YRKESHÖGSKOLAN NOