additional dimensions of mobility, which affects coil diameter and pitch.

Regardless of type, CNC spring coiling machines are highly versatile in production of coiled parts. The spring coiling machine can produce not only regular compression springs, but many other types of springs. By changing the position of coiling tool during the process, these machines can produce springs with varying diameters, resulting in different spring shapes [4]: conical, hourglass, barrel. By varying the speed of the pitch tool during the coiling process, variable pitch springs can be produced as well.

The universal coiling machines can be equipped with additional bending tools, that can bend wire by using servomotors. Such additional equipment can help create more complex shaped springs, by allowing to bend the ends of the spring. With this method, torsion springs and spring belts can be produced.

1.2. Lathe type spring coiling machines

As the name suggests, this machine working principle is based on the lathe. Conventional computer numerical control (CNC) turning lathe could be modified and converted into a spring manufacturing machine, by installing a wire feeding device, wire bending tool and additional components, such as wire cut-off shears. CNC lathe spring coilers are sold as separate specialized machinery because it requires knowledge of wire bending technologies and expertise of CNC technicians to set up the machine and its programming. The main components of the lathe type machine are given in Fig. 4.

1. Feeding device – consists of feed rollers and feed guides, that push the wire towards the mandrel. The device moves in the axis of spindle rotation, which determines the pitch of the spring.
2. Bending tool – a tool that secures the wire and forces it to coil around the mandrel. The tool is a block with a cutout to support the wire and keep it secure to the shaft. A bending tool is attached to the chuck and rotates together.
3. The mandrel – a cylindrical shaft where the wire is wrapped around. The inner diameter of the spring depends on the shaft diameter. It is secured in the chuck jaws.

4. Chuck – a clamping device that transmits torque from the spindle to the workpiece, in this case, the mandrel.
5. Spindle – a rotating part of the lathe, that transmits torque from the motor and gearbox to the workpiece. It holds different sizes of chucks.

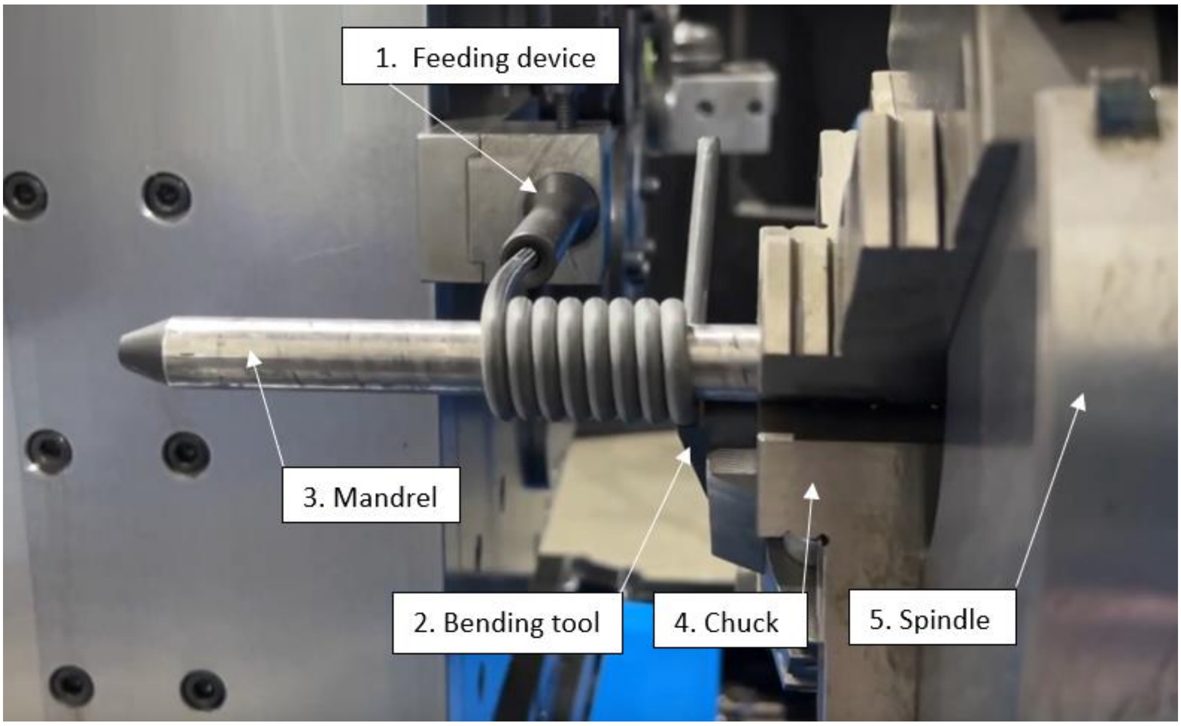

Fig. 5. Lathe type spring coiling machine

Lathe type spring coiling process starts the same as for the universal spring coiling. The wire is unwound from the spool, where it is fed through the feed rollers and guides (1), that provide the feeding force to unwind the wire and move it towards the mandrel. Initially, the wire is fed until it passes through the bending tool slot (2), then the spindle (5) starts rotating and the wire begins forming into a coil around the mandrel (3). The feeder moves away from the spindle, which determines the spacing between coil windings (pitch).

Lathe type machines [5] are different from universal machines in a few aspects. First, the wire is formed by rotational bending or torque, provided by the spindle. The universal machine uses high feeding force to deflect the wire into the shape, whereas the lathe spindle uses torque to coil the wire. The feeding force is limited by the friction force of the rollers – if the friction force is insufficient the wire will not be fed, and the rollers will slip on the surface of the wire. The lathe machine can have much higher torque to bend the wire, the limiting factor being the maximum torque of the spindle and the strength of the bending tool. For this reason, the lathe can coil wires of much larger diameters. For example, The WIM 20 CNC coiling lathe [6] can manufacture springs from 20 mm diameter wire. Whereas the multi-axis universal CNC coiling machines most powerful model GT80-12R can coil up to 12mm soft wire.

Another difference of lathe type machine is the types of springs it can produce. The feeding device can translate, and its speed of translation can be automatically controlled by a CNC program. The feeder movement controls the springs pitch, thus the variable pitch springs can be produced by lathe and by universal machines. However, the lathe coils the spring around the mandrel, which determines a constant inner radius of the spring. For this reason, variable diameter springs cannot be produced, such as hourglass, helical, or conical shaped springs.

1.3. Internal coil heater production machine

This machine is specifically set up for internal coil inductor production. From CSM Machinery, bending machine for coiled elements [7] is used to produce different types of heating elements. The configuration for internal coil inductor production requires an operator to insert the workpiece into the mandrel opening to begin the coiling process. The coiling process is performed automatically, by using CNC programming to determine the timing of mandrel rotation and position of guide rollers that support the workpiece. After the product is bent into the final shape, an operator must remove the finished part and insert a new workpiece. Because the machine cannot function continuously without the help of an operator, it is a semi-automatic machine.

The working principle of the machine is similar to the lathe spring coiling one,- because the wire is wrapped around a mandrel. The main components of the machine are given in Fig. 6.

1. Spindle block – a mechanism that powers the rotation of the spindle and linearly translates along guide rails. It houses an adjustable speed gearmotor that provides torque for the spindle head and the mandrel. The mechanism is attached to the guide rails that allow it to move in the direction along z axis, where z axis corresponds to the axis of spindle rotation. The spindle block moves and rotates the mandrel.
2. The mandrel – like the lathe machine shaft, it is a cylindrical rod that wraps the wire into a coil. It has a hole at the end of the shaft, that is eccentrically positioned away from the centre, to maximize the bending moment of the wire. Since there is no bending tool, the wire has 90-degree bend that is secured in the eccentric hole. The bend corresponds to one of the heating elements leads that go through the centre of the coil.
3. Vertical guide roller – a roller that keeps the wire close to the mandrel during coiling. It has a groove in the shape of the wire, that keeps the wire in place while the spindle block and the mandrel are moving. By holding part of the coil from moving, while the rest of the coil is moved by the mandrel, the guide roller helps to separate the windings of the wire. The roller has pneumatic cylinders that help control the vertical movement of the roller and compensate for the difference in diameter between the beginning and the constant part of the coil.
4. The table – a fixed platform with a low friction surface, where the wire is dragged by the mandrel during the coiling process.
5. Horizontal guide rollers – these rollers help to straighten the direction of the wire towards the vertical guide roller, to help direct the wire into its groove. The rollers are attached to the levers that allow the rollers to separate during the initial setup and the end of the coiling operation to let the bends at the beginning and end of the wire pass through unobstructed.
6. Support roller – a fixed roller that functions as a third point of bending, during coiling operation.
7. Spindle steady rest – fixed rollers that keep the mandrel shaft steady during its rotation and translation. It supports the shaft and stops it from deflection, caused by downward reaction force during coiling operation.

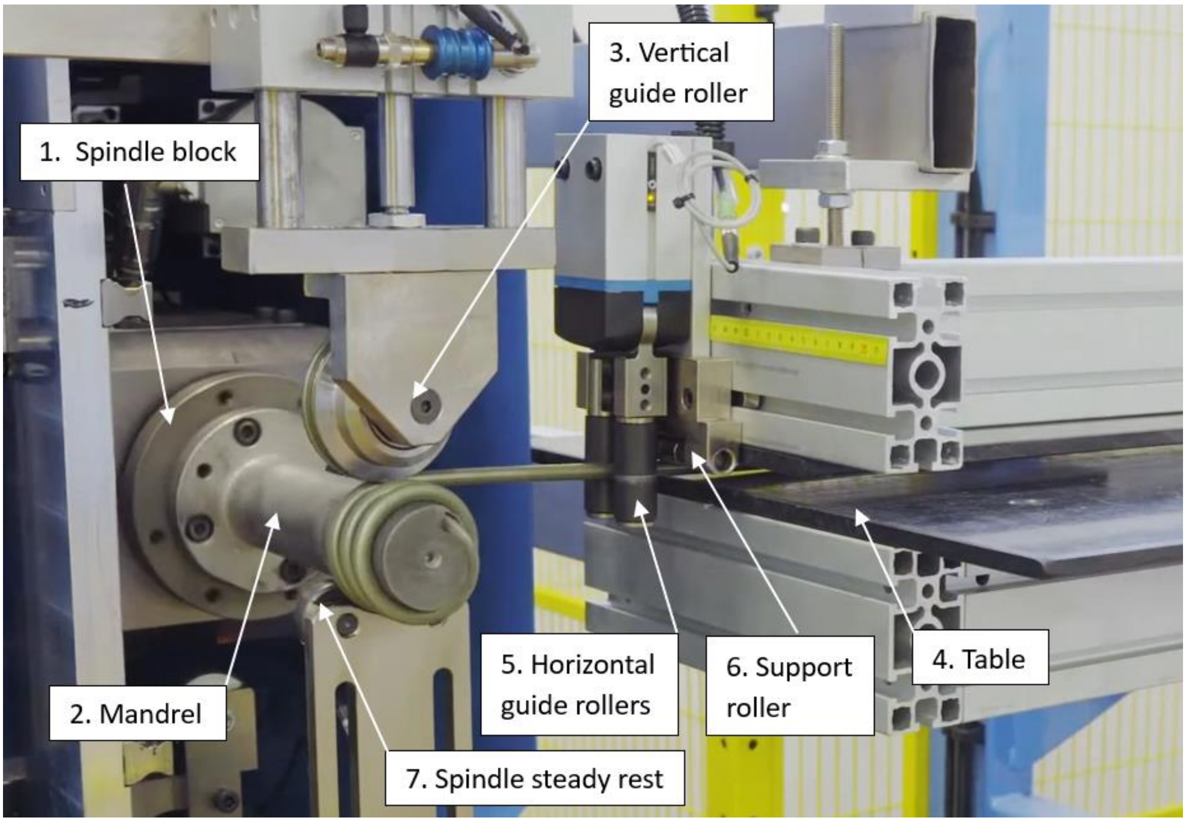

Fig. 6. CSM inductor manufacturing machine [4]

The manufacturing process begins with a workpiece, which is a long straight wire with two ends bent at right angles. The ends of the wire correspond to two leads of the heating element after the coiling process, while the middle section becomes the coil. The wire ends are bent at the 2D bending station and the workpiece is brought to the coiling machine. An operator places the workpiece on the table (4) and inserts the segment of bent wire into the mandrel (2). Then vertical guide roller (3) descends to secure the wire and the horizontal guide rollers (5) close to keep the wire on a straight path. Bending requires three points: two on the mandrel and one on the guide roller (3). The coiling process is initiated, where the mandrel spins and coils the wire, while the spindle block (1) with the mandrel moves forward, which offsets the windings by a specified pitch parameter. After the product is formed into a coiled shape, the guide rollers release and an operator removes the finished part by hand. Afterwards, the spindle returns to its initial position and the production cycle is restarted.

The machine limitations and advantages are closely similar to the lathe spring coiling machine, because of the process of coiling wire around a shaft. It has larger allowed maximum wire diameter than universal spring coilers, because the bending capability depends on torque of the spindle and mandrel shaft, instead of roller feeding force. CSM bending machine has interchangeable mandrels, thus it is possible to manufacture coiled elements with large diameters, conical coil shaped elements and straight coil shaped elements. The limitation of this manufacturing setup is the automation – the production process is not automated and requires the input of an operator.

2. Shape study of internal coil inductor

The purpose of this chapter is to analyse the shape of the induction heater's internal work coil and consider possible techniques for producing it. Within the context of the induction heater, the heater body is coiled from a hollow copper tube, which is referred to as "wire" for simplicity. Resistance heaters use solid wires to maximize current throughput, but induction heaters do not need such high amperage to generate heat, thus a copper tube is sufficient. A tube has an advantage compared to solid wire of the same diameter. The tube section modulus is smaller than solid wire, thus the required bending moment is significantly smaller.

The induction heater shape can be separated into three parts: coiled body, internal lead, external lead. The body of the heater is a helical coil because it is proven to be the simplest shape to effectively distribute heat over a surface. Coils are widely used in industry for production, such as springs, solenoids, heaters. Most heaters have a helical coil shape because the methods of coiling a wire are well known in the industry. Induction heaters must have a coil because the coil generates an electromagnetic field. As described previously, an induction heater works by passing electricity through a coiled wire. It works by connecting both ends of the wire to the terminals of the alternating current generator, thus both leads of the coiled wire should be easily accessible. The external lead should not be outside the heater's boundary cylinder, which diameter is equal to coiled body external diameter. The external lead is usually positioned the same distance from the centre axis of the coil as the windings because the heater coiling process ends with the external lead being pressed against the mandrel. The internal lead is positioned eccentrically, close to the coiled body. After forming, both leads must be in a position where the distance between leads matches heater design specification. Considering the lead A position is constant, the distance between leads is determined by final position of lead B, which is determined by number of windings in a coil and a wire length in coiled body.

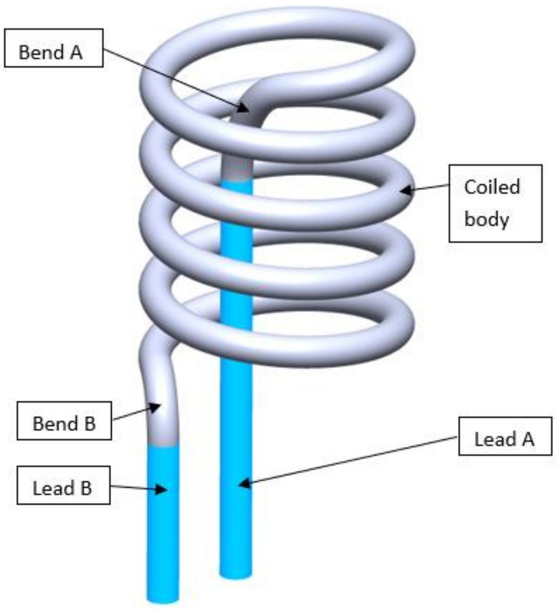

Fig. 7. Inductor segments

The semi-automatic production of internal coil inductors has been analysed, by focusing on components and their function. Now, the analysis is repeated, by focusing on the shape of the part. The first operation is bending the wire twice and inserting it into the mandrel (Fig. 8.1.). The workpiece has two bends, that correspond to two leads of the heater - longer lead A and shorter lead B. The second operation is coiling – the mandrel rotates around its axis in counterclockwise direction and forms the wire into a coil shape (Fig. 8.2). After the coiling process (Fig. 8.3), the coil has exactly four full windings, because full windings results in the smallest distance between leads A and B.

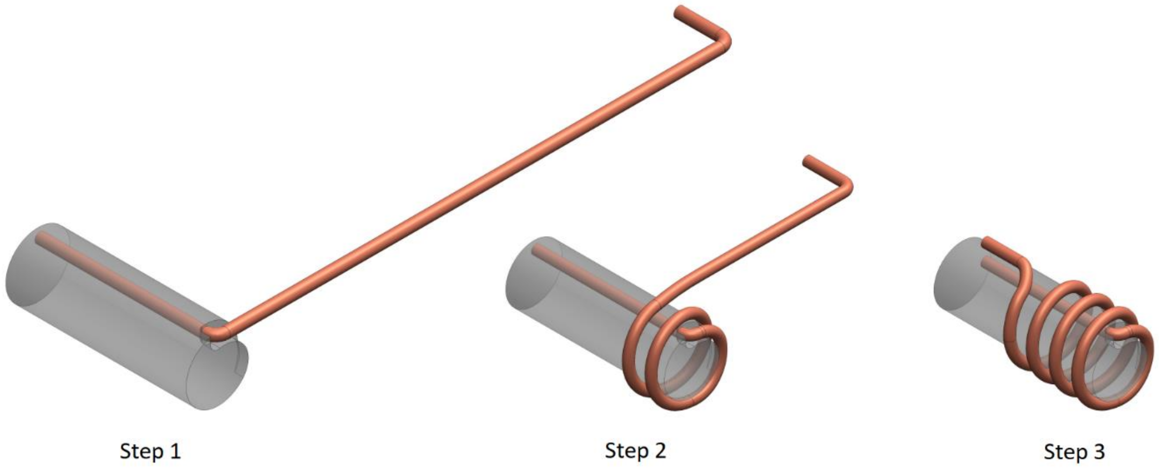

Fig. 8. Inductor coiling process

It is possible to automate this production process by replacing an operator with a programmed robot. The production cell would consist of two machines: a bending station and a coiling station. Both stations would be connected by a pick and place robot, that would supply the coiling station with a bent wire from the first station. However, there are disadvantages, such as high investment cost, skilled maintenance of the robot, large space requirement.

An ideal solution would be a single station that incorporates both coiling and bending into a single machine, but it cannot be done with the current wire forming method.

Consider using a universal CNC spring coiling machine for manufacturing induction heaters. The machine can produce a helical coil, and, with additional wire bending tools, it can make coils with various bends. While the machine can perform simple bending operations, it cannot bend an external lead inside the coiled body (Fig. 9).

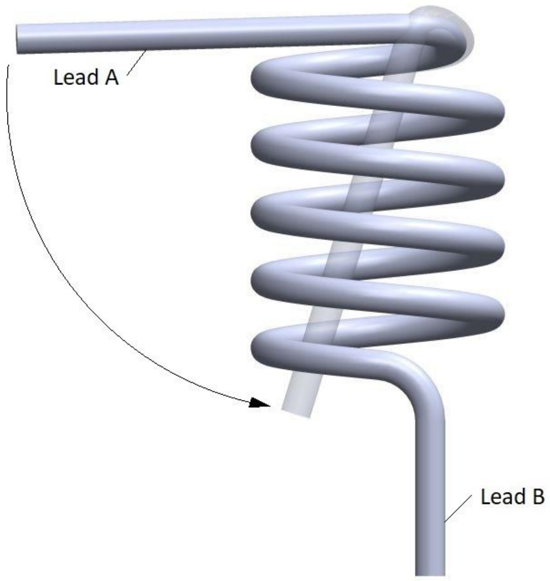

Fig. 9. Inductor internal lead bending concept

The internal coil heater shape must begin with an internal lead A, followed by bends A and B, and coil being wrapped around the lead, as it was shown in Fig.7. Consider skipping the first two steps – bending the wire ends and inserting the workpiece into the mandrel. The workpiece can be fed through the mandrel and bent twice in such a way that the shape of the wire is identical to Fig.8.1. After the workpiece is shaped as in step 1, the remaining part of the coiling process is unchanged. A more detailed analysis of operations is required to create the final shape, suitable for the coiling process.

This process would result in a 2D bent part that is in a suitable position for the following coiling operation. If this concept is feasible, it would incorporate a 2D bending tool into the coiling machine and it would not require an operator to move the workpiece between two machines.

3. Conceptual design

The conceptual design of an automated inductor machine is created by placing its main components on a drawing (Fig.10.). The components are arranged in the order of operations, that transform the raw material into the final product. The main components of the machine: a wire spool, feeder, cutting tool, spindle head and mandrel, guide roller, bending tool.

The production process begins with a raw material – a spool of wire. The spool is uncoiled by the force of the feeding mechanism and the wire is fed through the mandrel. After feeding and bending operations, the workpiece is parted-off by a cutting tool. Finally, the wire is coiled, by using a mandrel and guide roller, and the finished part is removed.

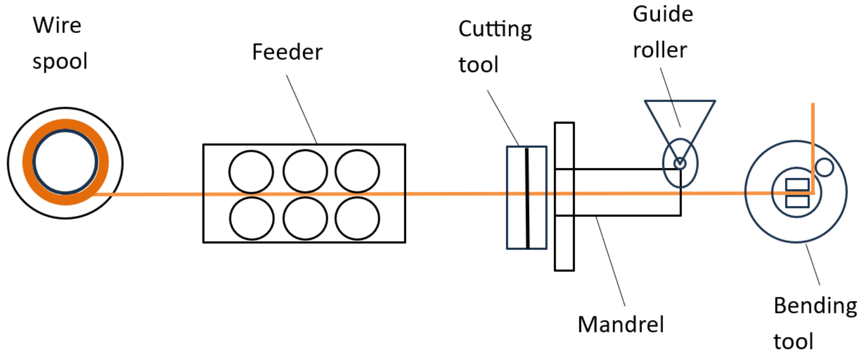

Fig. 10. Initial design of the machine

A more detailed conceptual design is required to visualize the machine components in 3D space. The concept design of the machine is separated into three parts: the bending stage, the parting-off stage, and the coiling stage.

3.1. Bending stage

The purpose of the bending stage conceptual design is to check the feasibility of the new idea of workpiece preparation, using feeding and bending tools. The conceptual design of the machine can be developed further by considering the tools and actions that are required to form the wire into a suitable workpiece. The bending process involves three main components: a feeding mechanism, a spindle block with a mandrel and a 2D bending mechanism. The detailed design of these mechanisms is not known, thus only their function may be considered. Assume the mandrel is identical to the previously reviewed CSM machine, and the 2D bending mechanism uses a conventional one bending pin and four fixed pins in the centre. The function of the feeder is to translate the wire in a straight pre-determined path, while the function of the bending tool is to bend the wire at a specified angle on a two-dimensional plane. The order of operations (Fig.11.) for feeder and bending tool can be listed as following:

1. Step 1
    a. 2D bending head is positioned next to path of the wire.
    b. The feeder pushes the wire through the mandrel into the bending head fixture.
2. Step 2
    a. Wire bending head makes a 90-degree bend (bend B).

   b. Wire bending pin returns to initial position.
3. Step 3
   a. The feeder pushes the wire forward by a distance equal to length of the wire, that forms coiled body.
   b. Wire bending head makes a second 90-degree bend (bend A)
   c. Bending head pin returns to previous position.
4. Step 4
   a. The bending head moves down from the wire.
   b. The feeder retracts the workpiece into the mandrel.

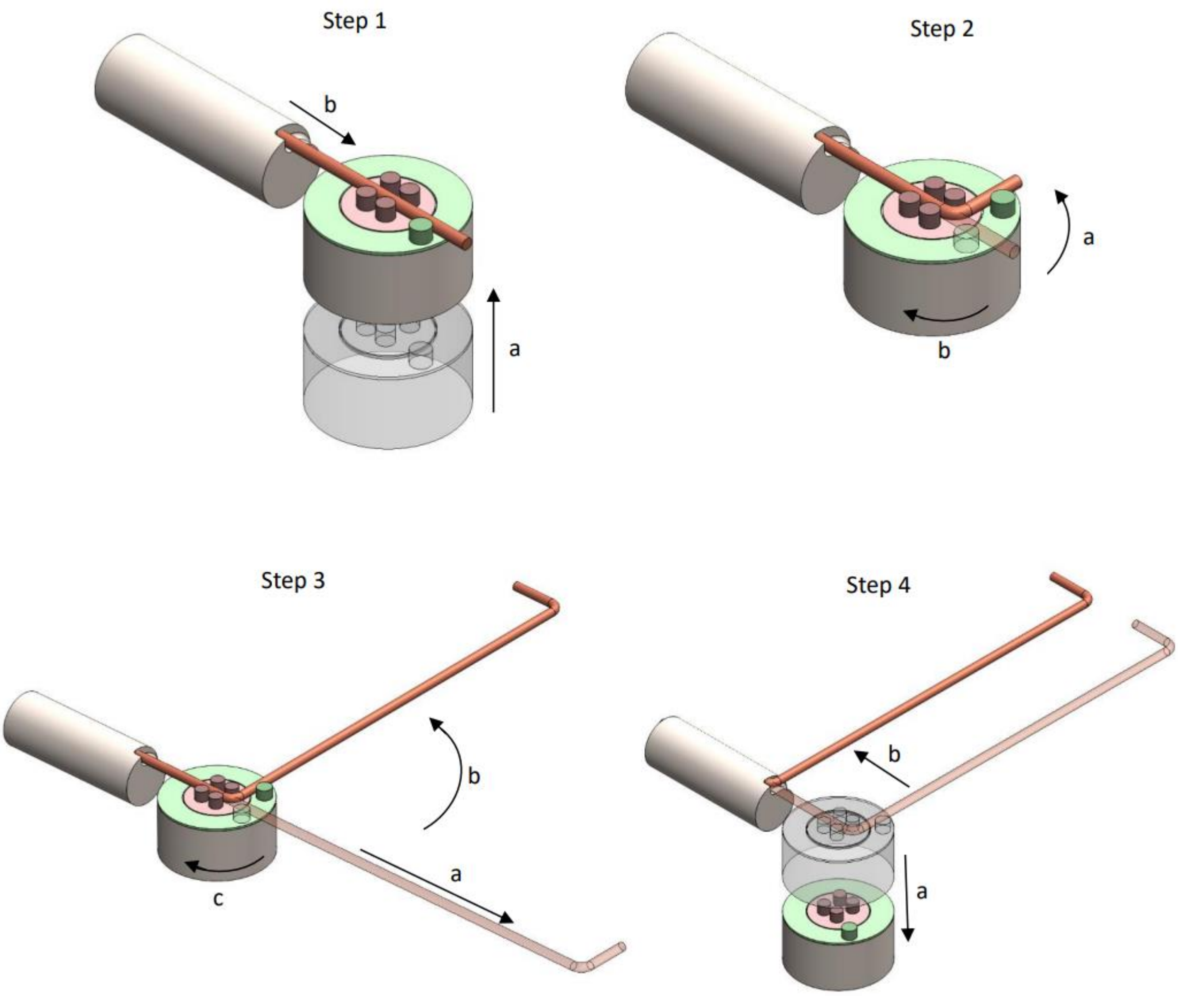

Fig. 11. Wire bending steps

The bending stage begins with feeding the wire through the mandrel. The wire moves into the bending head and is bent 90 degrees. The process of feeding and bending is repeated for the second bend. Afterwards, the bending head moves and releases the wire from a fixture, and the wire is retracted without obstruction.

The listed operations are within the capabilities of existing 2D bending machines [8], thus the design of the bending stage can be considered feasible to be replicated physically.

3.2. Parting-off stage

Before the coiling operation, consider the mandrel rotation. After the bending stage, the wire has been transported through the feeder into the mandrel. Assuming the feeder is fixed, and the mandrel is rotating, the feeder would resist the wire rotation and would deform it, thus the wire should be cut between mandrel and feeder. Parting off operation is required, where the wire is cut at the base of the mandrel.

There are several methods for separating cylindrical workpieces [9]. Most common methods, that require automated machinery, are parting-off by turning, shear cutting, saw cutting, laser cutting. The inductor is made from hollow copper tube, thus shear cutting cannot be used, because it would deform the tube. Both laser cutting and turning require expensive dedicated machinery for those operations, thus it would not be suitable to incorporate it into the inductor production machine. The most applicable tool for parting-off is a circular saw. A small circular saw can be automated and installed into the machine.

The position of the cutting tool will determine the length of the inductor lead A. If the cutting tool is placed before the spindle head, lead A would be longer than lead B by the length of the spindle head. Since it is required to have inductor leads end at the same position, the cutting tool should cut the wire near the base of the mandrel. The circular saw can be installed after the spindle head, and it would cut the wire through the slot in the mandrel (Fig. 12).

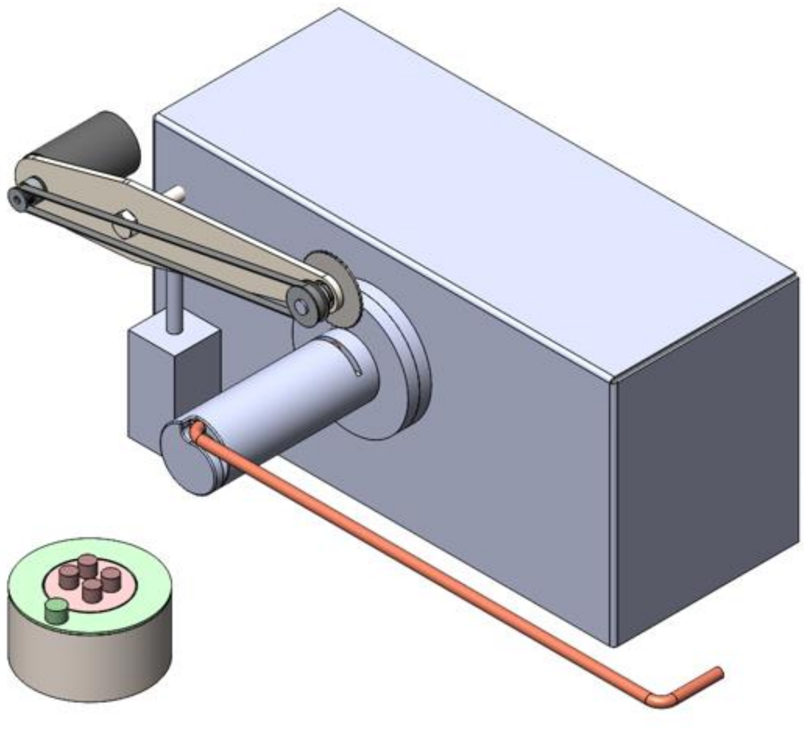

Fig. 12. Cutting tool design

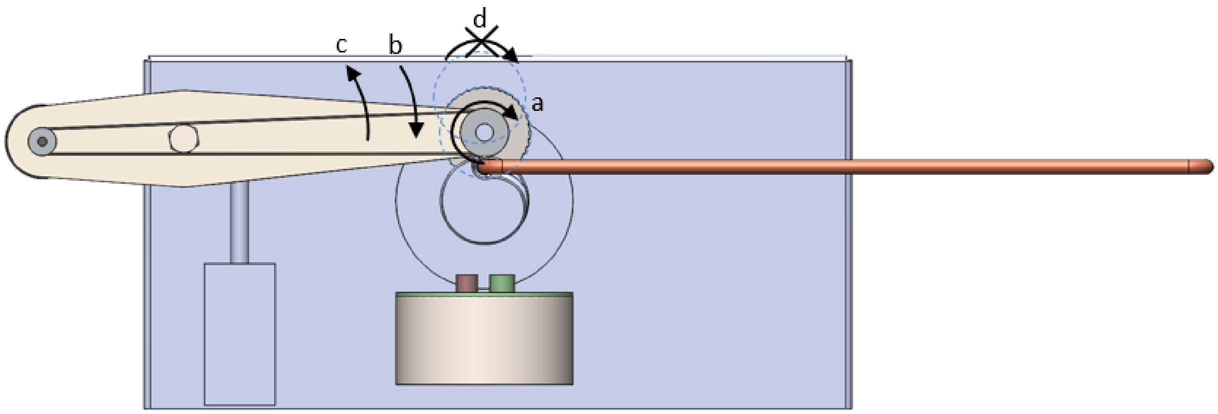

Fig. 13. Cutting tool operations

The working principle of the parting off tool is given in Fig. 13. The saw operates in following steps:

a) The circular saw blade starts rotating.
b) The lever is pulled down and the saw cuts the wire.
c) The lever is retracted up.
d) The saw blade is stopped.

The purpose of the saw is to separate the section of the wire (workpiece) from the rest of the raw wire. The separation process allows to free the wire from the spindle-mandrel joint, to prepare for mandrel rotation during coiling stage. After cutting, the wire is removed by feeding it backwards until the required clearance from the joint is reached.

3.3. Coiling stage

In this stage, the final shape of the internal coil inductor is produced. The workpiece from the previous stages is used for coiling operation, thus the starting workpiece of coiling stage must correspond to the end of the bending stage step 4.b.

The coiling process requires two main components [10] :the mandrel and the vertical guide roller. The process of coiling involves the mandrel rotation around its axis and constant relative translation between mandrel and guide roller. Relative motion can be achieved in two methods: fixed mandrel and moving guide roller (such as lathe type spring coiling machine) or moving mandrel and fixed guide roller (CSM coiling machine). The first method is better, because the mass of the guide roller is smaller than the mandrel and the spindle head mechanism, thus a motor needed to drive a guide roller would be much smaller and cheaper. The guide roller requires a vertical actuator to hold the wire during coiling and release it afterwards. The guide roller has two degrees of freedom: move forward/backward continuously along the mandrel and move vertically up/down.

The coiling stage steps are given in Fig.14. :

1. The guide roller moves down until it touches the mandrel.
2. The spindle head rotates and coils the wire, while guide roller moves the wire along the mandrel.

3. The guide roller moves up and returns horizontally to the previous position, completing the full cycle.

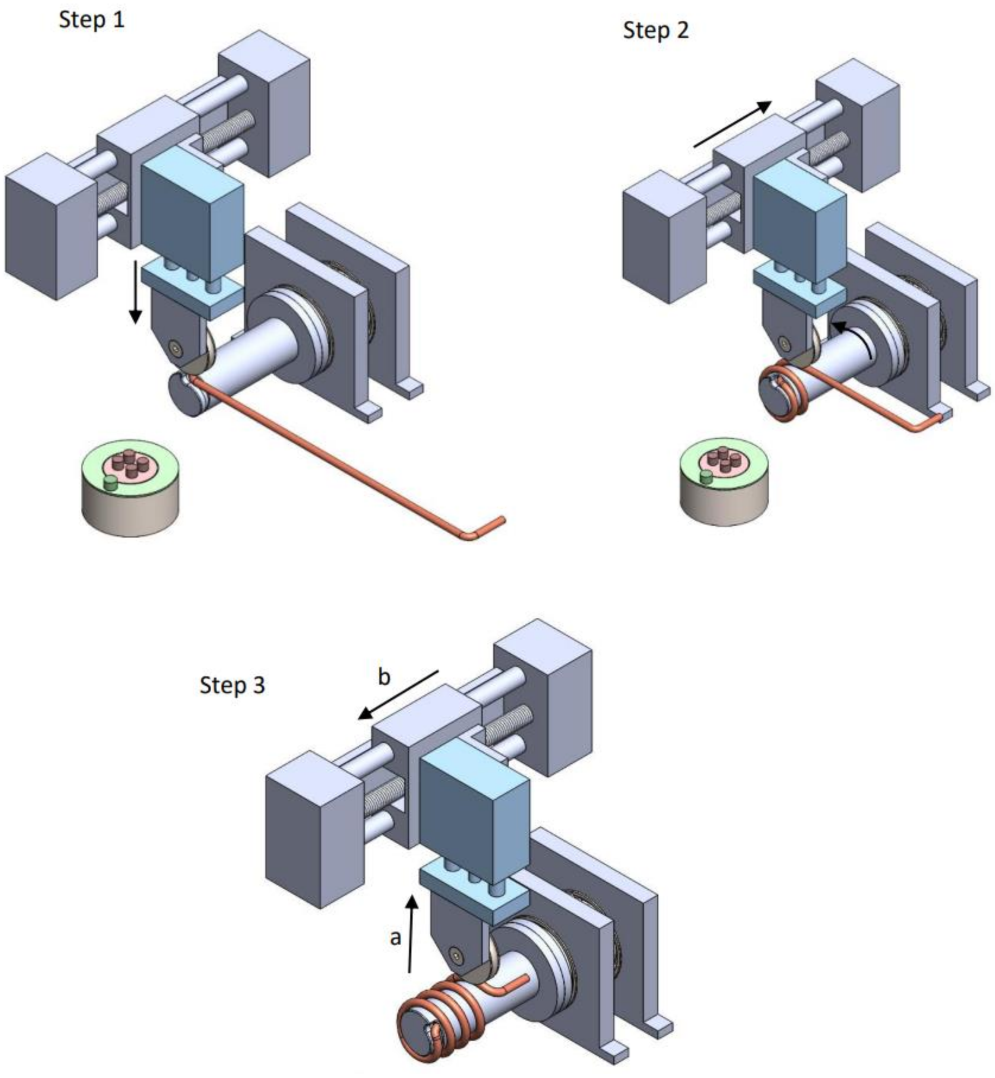

Fig. 14. Coiling mechanism design

The design of the coiling stage closely matches the operations that are carried out by CSM bending machine, thus it is reasonable to assume that the production process could be replicated in reality with similar results.

3.4. Full machine design

The main components of the machine, that participate in three stages of manufacturing, are roughly designed. Based on the conceptual drawing of the machine and the approximate design of the components, the full model of the machine is created. The machine is 3D modelled using SolidWorks software assembly mode. The main components of the machine (Fig.15.) can be separated into custom designed and purchasable components.

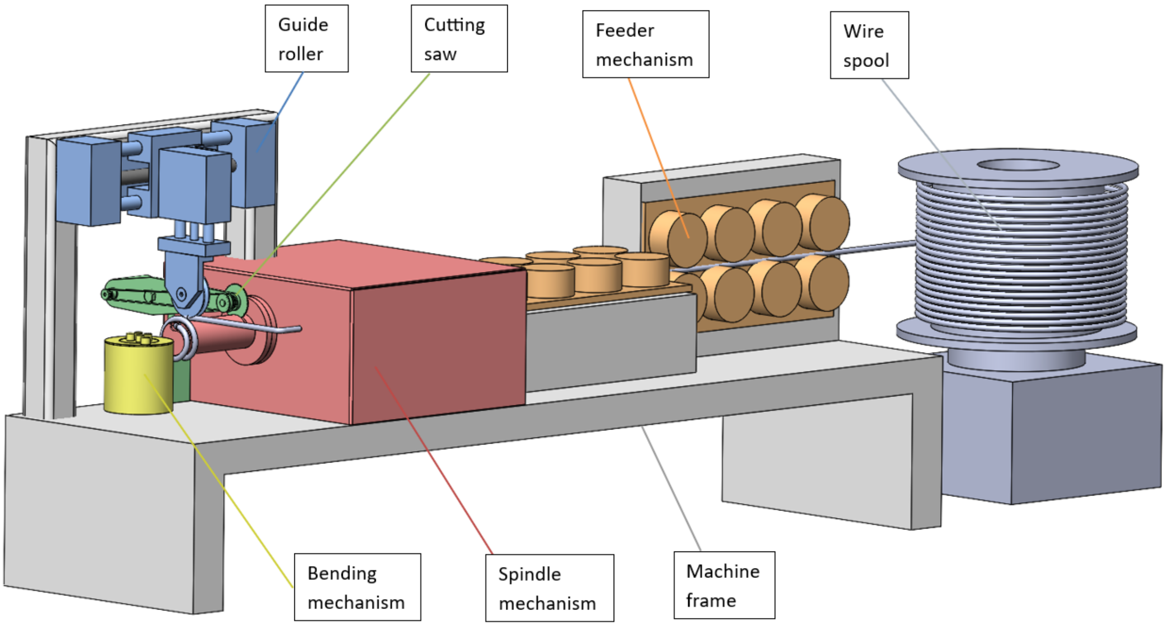

Fig. 15. Full machine 3D design

The components that can be bought are wire spool and feeder mechanism. The wire spool could be ordered from the company "Luvata" from Mitsubishi Materials, that sells hollow tube conductors. The feeder mechanism is an assembly of wire feeder and wire straightener, both of which can be purchased from and installed by Automated Industrial Motion company (AIM).

The remaining components are specific to the induction machine, thus they are designed based on the required criteria: inductor product specifications, power requirements, maximum loads and deformations, standards. These following components are the most important, because they perform all the operations during manufacturing: guide roller assembly, cutting saw mechanism, bending mechanism and spindle mechanism.

4. Product specification

The induction heater manufacturing machine is designed based on dimensions and shape of the final product – internal coil inductor. The dimensions of inductor coil are given in Fig. 16., which are based on a compression spring parameters [11].

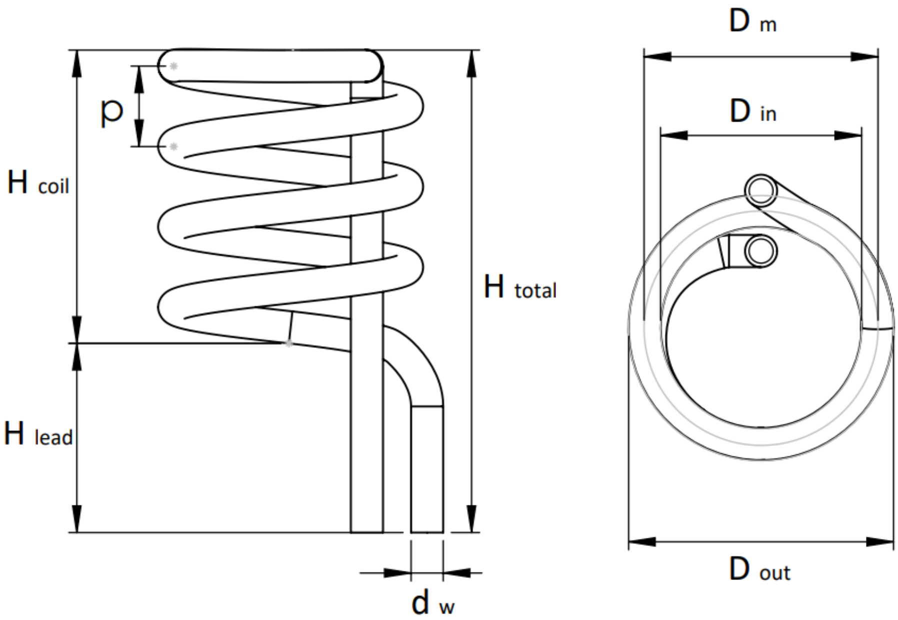

Fig. 16. Inductor geometry dimensions

H_{coil} – height of the coiled body
H_{lead} – height of the coil external lead
H_{total} – height of the inductor
d – coil tube diameter
D_{out} – coil outer diameter
D_{in} – coil inner diameter
D_{m} – coil mean diameter
p – coil pitch
N – number of turns of the coil

The purpose of the induction heater is to heat treat an engine cylinder, which internal bore diameter is 80 mm. Take coil outer diameter 66 mm, with 12 mm clearance from the bore.

The inductor "wire" is an annealed copper tube. The conventional induction heater inductor tube diameters are up to 8 mm. For 8 mm copper tube, according to DIN EN 1057 standard, the suppliers offer 8x6 mm tube with t=1 mm wall thickness. Coil dimensions:

- $D_{out} = 66\ mm$
- $d = 8\ mm$
- $D_{in} = D_{out} - 2 \cdot d_w$ = 50 mm
- $D_m = \frac{D_{in}+D_{out}}{2} = 58\ mm$

- $t = 1\ mm$ (tube wall thickness)

The maximum height of the inductor depends on the maximum length of the raw tube required to form the inductor (L_{max}), that would not plastically deform under its own weight during bending operation (Fig. 11. step 3).

Section modulus of copper tube:

$$S = \frac{\pi(d_2^4 - d_1^4)}{32d_2} \quad (4.1)$$

where d_2 – wire outer radius, d_1-wire inner radius, S-section modulus.

$S = 34.3\ mm^3$

Yield strength (Annealed Cu) [12]: $\sigma_{yield} = 33.3\ MPa$

Density (Annealed Cu): $\rho = 8930\ kg/m^3$

Bending moment at yield point:

$$M = \sigma_{yield} \cdot S \quad (4.2)$$

$M = 34.3 \cdot 10^{-9} \cdot 33.3 \cdot 10^6 = 1.14\ Nm$

Assume the tube behaves as a cantilever beam [13]:

$$M = \frac{FL_{max}}{2} \quad (4.3)$$

Force F equals to the weight of the pipe (mass from volume):

$$F = \frac{\pi(d_2^2 - d_1^2)}{4} \cdot L_{max} \cdot \rho \cdot g \quad (4.4)$$

$$F = 1.96 \cdot L_{max} \quad (4.5)$$

Substitute (4.5) into (4.3) formula, express L:

$$L_{max} = \sqrt{\frac{2M}{1.96}} = 1.08\ m \quad (4.6)$$

The maximum length of the tube is 1.08 meters. The maximum number of coils can be calculated next. The maximum length of the raw tube required to make the coiled body can be denoted as L_{coil} and calculated by subtracting heights of both leads. The height of external lead is H_{lead}, and the internal lead is H_{total}:

$$H_{total} = H_{coil} + H_{lead} \quad (4.7)$$

$$H_{coil} = N \cdot p \quad (4.8)$$

$$L_{coil} = L_{max} - H_{lead} - (H_{coil} + H_{lead}) \quad (4.9)$$

After substituting (4.7) and (4.8) into (4.9):

$$L_{coil} = L_{max} - 2H_{lead} - N \cdot p \quad (4.10)$$

Length of the coil can be expressed as the perimeter of each winding multiplied by their number:

$$L_{coil} = \pi D_m N \quad (4.11)$$

By equating both (4.10) and (4.11)formulas, number of windings N can be expressed:

$$N = \frac{L_{max} - 2H_{lead}}{\pi D_m + p} \quad (4.12)$$

Take the pitch of the coil to be double the tube diameter: $p = 2 * d = 16\ mm$.

Take the height of the external lead: $H_{lead} = 50\ mm$.

$$N = \frac{1080 - 2 \cdot 50}{3.14 \cdot 58 + 16} = 4.95$$

The maximum number of coils should be rounded to 4, because the tube should be shorter than the maximum length by a safety margin of at least 20%. However, the maximum length can be significantly increased if a support table is used, which would support the tube from bending and would have a low friction surface to let the wire slide during bending. With the use of support table, assume the maximum number of coils to be 5.

The machine will be designed to manufacture inductors with the following geometry parameters (Table 1).

Table 1. Inductor geometry parameters

Parameter	Description	Value	Units
D_{out}	Coil outer diameter	66	mm
d_w	Coil tube diameter	8	mm
t	Coil tube wall thickness	1	mm
p	Coil pitch	16	mm
N	Number of coil turns	5	-
H_{lead}	External lead height	50	mm
H_{coil}	Coiled body height	80	mm

5. Bending test

5.1. 3-point bending test

To design machine components that participate in bending and coiling operations, it is required to be able to calculate maximum loads that the components will be subjected to. During bending, most of the deformation is plastic and Hooke's law cannot be applied. The stresses can be converted from strains by using a stress-strain curve, which is obtained experimentally. A bending experiment is carried out to obtain a stress-strain curve for annealed copper material.

A three-point bending test is carried out, following ISO 7438 standards. The test setup is a simply supported beam, subjected to centre-point loading. The bending machine [14] (Fig. 17.): Tinius Olsen, H10KT dual column, tabletop universal testing machine with 500N force sensor.

Fig. 17. Tinius Olsen, H10KT universal testing machine [5]

Table 2. Test specimen information

Description	Copper cable core, without insulation
Type	H07V-U
Material	Annealed copper, monolithic
Cross-sectional area	10 mm^2
Conductor standard	1st class, LST EN 60228+AC

The bending setup is given in Fig. 18.

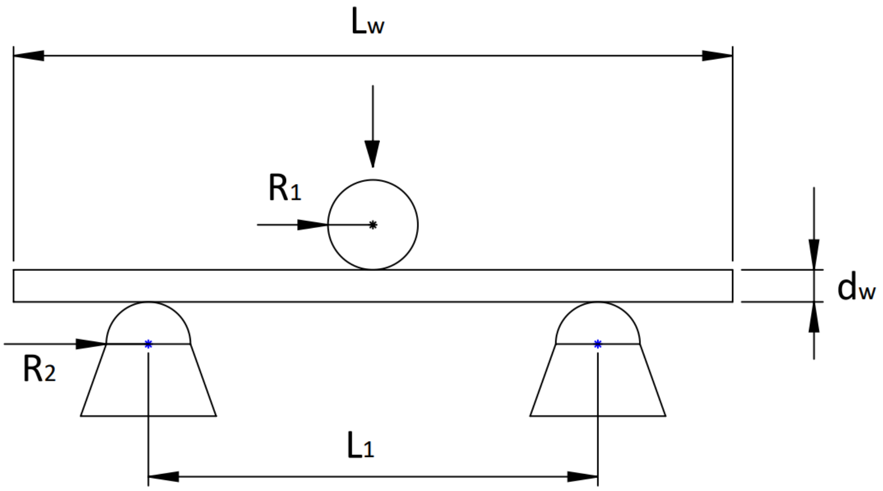

Fig. 18. Three point bending main dimensions

The diameter of the wire is calculated from cross-sectional area:

$$d_w = \sqrt{\frac{4A}{\pi}} \tag{5.1}$$

$$d_w = \sqrt{\frac{4 \cdot 10}{3.14}} = 3.57\ mm$$

R_1 – radius of the former, R_2 – radius of the supports.
$R_1 = 5\ mm$
$R_2 = 5\ mm$

According to ISO 7438, the distance between supports is calculated from the formula (D - diameter of the former, a - thickness or diameter of test piece) :

$$l = (D + 3a) \pm \frac{a}{2} \tag{5.2}$$

$$l = (5 \cdot 2 + 3 \cdot 3.57) \pm \frac{3.57}{2} = 20.71 \pm 1.78\ mm$$

The standard specifies the distance between supports (Fig. 18.), but the distance between centres of the supports (L_1) is graded on the adjustment dial. The L_1 distance was selected:

$$L_1 = 50mm$$

The specimen length was selected by adding 15mm overhangs to the distance L_1:

$$L_w = 80\ mm$$

The raw data contains tests of three specimens with identical testing conditions. The rate of displacement of the former was 1mm/min. The specimen were bent from straight wire up to 130 degree angle (Fig. 20). The sensors registered the force and the displacement data and plotted a graph (Fig. 19) using a dedicated computer program.

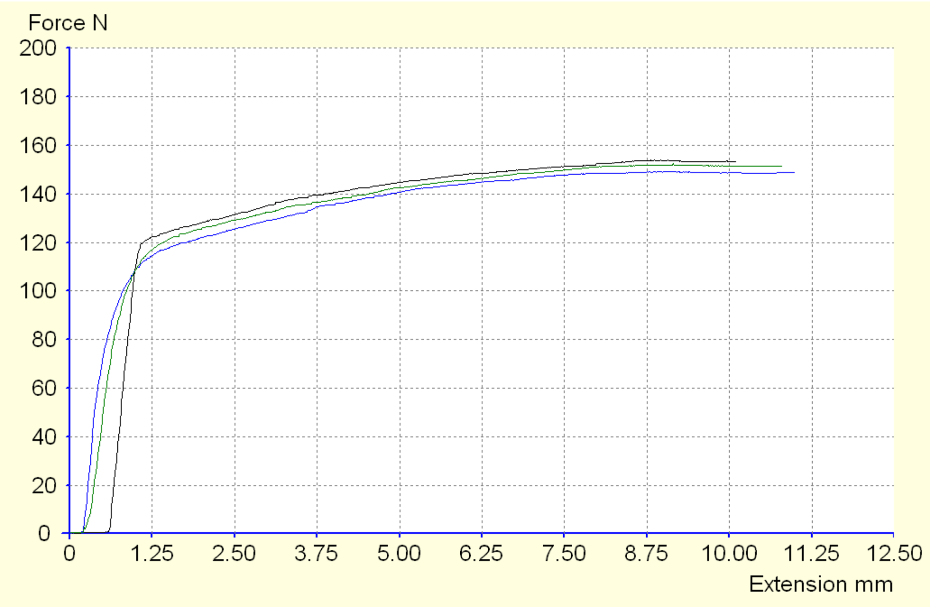

Fig. 19. three-point bending force-extension graph

Fig. 20. The specimens after bending

5.2. Data processing

There are three steps, that process the raw data, until it can be used for further calculations:

1. Match starting point.
2. Average curves.
3. Compensate for the bending distance changes.
4. Resample the curve.

The data is processed by setting the force-extension curves (Fig. 19) at (0,0) point, by subtracting the extension that increased while the force was zero. Then, separate test results are averaged into one graph (Fig. 21). The data range is created in Excel software, by using “Average” function to get a new averaged data column from three separate force data columns.

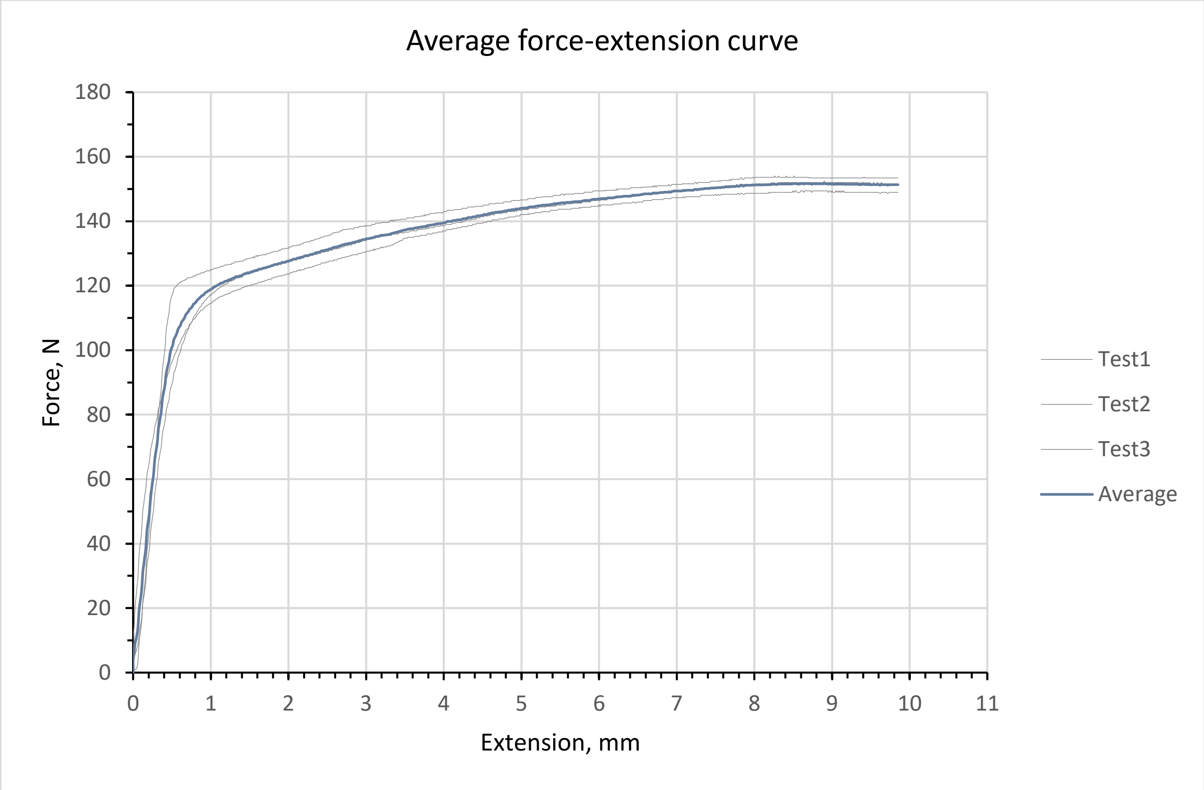

Fig. 21. Averaged force-extension curve

There can be seen from the force-extension graph, that the force starts decreasing, when extension gets large enough. Most plausible explanation is the change in distance between support and former contact points (Fig. 22.). Initially, the former is higher than the support, thus the distance decreases from c_1 to b_1. After some displacement, the distance starts increasing from b_1 to c_2. The distance increase is significant enough to reduce the acting force, for the same bending moment. Because of distance increase, the eventual force decrease is seen in the graph (Fig. 21). If the force is compensated by a multiplier, proportional to distance c (Fig. 22.), the bending moment could be calculated at any point in graph, from a simple formula (where L_1 is constant):

$$M = \frac{F}{\frac{L_1}{2}} \tag{5.3}$$

From formula 5.3, when the length L_1 is constant, the relationship between the force and bending moment becomes directly proportional. The length between contact points decreases from c_1 to b_1, where it reaches the minimum value and starts to increase from b_1 to c_2. The length compensation formula is divided into two parts, based on the position x of the bending pin.

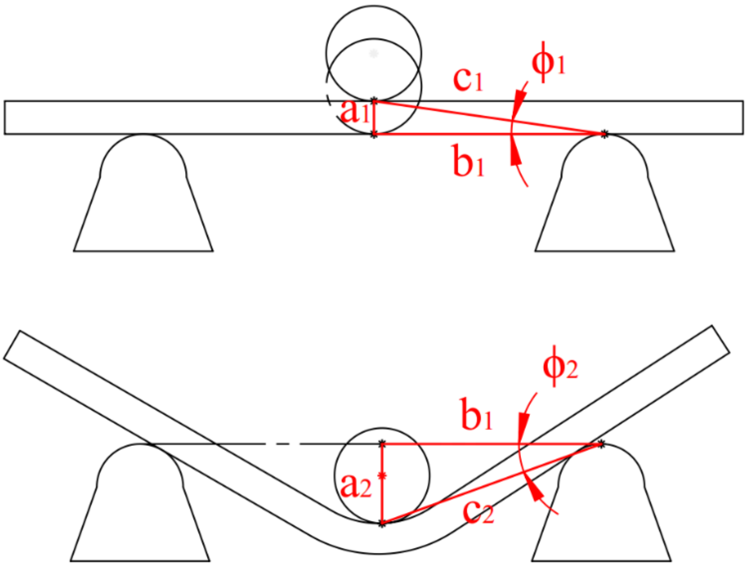

Fig. 22. Bending pin position

The compensation multiplier is expressed as a function:

$$f(x) = \begin{cases} \dfrac{b_1}{\sqrt{x^2 + b_1^2}} & if\ x \leq a_1 \\ \dfrac{b_1}{\sqrt{a_1^2 + b_1^2}} \cdot \dfrac{\sqrt{(x - a_1)^2 + b_1^2}}{b_1} & otherwise \end{cases} \quad (5.4)$$

Where x – extension of former, $a_1 = 3.57mm, b_1 = 25mm$:

$$f(x) = \begin{cases} \dfrac{25}{\sqrt{x^2 + 625}} & if\ x \leq 3.57 \\ \dfrac{25}{\sqrt{x^2 + 625}} \cdot \dfrac{\sqrt{(x - 3.57)^2 + 625}}{25} & otherwise \end{cases}$$

By applying the multiplier to the force data column, the compensated force-extension graph is created (Fig. 23.). The graph is smoothed out by resampling the curve. The resampling is done by selecting one data point every 10 rows, by using an incremental number list and “Indirect(Adress())” function to create new force and extension data columns.

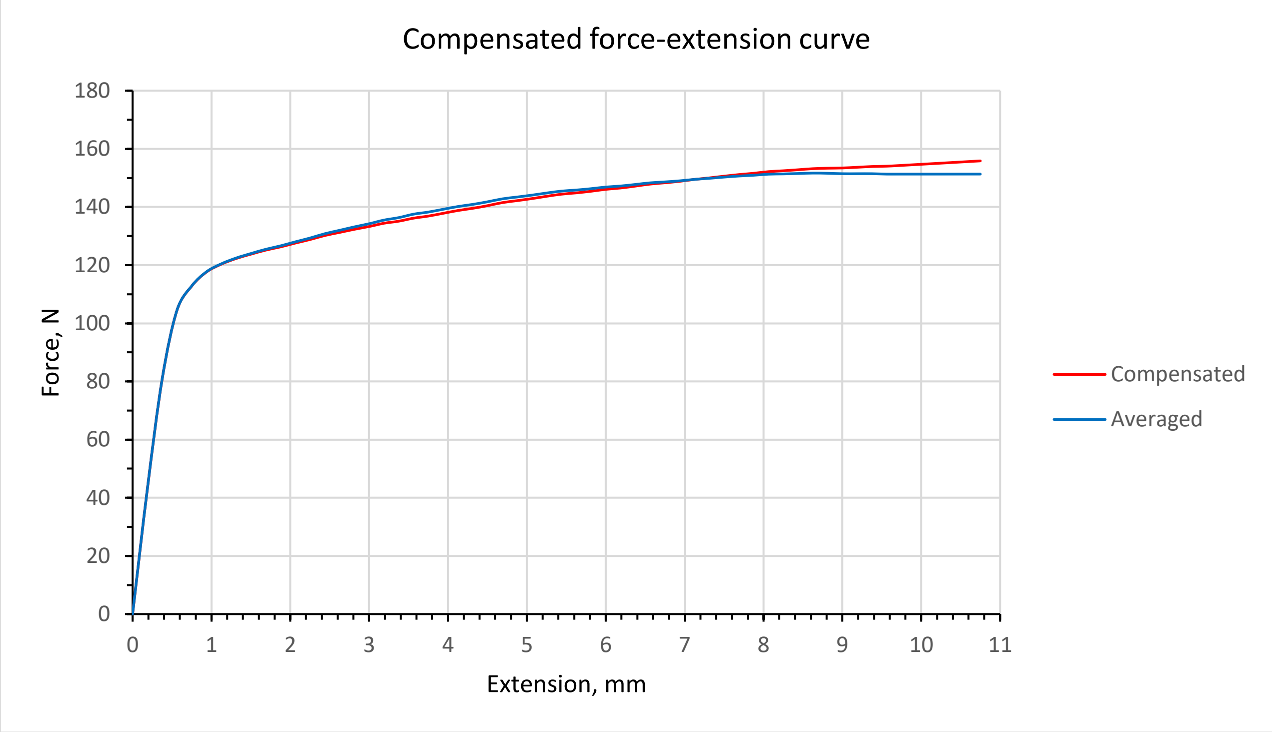

Fig. 23. Compensated force-extension curve

5.3. Flexure stress-strain curve

The strain can be calculated by measuring the bend radius of the specimen. The precise measurement can be taken by coordinate measuring machine, or it can be approximated from a picture of specimen on grid paper (Fig. 24.). The strain formula calculates total strain from radius of bend neutral axis, thus measured outer radius should be offset by wire radius:

$$\varepsilon = \frac{r}{R_{neutral}} = \frac{r}{R_{outer} - r} \tag{5.5}$$

where ε – strain, r – wire radius, R – bend radius.

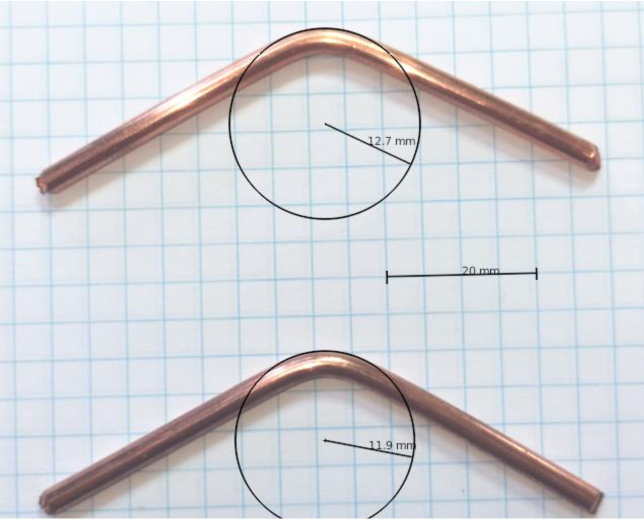

Fig. 24. Specimen bend radius measurements

$$\varepsilon = \frac{3.57/2}{12.3 - 3.57/2} = 0.1697 \approx 0.17$$

The bending stress can be calculated from bending moment and section modulus of a circle:

$$\sigma = \frac{M}{S} \tag{5.6}$$

$$M = \frac{FL}{4} \tag{5.7}$$

$$S = \frac{\pi r^3}{4} \quad (5.8)$$

Where M – bending moment, S – section modulus, F – measured force, L – span between supports, r – wire radius. The bending stress formula is combined:

$$\sigma = \frac{FL}{\pi r^3} \quad (5.9)$$

The strain data is linear, with a range from 0 to 0.17. The force data is taken from Fig. 23. (range from 0 to 10 mm extension) and converted to stress data using bending stress formula. The flexure stress-strain curve (Fig. 25.) reaches 430 MPa at maximum measured strain, more than double of ultimate tensile strength (210 MPa), which is common for ductile materials, such as annealed copper [15]. The maximum elongation of 17 % is less than elongation at break [16], which range is 40-60 %.

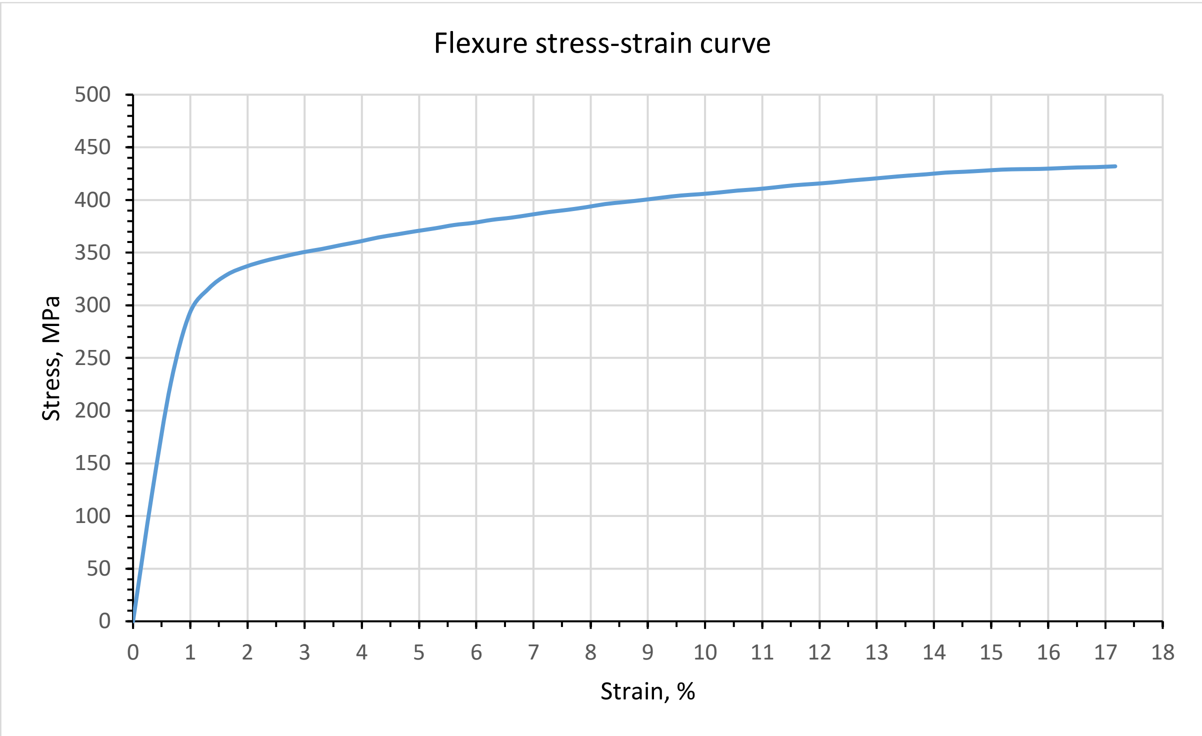

Fig. 25. Flexure stress-strain graph

5.4. Verification by simulation

The validity of the results is determined by comparing calculated and simulated maximum strain. The simulation was run using Ansys Workbench software with Static Structural solver. The setup used frictionless contacts between supports and test piece, the model was split using symmetry on XY plane. The generated mesh (Fig. 26) had 15700 elements (tetrahedrons). The material had multilinear isotropic hardening property, with flexure stress-strain curve data (Fig. 25).

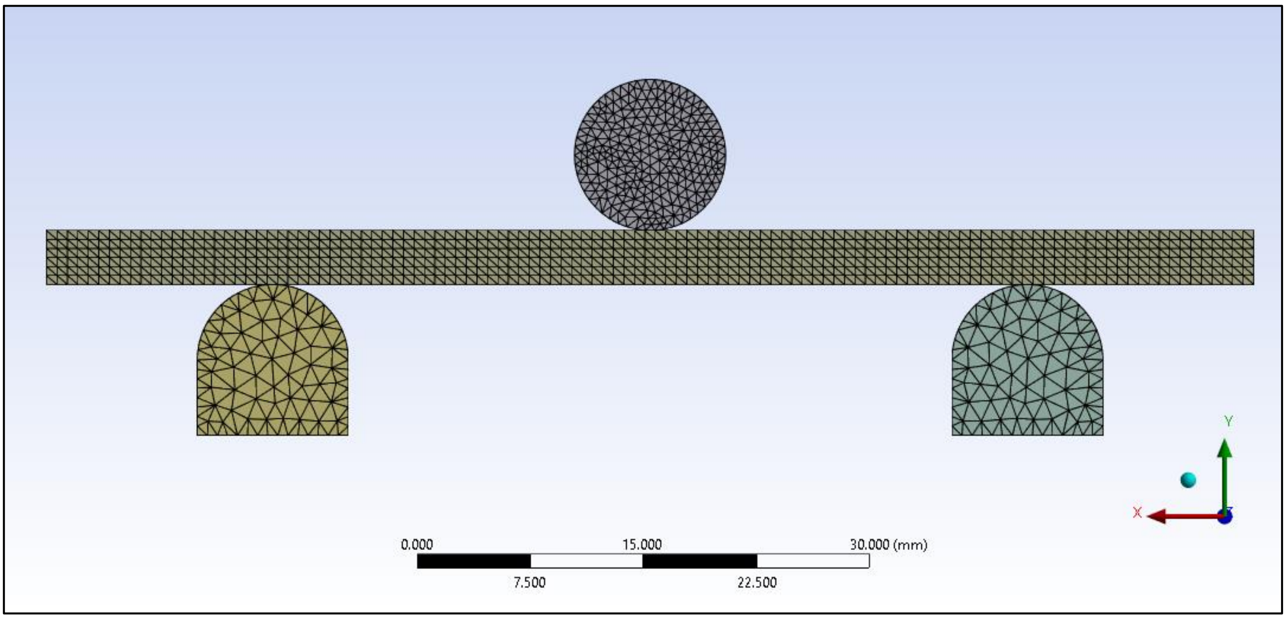

Fig. 26. Three-point bending simulation mesh (simulated with Ansys Workbench)

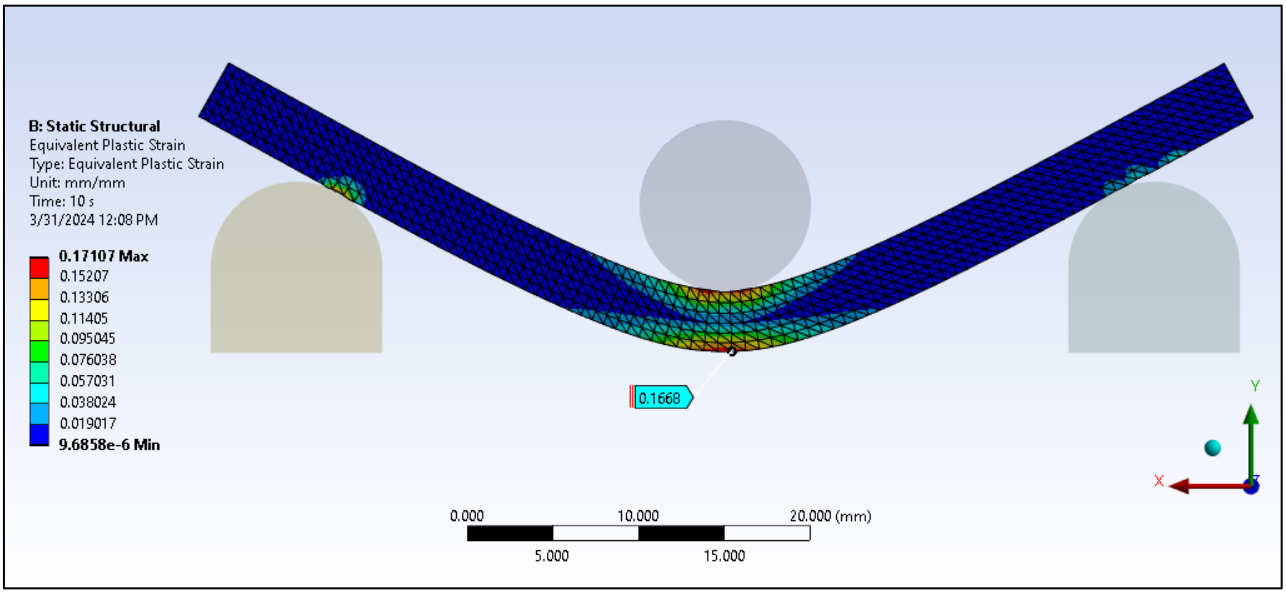

Fig. 27. Three-point bending simulation maximum deformation (simulated with Ansys Workbench)

After the simulation was completed, the equivalent plastic strain result (Fig. 27) was generated. Using Ansys Workbench probe tool, the maximum tensile plastic strain in the middle of the specimen was measured:

$$\varepsilon_{simulation} = 0.1668$$

Plastic strain values from simulation and calculation are compared using percentage error equation (consider the simulation result as measured, and calculated result as true):

$$PE = \frac{\varepsilon_{simulation} - \varepsilon_{calculated}}{\varepsilon_{calculated}} \tag{5.10}$$

$$PE = \frac{0.1668 - 0.1697}{0.1697} = -0.017 \; or \; 1.7\%$$

The error is only 1.7%, thus the calculations are correct with a high degree of accuracy and the data validity is confirmed.

6. Detailed design

6.1. Spindle mechanism

The spindle mechanism consists of a motor-powered spindle head, on which the mandrel is mounted and secured. The spindle head is mounted inside two bearings, that are pressure fit in the frame. The transmission from motor to the spindle head can be accomplished by a chain drive. The torque is transmitted from the motor gearbox to the spindle head by a chain and two sprockets (Fig. 28).

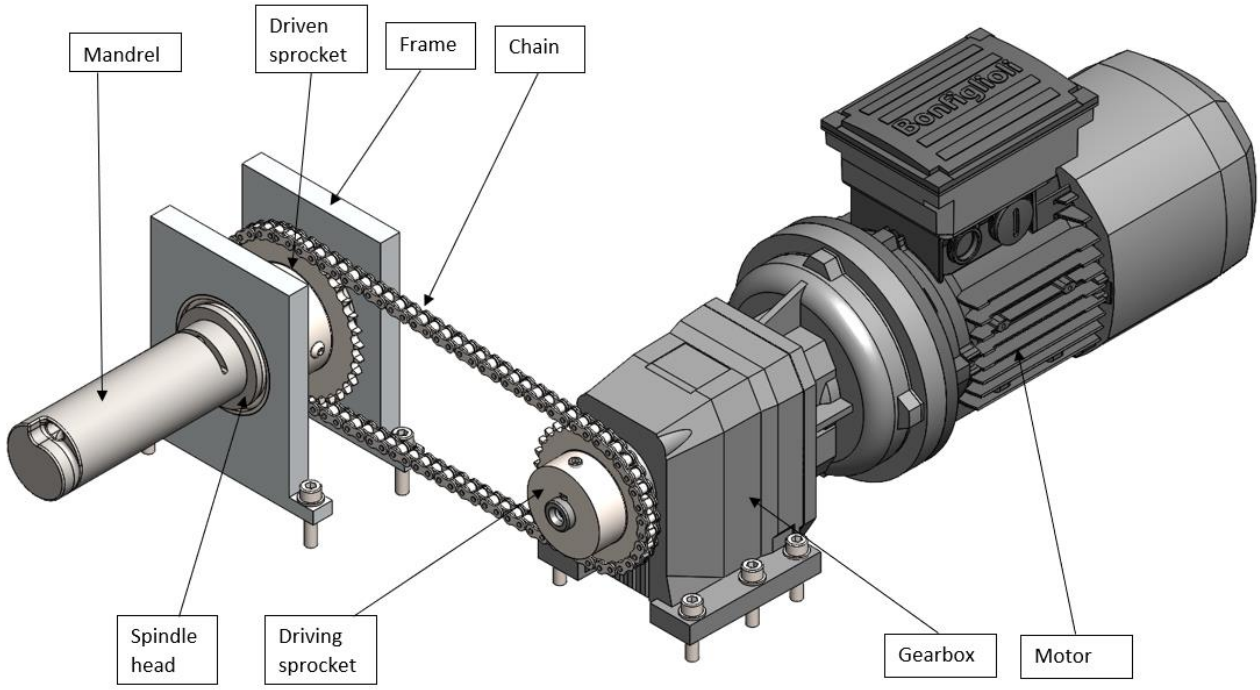

Fig. 28. Spindle mechanism

6.1.1. Mandrel

Mandrel design is based on previously specified inductor geometry. Mandrel shaft diameter is equal to inductor inner coil diameter, and shaft length is based on total inductor height. Because its design parameters are already determined, appropriate material needs to be selected, that would not exceed allowed stresses and deformations.

First, the reaction forces must be determined. The reaction forces that create wire bending moment, can be calculated from bending moment and distance between forces:

$$R_b = \frac{M_b}{d} \tag{6.1}$$

$$M_b = \sigma \cdot S \tag{6.2}$$

The bending stress inside the workpiece is obtained from flexure stress-strain curve. The strain of the wire is calculated:

$$\varepsilon = \frac{r_w}{r_b} \tag{6.3}$$

r_w - workpiece wire radius, r_b - neutral axis radius of the bend. The initial bend radius around mandrel cutout shape (R17) is smaller than the shaft radius, thus the strain value is largest. The strain is calculated from previous formula:

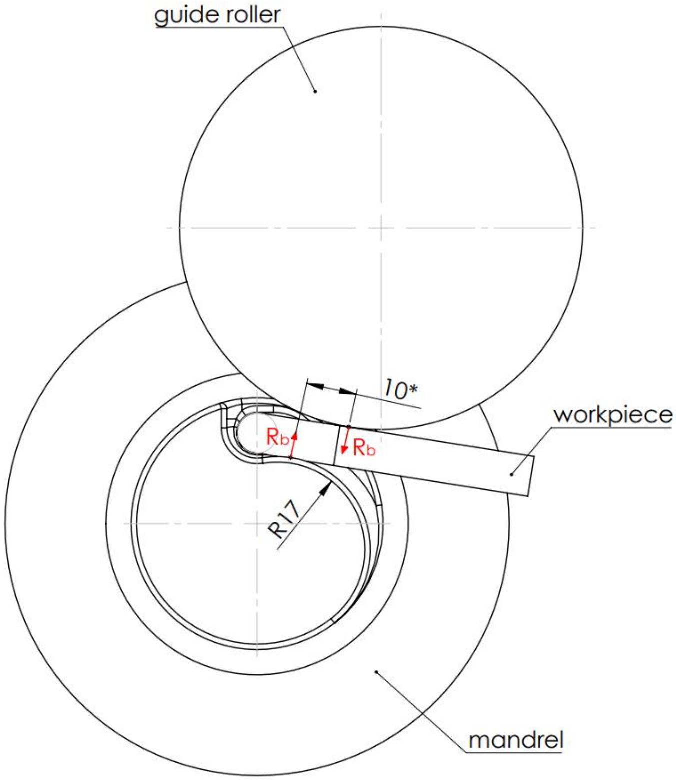

Fig. 29. Guide roller and mandrel reaction forces

$$\varepsilon = \frac{4}{(17+4)} = 0.19$$

Bending stress can be conservatively estimated from stress-strain curve: $\sigma = 440$ Mpa, when $\varepsilon = 19\%$. The reaction forces are obtained by calculating workpiece section modulus and taking approximate distance between forces d=10 mm (Fig. 29).

$$S = \frac{\pi(r_2^4 - r_1^4)}{4r_2} \tag{6.4}$$

$$S = \frac{3.14 \cdot (4^4 - 3^4)}{4 \cdot 4} = 34.3\ mm^3$$

$$M_b = 440 \cdot 10^6 \cdot 34.3 \cdot 10^{-9} = 15.09\ Nm$$

$$R_b = \frac{15.09}{10 \cdot 10^{-3}} = 1509\ N$$

The maximum stresses are obtained using Ansys Workbench static structural simulation. The simulation is too complex for non-linear bending calculations, thus the simulation is simplified by using bending moment M_b to add torque to wire model and evaluate compressive contact stresses near mandrel opening (Fig. 30). By disregarding stress concentrations of low-density mesh, the maximum averaged compressive stress is $\sigma_{max} = 400$ MPa.

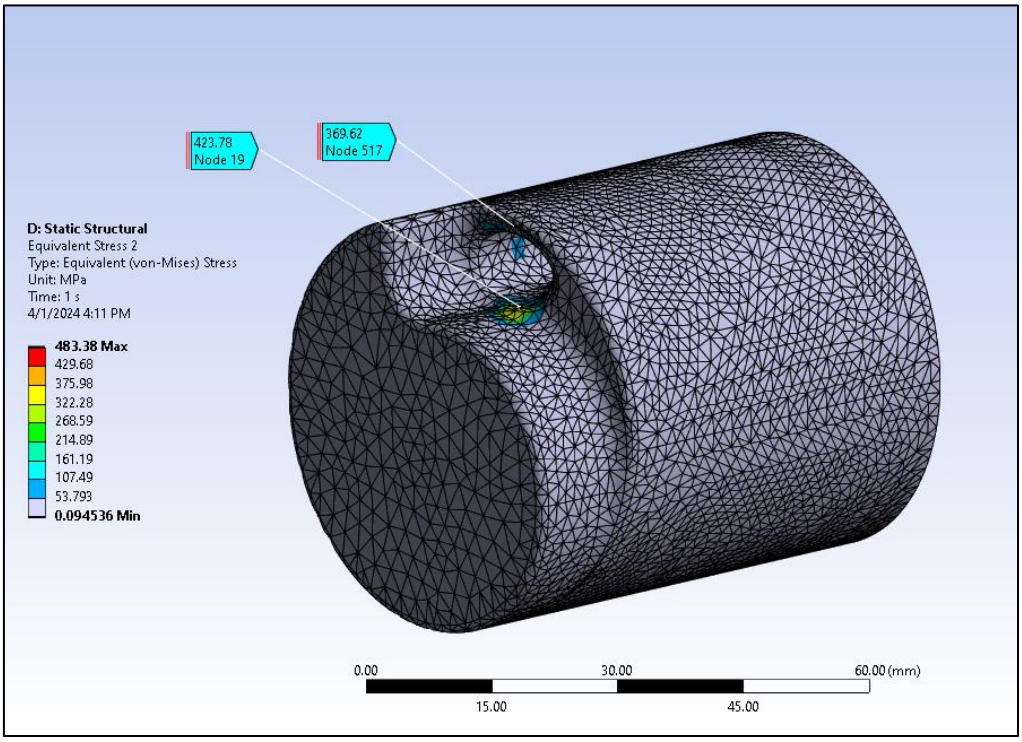

Fig. 30. Mandrel front part simulation mesh (simulated with Ansys Workbench)

The required factor of safety is taken against steel ultimate strength. The factor of safety of 2.0 is sufficient, considering dynamic stresses are small. Also, the mandrel is subjected to compressive stresses, which cause failure at higher values than tensile stresses. Select AISI 1080 hot-rolled steel rod, with ultimate strength $\sigma_{ult} = 870\ MPa$ [17]. The factor of safety is calculated:

$$FOS = \frac{\sigma_{ult}}{\sigma_{max}} \tag{6.5}$$

$$FOS = \frac{870}{400} = 2.18$$

The factor of safety is more than 2.0, thus the steel grade is suitable.

The deformation is evaluated by running a simulation of the entire mandrel (Fig. 31.). The deflection is created by downward force equal to R_b. The maximum allowed deflection is $\delta_{all} = 1\ mm$. The simulation results show maximum deflection $\delta_{max} = 0.064\ mm$, thus it is within allowed limit.

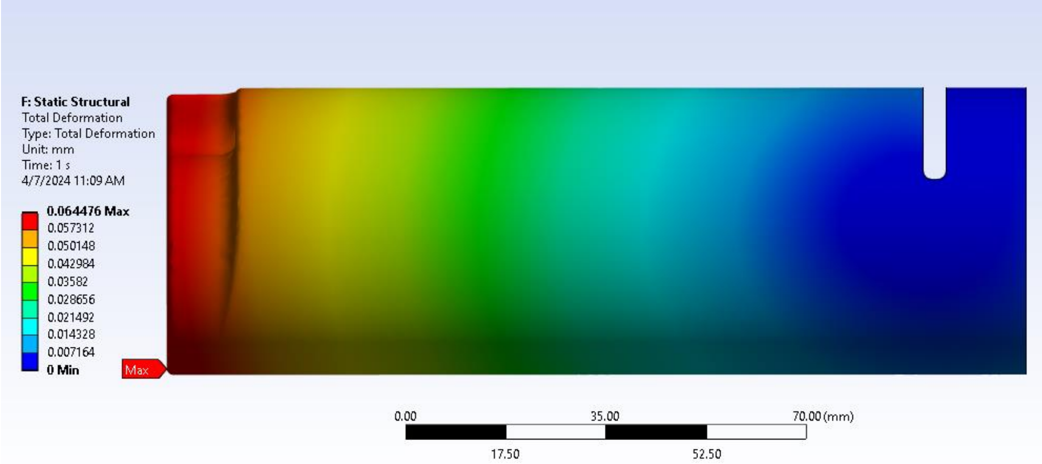

Fig. 31. Mandrel deformation results (simulated with Ansys Workbench)

6.1.2. Spindle head

The mandrel has a square cutout, which is mounted on spindle head square shaft and secured with a set screw. The shaft size is chosen by evaluating the maximum cutout geometry. The cutout square edge should be such that the distance from cutout to mandrel outside surface be approximately equal to half the square edge. The condition is met with 16x16 mm cutout square (Fig. 32), with 8 mm distance to the mandrel surface.

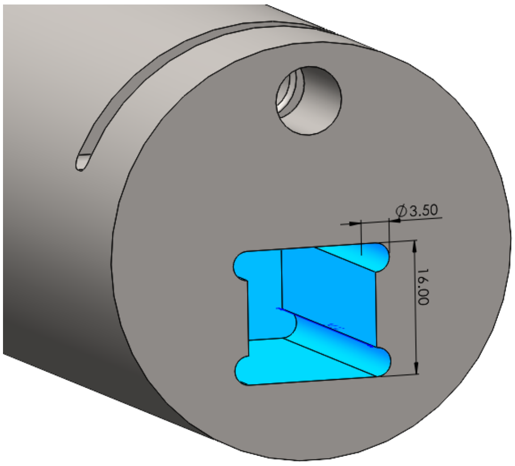

Fig. 32. Mandrel hole for square shaft

The depth of the cutout depends on the machining capabilities. If the square hole is milled, it will have a fillet radius, that may prevent inserting the shaft. "Dogbone" corner relief [18] is milled, to ensure a smooth fit (Fig.32.). Choose the relief diameter of 3.5 mm. The end mill of such diameter has a maximum flute length of 10 mm, which is not enough depth for the cutout. The relief holes can be drilled before milling the pocket [19], with a drill that has a maximum of 39 mm working length. Select the cutout depth to be 36 mm, and the shaft length of 34 mm.

The spindle head is subjected to bending moment and torque (Fig. 33.), thus bending and shear stresses must be evaluated, to check if the required criteria are met.

The material of the spindle head is selected, based on the bending moment of the mandrel. The square shaft is subjected to downward bending moment, that comes from downward force F, equal to reaction force R_b, and distance from mandrel to shaft L_{shaft}.

$$M_{shaft} = F \cdot (L_m - L_{shaft}) \tag{6.6}$$

$$M_{shaft} = 1509 \cdot (0.150 - 0.034) = 175\ Nm$$

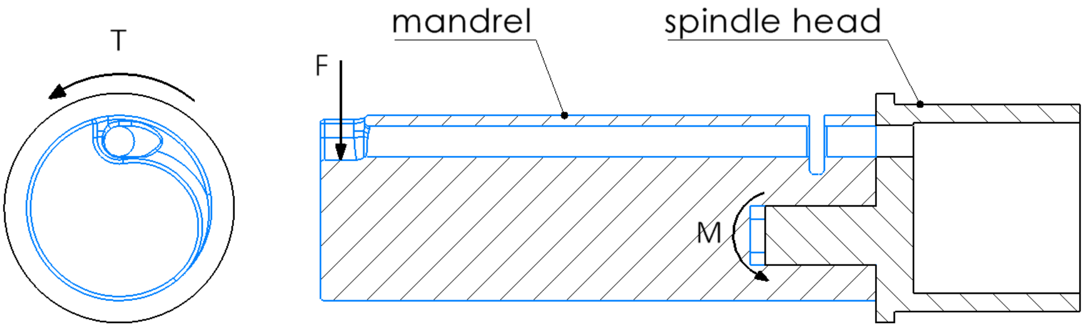

Fig. 33. Mandrel and spindle head loads

The bending stress is calculated from bending moment M, moment of inertia I and distance from centre y:

$$I = \frac{a^4}{12} \tag{6.7}$$

$$y = \frac{a}{2} \tag{6.8}$$

$$\sigma_b = \frac{M \cdot y}{I} \tag{6.9}$$

$$I = \frac{0.016^4}{12} = 5.46 \cdot 10^{-9}\ m^4$$

$$y = \frac{0.016}{2} = 0.008\ m$$

$$\sigma_b = \frac{175 \cdot 0.008}{5.46 \cdot 10^{-9}} = 256.4\ MPa$$

Select AISI 1080 hot-rolled steel for spindle head. The required factor of safety is 2.0. The factor of safety for bending against yield stress:

$$FOS_b = \frac{\sigma_{yield}}{\sigma_{max}} \tag{6.10}$$

$$FOS_b = \frac{480}{256.4} = 1.87$$

Factor of safety of 1.87 is less than required 2.0, thus select steel with higher tensile strength, such as AISI 1090 hot-rolled steel. The recalculated factor of safety:

$$FOS_{b*} = \frac{520}{256.4} = 2.02$$

Next, calculate the shear stress of the square shaft, caused by coiling torque T [20]. The shear stress is calculated from the formula:

$$\tau_{max} = \frac{T}{S_p} \tag{6.11}$$

where S_p – polar section modulus, T – torque.

$$S_p = 0.208 \cdot a^3 \tag{6.12}$$

$$S_p = 0.208 \cdot 0.016^3 = 85.2 \cdot 10^{-6}\ m^3$$

$$\tau_{max} = \frac{15.09}{85.2 \cdot 10^{-6}} = 177.1\ MPa$$

For carbon steels, shear stress is estimated to be equal to 60% of ultimate stress:

$$\tau_{ult} = \sigma_{ult} \cdot 0.6 \tag{6.13}$$

$$\tau_{ult} = 950 \cdot 0.6 = 570\ Mpa$$

The required factor of safety (FOS) for shear stress is 3.0, because of cyclic loads and stress concentrations on square shaft.

$$FOS_s = \frac{\tau_{ult_{1090}}}{\tau_{max}} \tag{6.14}$$

$$FOS_s = \frac{570}{177.1} = 3.22$$

The selected steel grade is sufficient because safety factor of 3.22 exceeds the required 3.0. Finally, the slope of the spindle head is calculated, to assess the deflection of the mandrel. Consider the spindle heads shaft as a cantilever beam, with moment applied on the shaft end (worst case condition). The slope is calculated from formula 6.15.

$$\theta_{max} = -\frac{ML}{EI} \tag{6.15}$$

where L – length of the beam, M – bending moment, E – elastic modulus, I – moment of inertia.

The length of the shaft: L_{shaft} =30 mm.
The elastic modulus for AISI 1090 steel: E=190 GPa.

$$\theta_{max} = -\frac{226.4 \cdot 0.030}{190 \cdot 10^9 \cdot 5.46 \cdot 10^{-9}} = 0.0065\,rad$$

The deflection of the mandrel is calculated from its length and slope:

$$\delta_{max} = L_m \cdot \tan(\theta_{max}) \tag{6.16}$$

$$\delta_{max} = 0.150 \cdot 0.0065 = 0.00097\,m$$

The maximum deflection of 0.97 mm is smaller than the required 1 mm. Because deformation does not exceed the limiting value, there is no need to use spindle steady rest, like in CSM machine.

6.1.3. Spindle fixture

The spindle head is supported by two bearings at each end, as it is the minimum number of bearings to secure the shaft. The spindle head body is a hollow tube, which dimensions should be selected with respect to standard bearing bore sizes. Let spindle outer diameter be 60 mm, with wall thickness of 4 mm. The bearing frame should be secured to the machine bed with M8 screws, thus the desired frame thickness is approximately 16 mm. The bearing load can be approximated from bending moment on spindle shaft (M_{shaft}) and distance between two bearings (~ 100 mm):

$$F_b = \frac{M_{shaft}}{d_b} \tag{6.17}$$

$$F_b = \frac{175}{0.1} = 1750\,N$$

Select a deep-groove ball bearing 61812-2RZ. The bearing factor of safety is calculated against its rated static load R_{static} , because of very low rotational speed:

$$FOS_{bearing} = \frac{R_{static}}{F_b} \tag{6.18}$$

$$FOS_{bearing} = \frac{8800}{1750} = 5.02$$

The factor of safety is acceptable, because it is high enough to compensate for load approximation errors.

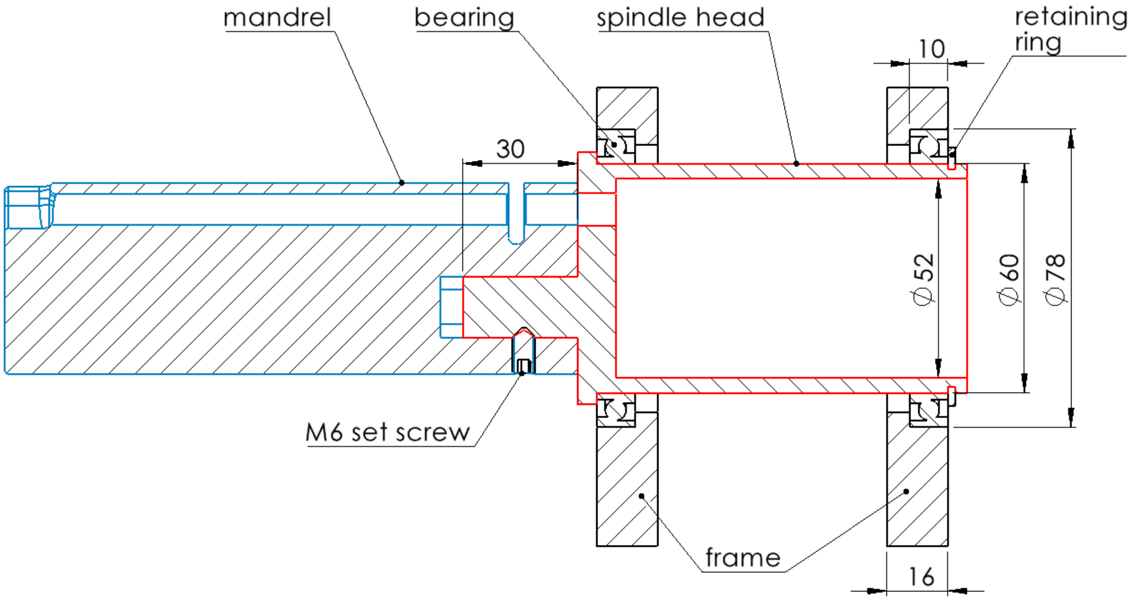

Fig. 34. Spindle head and mandrel fixture

The mandrel is fixed on a rectangular shaft with a single set screw, because there are no horizontal loads acting on the mandrel or the spindle. The spindle heads front step is secured to the first bearing and its back side is secured with a retaining ring (Fig. 34.). The spindle head is fully secured to the frame.

6.1.4. Gearbox and motor

A driving mechanism is required to provide torque for the spindle head. For low-speed coiling operation with a continuous rotary motion, the best option is to use a motor and speed reducer setup. The required torque for coiling was 15 Nm. With a factor of safety of 2.0, the spindle driving torque should be 30 Nm. The spindle rotation speed for CSM inductor machine is one rotation in 2 seconds or 30 rpm. The current machine is designed to bend lower strength tubes than CSM machine, thus the rotation speed can be as high as 50 rpm.
Spindle characteristics:

- Output speed n_{out} = 50 rpm
- Output torque T_{out} = 30 Nm

Consider using asynchronous motor BN-80B [21] from Bonfiglioli. Motor characteristics:

- $n_{motor} = 680\ min^{-1}$
- $T_{motor} = 3.51\ Nm$

A spur gear reducer can be used to get the required output speed and torque. The gear ratio is calculated:

$$i = \frac{n}{n_{out}} \tag{6.19}$$

$$i = \frac{680}{50} = 13.6$$

For gear ratio of 13.6 the smallest number of teeth for a pinion gear is 17 teeth, then the driven gear has approximately 232 teeth. Even with a small module of 1.5, the gear pitch diameter is very large:

$$d = z \cdot m \tag{6.20}$$

$$d = 1.5 * 232 = 348\ mm$$

To minimize the gear sizes, a two-gear train compound gearbox could be used, but it would increase the complexity and price of the gearbox. Consider using a gearmotor with built-in gear reducer. Take C series in-line gearmotor C-12-2_25.4, that has larger output speed than required. Gearmotor specifications:

- Gearmotor output speed n_2 : 55 rpm
- Rated motor speed n_1 : 1400 rpm
- Gear ratio i: 25.4

The required power of the motor can be calculated, based on spindle output torque [22]:

$$P = T_1 \cdot \frac{\pi \cdot n_1}{30} \tag{6.21}$$

Motor input torque is calculated:

$$T_1 = \frac{T_{out}}{i} \tag{6.22}$$

$$P = \frac{T_{out}}{i} \cdot \frac{\pi \cdot n_1}{30} \tag{6.23}$$

$$P = \frac{30}{25.4} \cdot \frac{3.14 \cdot 1400}{30} = 173\ W$$

The motor, that satisfies this power requirement is asynchronous motor BE_71_A. Motor characteristics:

- Power P_{1m} : 0.25 kW
- Speed n_{1m} : 1380 min^{-1}
- Torque T_{1m} : 1.73 Nm

The final speed and torque output (with efficiency of 96%) is recalculated for the selected motor and gearbox combination:

$$n_{2f} = \frac{n_{1m}}{i} \tag{6.24}$$

$$n_{2f} = \frac{1380}{25.4} = 54.3\ min^{-1}$$

$$T_{2f} = T_{1m} \cdot i \cdot \eta \tag{6.25}$$

$$T_{2f} = 1.73 \cdot 25.4 \cdot 0.96 = 42.2\ Nm$$

The spindle shaft was designed for torque of 15 Nm with a factor of safety of 3.22. The spindle working torque is 15 Nm and its maximum torque is 30 Nm, when subjected to high dynamic loads. The gearbox output torque is higher than the allowed, thus a torque limiter must be installed.

6.1.5. Chain and sprocket

The spindle head is hollow, therefore the gearbox output shaft cannot be directly connected to the spindle. There are two inexpensive options to transfer torque from gearbox to spindle: chain drive or belt drive. The belt drive cannot be installed without removing the spindle, which is supported by two bearings (Fig. 34.). The chain does not have such limitations, because it can be wrapped around the spindle and joined by a pin. Select a chain drive, that will connect spindle and gearbox shaft by a chain and two sprockets (desired ratio 1:1).

The driving sprocket is mounted on the gearbox output shaft. Driving sprocket is a standard B-type sprocket with a hub and a keyway. It must have a Ø20 mm bore hole, to be mounted on the shaft. The driven sprocket is mounted on a Ø60 mm spindle head, thus a bore hole can be custom machined, if the hub diameter is no less than 70 mm.

From standard sprocket catalogue, according to DIN8187, there is one couple of sprockets, that match all the criteria. The chain size is DIN06B-1, driving sprocket is PCS37-30H-20K and driven sprocket is PCS37-36 from HPC catalogue. Driving to driven sprocket gear ratio is 30:36, thus the spindle output speed is calculated, while torque remains limited to 30 Nm:

$$n_{spindle} = n_{2f} \cdot \frac{z_1}{z_2} \tag{6.26}$$

$$n_{spindle} = 54.3 \cdot \frac{30}{36} = 45.3\ min^{-1}$$

The driven sprocket must be modified to transmit torque to the spindle. The bore diameter is increased from standard 14 mm to 60 mm. The sprocket is secured to the spindle with two bolts, that go through holes in the sprocket hub and screw into the spindle head.

For sprocket-spindle connection, the weakest point of failure is bolts shear stress due to torque. Take two bolts ISO 7380 M6x10 grade 4.6.

The maximum force is calculated from spindle torque limit T and its diameter d:

$$F_{sprocket} = \frac{T}{\frac{d}{2}} \tag{6.27}$$

$$F_{sprocket} = \frac{30}{0.03} = 1000\ N$$

Factor of safety for sprocket-spindle bolted joint is calculated by comparing maximum load to rated bolt shear resistance (from EN 1993-1-8 standard):

$$FOS_{bolt} = \frac{2 \cdot F_{\text{v M6-4.6}}}{F_{sprocket}} \tag{6.28}$$

$$FOS_{bolt} = \frac{7720}{1000} = 7.72$$

The chain DIN06B-1 F.O.S is evaluated by comparing its rated load and sprocket force:

$$FOS_{chain} = \frac{F_{rated}}{F_{sprocket}} \tag{6.29}$$

$$FOS_{chain} = \frac{9000}{1000} = 9.0$$

The safety factors are suitable and conservative.

6.2. Guide roller mechanism

The guide roller mechanism consists of a roller wheel, that is positioned by the movement of two actuators (Fig. 35). The combination of horizontal and vertical actuators allows the roller wheel to translate in two corresponding directions. The components are joined together by machined aluminium brackets and screws.

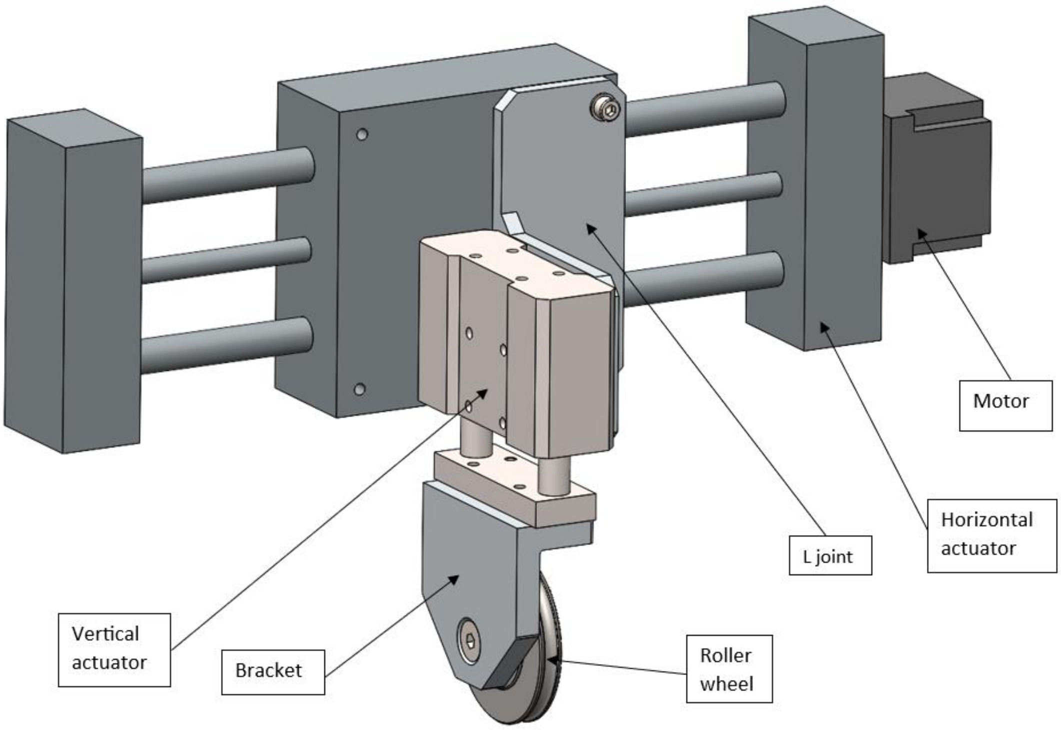

Fig. 35. Guide roller mechanism

6.2.1. Reaction forces

A guide roller wheel is subjected to two loads, which correspond to two reaction forces: coil forming force (R_c) and pitch forming force (R_p), shown in Fig. 36. The coil forming force magnitude is equal to wire bending reaction force R_b, by Newton's third law:

$$\left|\overrightarrow{R_c}\right| = \left|-\overrightarrow{R_b}\right| = 1509\ N \tag{6.30}$$

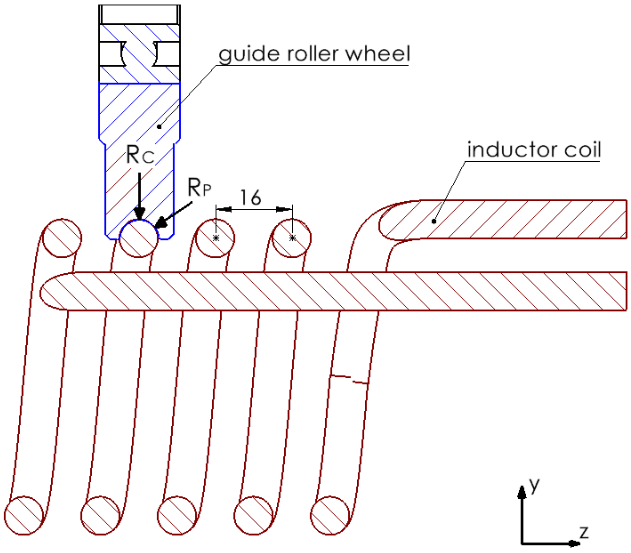

Fig. 36. Guide roller wheel reaction forces

The pitch forming force is found from the simulation. A semicircular coil segment is offset in z axis by the coil pitch (16 mm). The simulation object is a 90-degree coil segment, which is in contact with roller wheel and is displaced by a distance of half the pitch (8 mm).

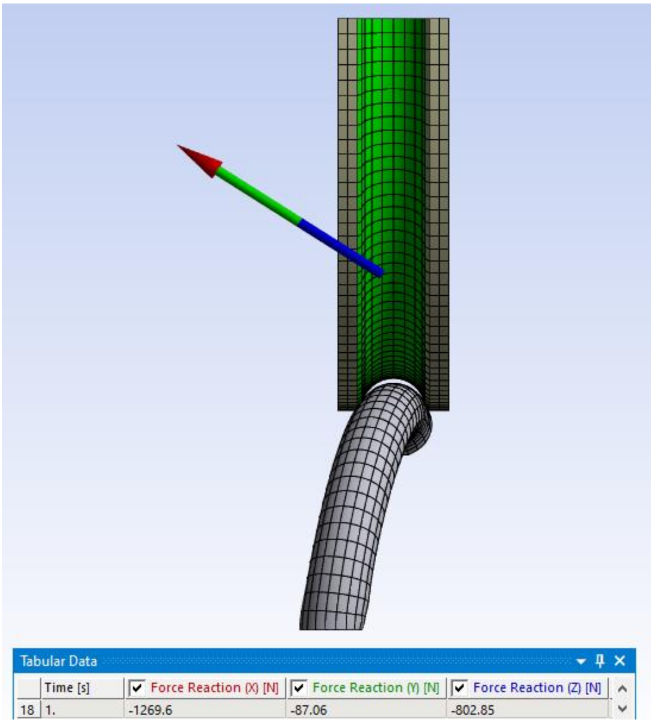

Fig. 37. Guide roller wheel simulation total reaction force (simulated with Ansys Workbench)

Pitch forming reaction force vector consists of z and y components and their values are found from the simulation (Fig. 37.):

$R_{Pz} = 1270\ N$

$R_{Py} = 803\ N$

6.2.2. Roller wheel and bearing

The roller wheel diameter is approximately double of the mandrel diameter, based on CSM Machinery.

$$d_{roller} = 2 \cdot d_{mandrel} \tag{6.31}$$

$$d_{roller} = 2 \cdot 50 = 100\ mm$$

The wheel bearing is subjected to radial and axial loads, calculated from the roller wheel reaction forces:

$$F_{radial} = R_C + R_{Py} \tag{6.32}$$

$$F_{radial} = 1509 + 803 = 2312\ N$$

$$F_{axial} = R_{Pz} = 1270\ N \tag{6.33}$$

Let roller wheel bearing have 12 mm bore hole for M12 bolt. Select a double row deep-groove ball bearing 4301-ATN9 from SKF catalogue [23]. The factor of safety for the bearing is calculated for its rated dynamic load because it can freely rotate. The factors are calculated for radial and axial loads. The safety factors are required to be higher than 3.0 for radial and 2.0 for axial loads.

$$FOS_{radial} = \frac{C_{dynamic}}{F_{radial}} \tag{6.34}$$

$$FOS_{radial} = \frac{13000}{2312} = 5.62$$

$$FOS_{axial} = \frac{C_{axial}}{F_{axial}} = \frac{0.25 \cdot C_{dynamic}}{F_{axial}} \tag{6.35}$$

$$FOS_{axial} = \frac{0.25 \cdot 13000}{1270} = 2.56$$

The safety factors are sufficient – the bearing is suitable. The roller wheel is secured to the bracket with a bolt and nut. Choose M12 ISO10642 grade 4.8 bolt. Its factor of safety against shear stress:

$$FOS_{bolt_{shear}} = \frac{F_{\mathrm{v\ M12-4.8}}}{F_{radial}} \tag{6.36}$$

$$FOS_{bolt_{shear}} = \frac{13500}{2312} = 5.84$$

The guide roller wheel material is selected based on maximum stresses, found from the simulation (Fig. 38.). By disregarding the stress concentration of low-density mesh, the maximum stress is approximately 420 MPa.

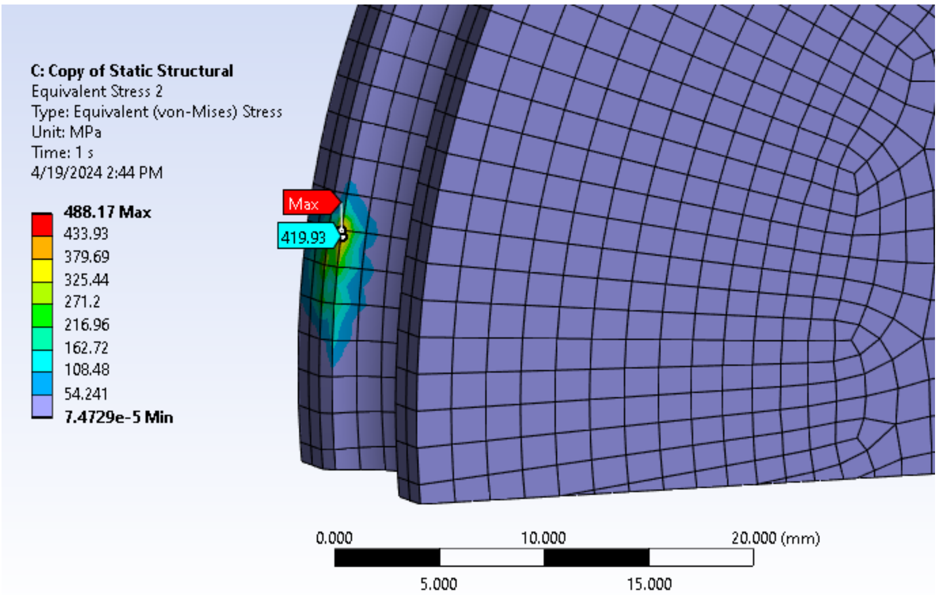

Fig. 38. Guide roller wheel contact stress simulation (simulated with Ansys Workbench)

Consider using AISI 1090 hot rolled steel, then the factor of safety against ultimate stress:

$$FOS = \frac{\sigma_{ult}}{\sigma_{max}} \tag{6.37}$$

$$FOS = \frac{950}{400} = 2.38$$

The safety factor 2.38 > 2.0, and the material is suitable for the guide roller wheel.

6.2.3. Bracket

The bracket is a fixture that is secured to the vertical actuator and holds the M12 bolt, where the guide roller wheel is mounted. The bolt bearing stress on the bracket is calculated based on its hole contact area:

$$\sigma_{bracket} = \frac{F}{A} = \frac{F_{radial}}{d \cdot t} \tag{6.38}$$

Where d – bolt hole diameter, t – hole depth.

$$\sigma_{bracket} = \frac{2312}{0.013 \cdot 0.008} = 22.2\ MPa$$

Select aluminium alloy 1070 with tensile strength of 95 MPa. The safety factor:

$$FOS = \frac{\sigma_{yield}}{\sigma_{bracket}} \tag{6.39}$$

$$FOS = \frac{95}{22.2} = 4.28$$

The selected material is acceptable. Analogically, the bracket that joins vertical and horizontal actuators is also made from Aluminium 1070 alloy.

6.2.4. Vertical actuator

The vertical movement is used to support the workpiece during coiling operation and release it afterwards. A pneumatic actuator is the most economical option because the actuator does not require high precision for “hold and release” functionality. The most precise movement for this actuator is during the beginning of coiling operation, where the wire is coiled around the mandrel semicircular cutout (R=17mm) until it reaches the mandrel radius (R=25mm). During this operation, the guide roller position is compensated by a difference in mandrel radii. The required stroke length should not be less than double this distance:

$$s_{vertical} = 2 \cdot (25 - 17) = 16\ mm$$

The vertical actuator must be capable of resisting loads from coil forming and pitch forming loads, but not necessarily both at the same time. The coil forming force is the highest at the beginning of coiling, and it decreases during 90-degree rotation, after which the pitch forming begins. Under normal conditions, the components are not subjected to both loads, but they are designed to resist both loads, to avoid failure in case of incorrect loading conditions. The pneumatic actuator with an overpressure valve would not be at risk of damage, even if the loads were too high, thus it can be designed for the maximum required load R_C.

For dual rod cylinder, with an operating pressure of 0.7 MPa, the cylinder bore diameter is calculated:

$$A = 2 \cdot \frac{\pi d_{bore}^2}{4} = \frac{R_c}{p} \tag{6.40}$$

$$d_{bore} = \sqrt{\frac{2R_c}{\pi p}} \tag{6.41}$$

$$d_{bore} = \sqrt{\frac{2 \cdot 1509}{3.14 \cdot 0.7 \cdot 10^6}} = 0.037\ m$$

Select a dual rod cylinder JMGP50-50 from SMC company catalogue [24]. Its specifications:

- Bore size: 40 mm x 2
- Cylinder stroke: 50 mm
- Operating pressure: 0.7 MPa
- Output force: 1759 N
- Stroke: 50 mm

6.2.5. Horizontal actuator

The purpose of horizontal actuator is to translate the guide roller wheel along the mandrel. This movement is constant, and it requires precision, because it forms the inductor coil pitch. The horizontal actuator moves the guide roller wheel, the bracket, and the vertical actuator. A screw driven actuator [25] is most suitable, due to the requirements in precision and control. The lead screw linear actuator is selected based on two requirements:

- Stroke length > 225 mm (mandrel length x 1.5)
- Radial load > 2312 (F_{radial})

Select Drylin® linear module: SHT-30 DS20x5. It has a maximum static load of 6000 N, custom stroke of 250 mm, maximum speed of 0.083 m/s, service life of 107000 double strokes, NEMA 34 stepper motor.

The lead screw actuator meets the given requirements, and it is suitable for the application.

6.3. Visualization of the machine

The detailed design focused on two main subassemblies of the machine: the guide roller mechanism and spindle mechanism, which participate in the coiling stage of manufacturing process. The design of the remaining components is outside the scope of this project. Those components include the wire feeders, wire straighteners, cutting saw, bending machine, wire uncoiler and the machine frame (Fig. 39). These components can be custom ordered or modified from available for purchase equipment. The machine frame must be specifically designed for this machine, as it joins the mechanisms together with great precision.

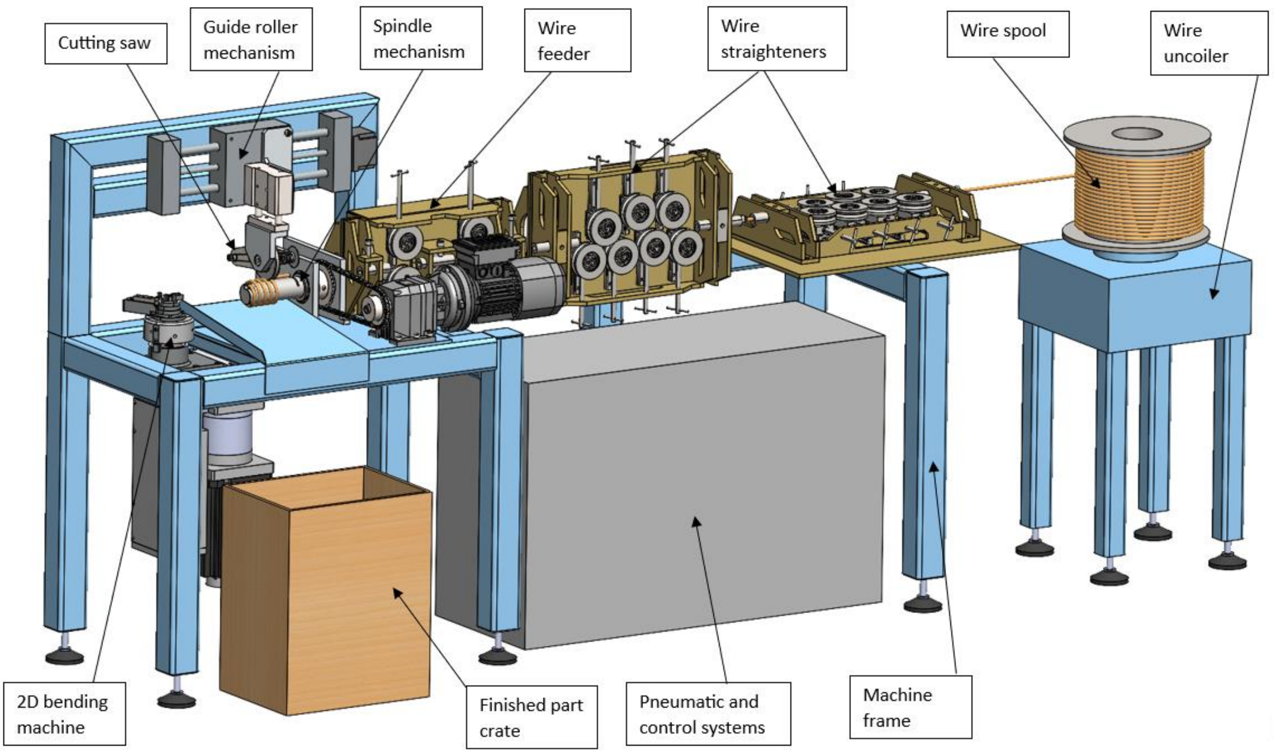

Fig. 39. Automatic machine all components (SolidWorks)

The full manufacturing process begins with a wire spool, that is uncoiled by the dedicated mechanism or by the force of the wire feeder, if the feeding force is high enough. The wire passes through wire straighteners and wire feeder, which shapes a wire into a straight line. The wire is pushed through the spindle mechanism into the bending machine, where the inductor leads are bent into position. After bending, the cutting saw separates workpiece from raw straight wire. Then, the spindle and guide roller mechanisms move in synchronization and coil the wire into shape of an inductor. The finished part is discharged from the mandrel by guide roller movement and the product rolls down the ramp into the crate.

7. Economical calculations

In this chapter, the full price of the inductor coiling machine is calculated. The calculations include cost of raw materials, manufacturing cost of parts, cost of purchased standard components, cost of custom ordered mechanisms and cost of assembly.

7.1. Cost calculations of manufactured parts

From the part list of spindle and guide roller assemblies, the total cost of non-standard components is calculated. The raw material price is lower, when manufacturing more than one machine. Take that the company has enough orders to manufacture a small batch of 10 inductor coiling machines. Then the raw materials are utilized with less losses. For example, the guide roller wheel, mandrel and spindle head are made of AISI 1090 steel bar, which is ordered in 3-meter length. A large portion of the steel bar would be discarded if only a single machine is made, but the costs of raw material would be the same as if the whole steel bar is used. The manufacturing time is taken from UAB BCT company 5-axis milling machine rate of 30 € / hour.

Table 3. Manufactured parts cost

Name	Units	Raw material price, €	Manufacturing time, h	Manufacturing price, €
Guide roller wheel	1	25	3	90
Bracket	1	97	2.5	75
L joint	1	97	3.5	105
Mandrel	1	24	5	150
Spindle head	1	24	5	150
Frame 01	1	10	4	120
Frame 01V	1	10	4	120
Sprocket PCS37-36	1	15	2	60
		Total: 302	Total: 29	Total: 870

7.2. Cost calculations of standard components

The cost of standard components does not significantly change with a batch size of 10 units, because the economics of scale when buying in bulk apply to large quantities of hundreds of parts. The cost of bolts, nuts, washers, set screws is added to the standard fasteners cost. The fasteners total cost is calculated based on their quantity and average price per unit.

Table 4. Standard components cost

Name	Units	Price € / unit
Pneumatic actuator JMGP50-50	1	128
Screw-drive actuator SHT-30 DS20x5	1	816
Screw drive actuator motor NEMA 34	1	364
Screw drive actuator motor control	1	696
Guide roller bearing 4301-ATN9	1	7
Sprocket PCS37-30H-20K	1	20
Chain DIN06B-1 (1m)	1	7
Standard fasteners	50	0.5
		Total: 2063

7.3. Cost calculations of custom ordered mechanisms

The machine frame

The frame of the inductor machine is made of welded rectangular tubes. The raw material cost is calculated from cost per meter and total length of tubes. The cost for 80x80x5 mm S235JR steel is 76 Eur / m. The total length of tubes is 13.5 m, thus the cost of the frame: $76 \cdot 13.5 = 1\ 026$ Eur. The cutting and welding cost of the frame is calculated by taking hourly rate of welder (10 Eur/h) and equipment (15 Eur/h). The building time of the table is approximately a full workday – 8h. The building cost: $(10 + 15) \cdot 8 = 200$ Eur. The cost of additional operations, such as sanding, painting, thread drilling is approximated to be 150 Eur. The cost of transportation between facilities: 80 Eur. The total cost: $1026 + 200 + 150 + 80 = 1\ 456$ Eur.

The cutting saw

The saw is modified from a lifting table saw. The cost of the saw is 80 Eur. The modifications include new components: a custom machined lever, pneumatic actuator, motor controller, thin saw blade. The total price of components: 66 Eur. The assembly cost is approximated: $6\text{h} \cdot 20\text{Eur/h} = 120$ Eur. The total cost: 266 Eur.

The automatic wire feeder and straightener

The cost of automatic wire feeding and straightening machine from Pilot Line Tools is 7 420 Eur (Fig. 40.). The machine is fully automatic, thus there is no added cost for numerical controllers.

Fig. 40. Automatic wire feeder and straightener [6]

The 2D bending machine

The bending machine cost can be estimated from existing similar machines on the market. The stirrup spiral bending machine is a close match. The machine has a fixture that can move up and down and a pin that performs the bending operation, which matches the required wire bending steps (Fig. 11.). The cost of stirrup machines (Fig. 41.) is up to 1 500 Eur, but for the custom-made machine the price can reach up to 3 000 Eur. The machine is not automatic, because it requires an operator to press and hold the pedal. The bending machine should be integrated into inductor coiling machine control system, to make the bending process automatic.

Fig. 41. 2D bending machine [7]

Electrical and pneumatic systems

The cost calculations of electrical and pneumatical systems are very complex. The cost can be estimated by adding the prices of the main components: CNC machine controller, motor variable frequency drives, pneumatic pump, pneumatic valve blocks, air filters, solenoids. The total price is estimated to be 15 000 Eur.

Machine covers

The additional cost to the inductor coiling machine is the manufacturing and installation of sheet metal covers, that protect the machine from external pollutants, such as dust and moisture. The covers are imperative in protecting the workers from potential injuries, such as cutting and crushing hazards. The estimated cost of covers is 500 Eur.

7.4. Total cost of the machine

The full cost of the machine includes the previous cost calculations. The cost of components is calculated, but their assembly cost must be calculated too. The assembly time is estimated to be a month (21 working days), with two workers and a single 8-hour shift. This includes mechanical and electrical assembly of the machine. The programming of the machine is considered a separate cost, equal to 15% of assembly cost. The assembly cost:

$$P_{asm} = 21 days \cdot 8 hours \cdot 2 workers \cdot \frac{30 Eur}{h} = 10\ 080\ Eur \quad (7.1)$$

Table 5. Production cost

Name	Cost, Eur
Manufactured parts	1 172
Standard parts	2 063
Machine frame	1 456
Cutting saw	266
Automatic wire feeder and straightener	7 420
2D bending machine	3 000
Electrical and pneumatic systems	15 000
Machine covers	500
Assembly cost	10 080
Programming cost	1 512
Total cost:	**42469**

Table 6. Sales cost

Total production cost	42 469 Eur
Sales and management cost (10 % of production cost)	4 247 Eur
Prime cost	46 716 Eur
Profit (10 % prime cost)	4 671 Eur
Sales price, no VAT (prime cost + profit)	51 387 Eur
Sales price, with VAT (+21% sales price)	62 179 Eur

The sales price of the machine is calculated from the previous total production cost [26]. The final sales price of the inductor coiling machine:

$$S_{VAT} = 62179\ Eur$$

7.5. Pay-back period

The pay-back period is a time, during which the cost of initial investment is recovered.

First, the profit per part is calculated by finding the price difference between workpiece and finished part. The inductor workpiece is approximately 1000 mm of copper tube. The 10m coil costs 26.80 Eur, thus the inductor workpiece cost is 2.68 Eur. The sell price of inductor, with similar specifications, is 9 Eur with VAT (Amazon website), and 7.10 Eur without VAT. To capture larger portion of market, the inductor cost should be less than 7 Eur. Take the 50 % profit margin, which results in inductor price of 4.02 Eur without VAT. The profit margin is acceptable because the product price is lower than the competitor’s price.

The daily manufacturing capacity of the inductor machine is calculated from the machine running time and manufacturing duration of one part. A product manufacturing time consists of wire feeding time, bending time, cutting time, and coiling time. Each operation takes approximately 60 seconds; thus, the total production time is 240 seconds per part. The machine is running 8 hours per day, with

30-minute setup time, thus the working time is 7.5 hours. The daily production capacity of one machine is calculated:

$$PC = daily\ working\ time\ \cdot 1h/production\ time \tag{7.2}$$

$$PC = 7.5\ \cdot 3600s/240s = 112.5\ parts$$

The daily profit is equal to price of profit margin and number of parts per day:

$$P_{day} = \mathrm{PC} * \left(\mathrm{S}_{workpiece} \cdot \frac{\text{profit margin}}{100\%}\right) \tag{7.3}$$

$$P_{day} = 112.5 * \left(2.68 \cdot \frac{50\%}{100\%}\right) = 150.7\ Eur$$

The pay-back period [27] is calculated from sales price of machine and daily profit:

$$PBP = \frac{S_{VAT}}{P_{day}} \tag{7.4}$$

$$PBP = \frac{62179}{150.7} = 413\ days$$

The data suggests that if the machine is running constantly 8 hours per day, the investment breaks even in 412 working days or 1.65 years. Realistically, considering the variables, such as machine downtime, additional setup time, maintenance time, repair time, the machine is likely to break even in approximately 2 years.

Current CSM induction manufacturing machines have an additional cost of paying a salary to the operator, because the machines are not fully automated. Considering identical costs of the machine it can be calculated what would be the pay-back period for machine and operator work. An operator is paid 150% of minimal Lithuanian hourly rate (min. 5.65 Eur/h) for 8 hours/day, the daily profit is reduced to:

$$P_{day\_new} = 150.7 - 5.65 \cdot \frac{150\%}{100\%} \cdot 8 = 82.9\ Eur$$

$$PBP_{new} = \frac{62179}{82.9} = 750\ days$$

Having an operator increases the pay-back period up to 750 days (3 years) instead of 413 days (1.65 years). Percent increase:

$$PI = \frac{750 - 413}{413} \cdot 100\% = 81.6\ \%$$

The addition of an operator increased pay-back duration by 81.6 percent.

Conclusions

1. The universal CNC spring coiling machine can produce variable diameter coiled parts, which cannot be done by other types of machines. The lathe type machine can coil much larger diameter wires (up to 20 mm) but has a fixed coil diameter. The internal coil heater machine is specifically designed to produce heating elements – it is most suitable for internal inductor manufacturing, thus the design of new components is based on this machine.
2. The inductor consists of two leads and coiled body. It was determined that the leads are formed first by bending operation, and coiled body is formed afterwards, during the coiling operation.
3. The main mechanisms of the machine are designed, based on three stages of manufacturing: bending, parting-off and coiling. The bending stage utilizes bending machine, the parting-off stage – cutting saw, the coiling stage – spindle mechanism and guide roller. The wire feeder is one of the main components, which participates in all production steps.
4. An annealed copper wire was used for three-point bending experiment to determine its mechanical properties. The experiment result was a force-extension graph, which reached 154 N at 10 mm extension. The data was calculated and converted to flexure stress-strain curve, which reached 431 MPa at 17% strain. The data was verified with a simulation, where the difference in results was 1.7%. The flexure curve is used to find bending stresses from known wire deformation and calculate the required bending moment.
5. Two main components of the machine were designed: spindle mechanism and guide roller mechanism. The spindle mechanism is driven by a motor and gearbox, which transmits torque via two sprockets and a chain. The maximum required torque for spindle was 15.09 Nm. The guide roller mechanism has two actuators: vertical pneumatic cylinder actuator and horizontal screw driven actuator. The components were designed against yield stresses with a safety factor higher than 2.0 and maximum deformation less than 1 mm.
6. The assembly drawings of previously designed mechanisms were designed with SolidWorks software. The drawings include a list of all components (bill of materials), main views and total mechanism size dimensions. The manufactured parts include type of machining – milling, turning.
7. The cost of standard and non-standard machine components was calculated, and the total machine price was 62179 Eur after tax. It was estimated that with 50% product margin and one shift per day, the machine pay-back period is 1.65 years. The main advantage of the automatic machine is an absence of the operator, whose salary costs would increase the pay-back duration to 3 years - 81 percent increase.

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Appendices

Appendix 1. Part list

FORMAT	ZONE	NO.	DESIGNATION	NAME	QTY.	NOTES
				Documentation		
			PR-01.00.000	Inductor manufacturing machine	1	
				Subassemblies		
A3		1	PR-01.01.000	Spindle mechanism	1	
A3		2	PR-01.02.000	Guide roller mechanism	1	
		3	PR-01.03.000	Cutting saw	1	
		4	PR-01.04.000	Wire feeder and straightener	1	
		5	PR-01.05.000	2D bending machine	1	
		6	PR-01.06.000	Machine frame	1	
		7	PR-01.07.000	Machine covers	1	
		8	PR-01.08.000	Pneumatic and control system	1	
				Parts		
A4		9	PR-01.01.001	Spindle head	1	turning op.
		10	PR-01.01.002	Mandrel	1	turning op.
		11	PR-01.01.003	Spindle frame 01	1	milling op.
		12	PR-01.01.004	Spindle frame 01V	1	milling op.
		13	PR-01.02.001	Guide roller wheel	1	turning op.
		14	PR-01.02.002	Guide roller bracket	1	milling op.
		15	PR-01.02.003	L joint	1	milling op.
				Standard items		
		16		Gearbox C12_2	1	Bonfiglioli
		17		Motor BE_71_A	1	Bonfiglioli
		18		Ball bearing ISO 15 ABB – 1860 - 32	2	

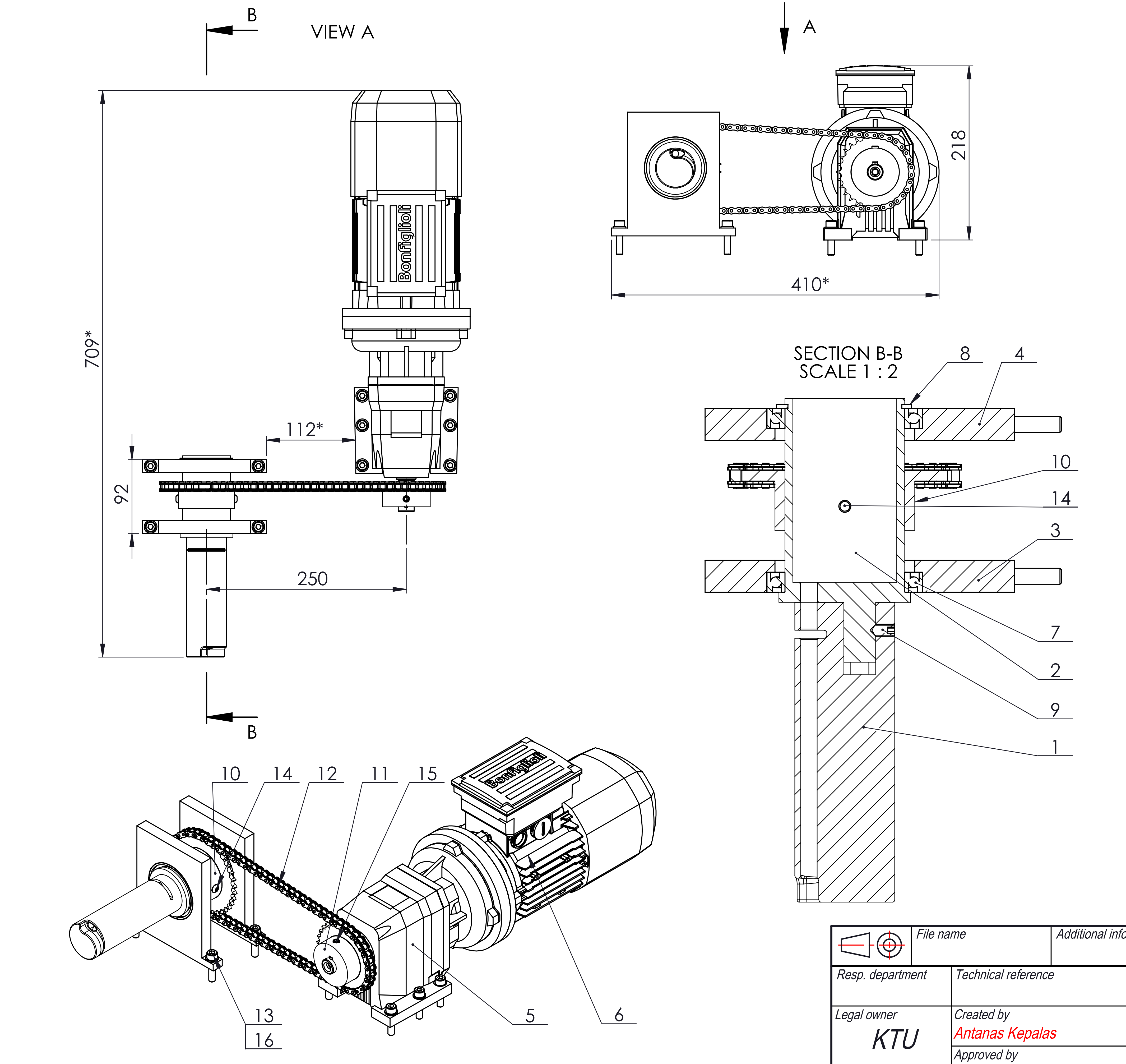
Resp. Department: MIDF	Technical reference	Document type: Part list		Document status: Training			
Legal owner: KTU	Created by: Antanas Kepalas	Title, Supplementary title: Inductor manufacturing machine	PR-01.00.000				
	Approved by: Darius Pauliukaitis		Rev.: A	Date: 2024-05-05	Lang.: En.	Sheet: 1/1	

FORMAT	ZONE	NO.	DESIGNATION	NAME	QTY.	NOTES
		19		Ball bearing ISO 15 RBB - 2312	1	
		20		Circlip DIN 471 - 60 x 2	1	
		21		Chain wheel DIN 8192 - B 36Z 06B-1	1	turning op.
		22		Chain wheel DIN 8192 - B 30Z 06B-1	1	
		23		Chain DIN 06B-1	1	1 meter
		24		Dual rod cylinder JMGP50-50	1	SMC
		25		Linear module SHT-30 DS20x5	1	Dryline
		26		Motor NEMA34	1	Drylin
				Fasteners		
		27		Bolt DIN 912 - M8 x 35 --- 35N	10	
		28		Bolt ISO 7380 - M6 x 10 - 10N	2	
		29		Bolt ISO 7380 - M8 x 30 - 30N	2	
		30		Bolt DIN 7991 - M12 x 50 --- 38.2N	1	
		31		Bolt DIN 912 - M8 x 40 --- 28N	6	
		32		Nut ISO 4034 - M12 - N	1	
		33		Set screw DIN 913 - M8 x 20-N	1	
		34		Set screw DIN 914 - M6 x 12-N	1	
		35		Washer DIN 125 - A 8.4	16	
		36		Washer DIN 125 - A 13	2	

Resp. Department	Technical reference	Document type	Document status
MIDF		Part list	Training

Legal owner	Created by	Title, Supplementary title	PR-01.00.000			
KTU	Antanas Kepalas	Inductor manufacturing machine	Rev.	Date	Lang.	Sheet
	Approved by: Darius Pauliukaitis		A	2024-05-05	En.	1/1

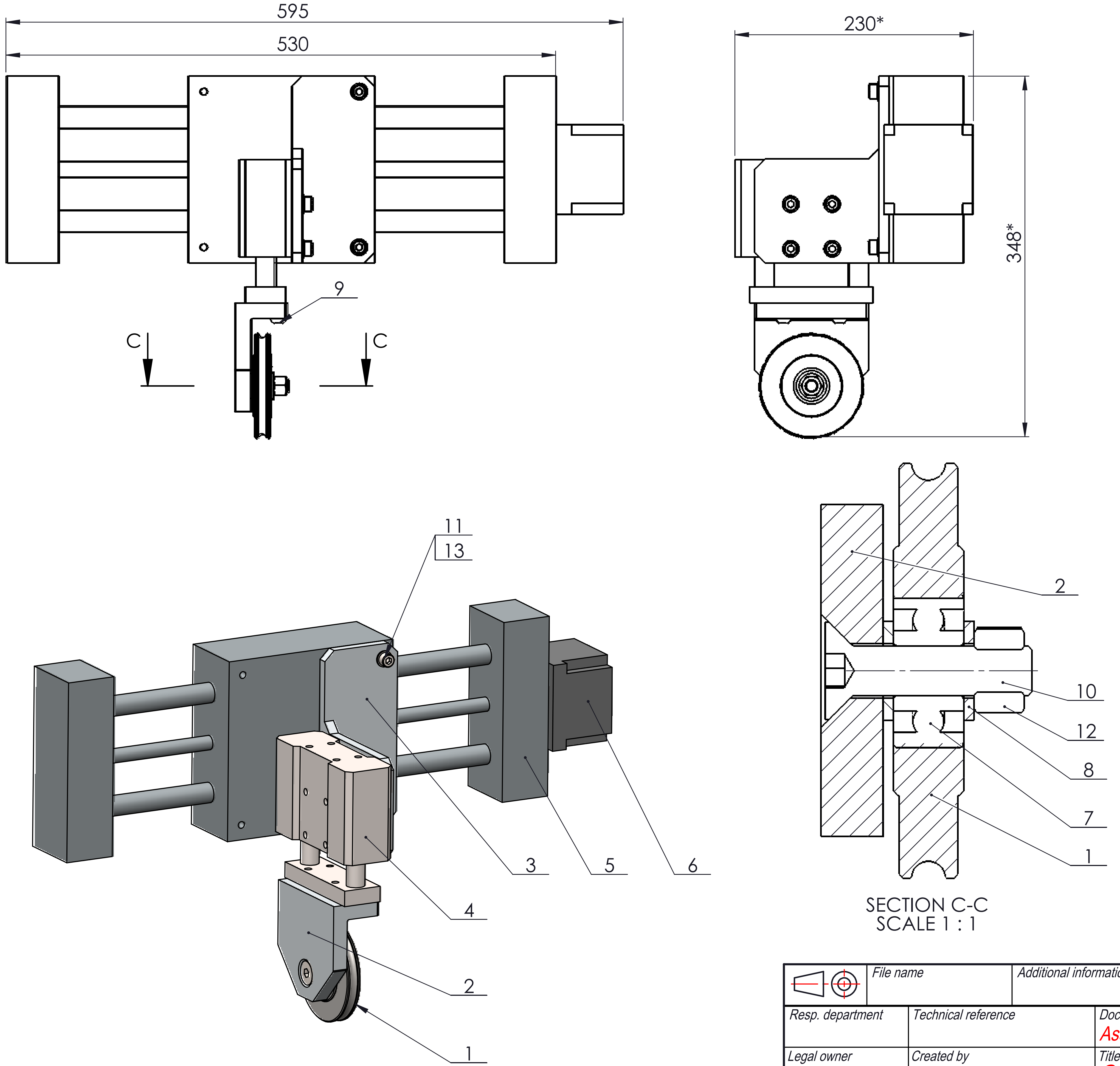
Appendix 2. Spindle mechanism assembly drawing



ITEM NO.	PART NUMBER	QTY.
1	mandrel	1
2	spindle head	1
3	spindle frame	1
4	spindle frame	1
5	Gearbox C_12_2.stp	1
6	Motor BE_71_A.stp	1
7	Ball bearing ISO 15 ABB - 1860 - 32,SI,NC,32_68	2
8	Circlip DIN 471 - 60 x 2	1
9	Set screw DIN 914 - M6 x 12-N	1
10	Chain wheel DIN 8192 - B 36Z 06B-1	1
11	Chain wheel DIN 8192 - B 30Z 06B-1	1
12	Chain DIN 06B-1	1
13	Bolt DIN 912 M8 x 35 --- 35N	10
14	Bolt ISO 7380 - M6 x 10 - 10N	2
15	Bolt DIN 913 - M8 x 20-N	1
16	Washer DIN 125 - A 8.4	10

File name	Additional information	Material		Scale M 1:5
Resp. department	Technical reference	Document type: Assembly drawing	Document status: Training	
Legal owner: KTU	Created by: Antanas Kepalas	Title, supplementary title: Spindle mechanism	PR-01.01.000	
	Approved by: Darius Pauliukaitis		Rev. A; Date 4/28/2024; Lang. En; Sheet 1/1	

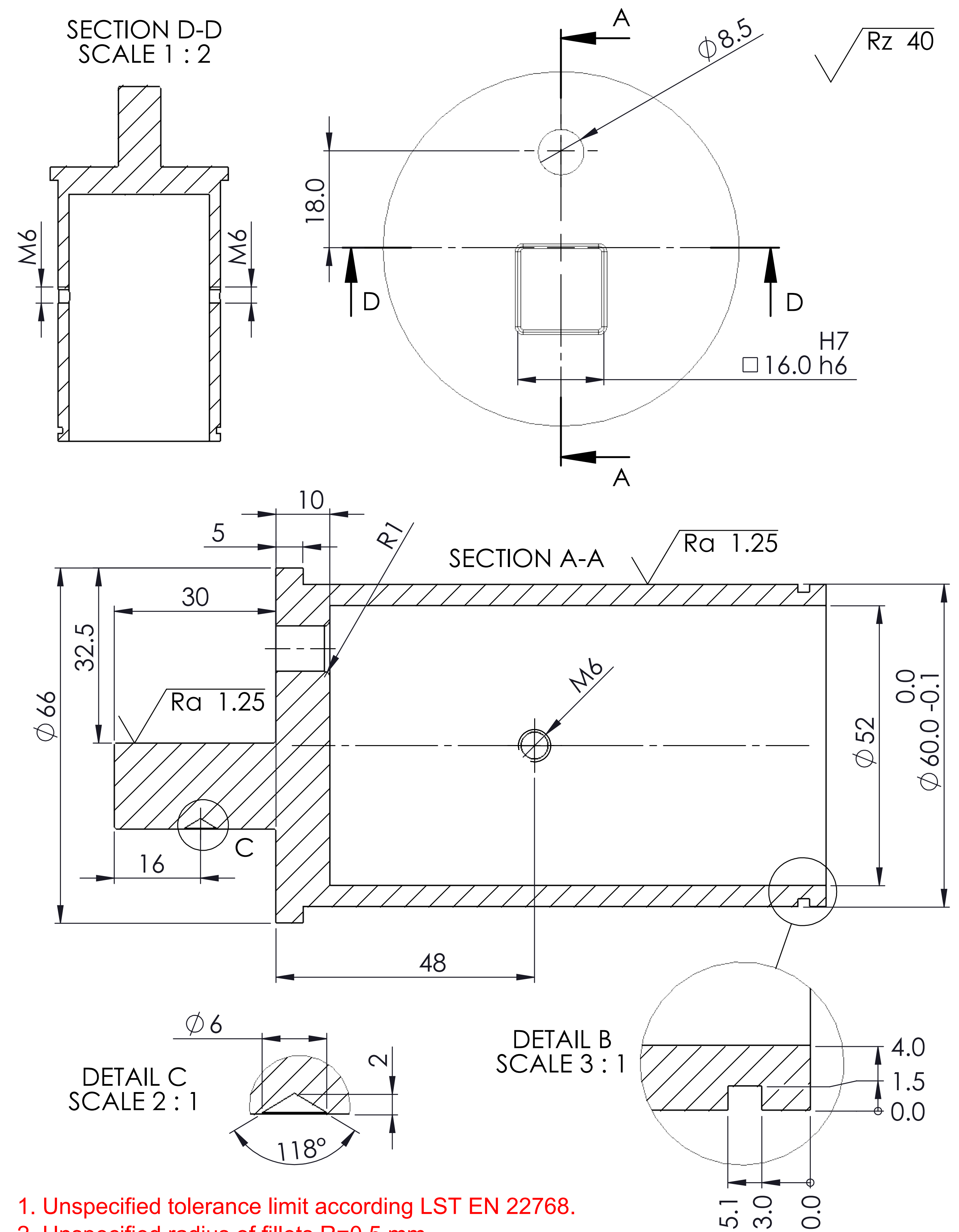
Appendix 3. Guide roller mechanism assembly drawing



ITEM NO.	PART NUMBER	QTY.
1	Guide roller wheel	1
2	Guide roller bracket	1
3	L joint	1
4	Pneumatic dual cylinder actuator	1
5	Lead screw actuator	1
6	Motor Nema 34	1
7	Bearing ISO 15 RBB - 2312	1
8	Washer DIN 125 - A 13	2
9	Bolt ISO 7380 - M8 x 30 - 30N	2
10	Bolt DIN 7991 - M12 x 50 --- 38.2N	1
11	Bolt DIN 912 M8 x 40 --- 28N	6
12	Nut ISO 4034 - M12 - N	1
13	Washer DIN 125 - A 8.4	6

	File name	Additional information	Material	Scale: M 1:4
Resp. department	Technical reference	Document type: Assembly drawing	Document status: Training	
Legal owner: KTU	Created by: Antanas Kepalas	Title, supplementary title: Guide roller mechanism	PR-01.02.000	
	Approved by: Darius Pauliukaitis		Rev.: A; Date: 5/1/2024; Lang.: En; Sheet: 1/1	

Appendix 4. Spindle head detail drawing



1. Unspecified tolerance limit according LST EN 22768.
2. Unspecified radius of fillets R=0.5 mm.

	File name	Additional information	Material	Scale
			Steel AISI 1090 hot rolled	M 1:1

Resp. department	Technical reference	Document type	Document status			
MED		Detail drawing	Training			
Legal owner	Created by	Title, supplementary title	Žymuo			
KTU	Antanas Kepalas	Spindle head	PR-01.01.001			
	Approved by		Rev	Date	Lang.	Sheet
	Darius Pauliukaitis		A	5/1/2024	En	1/1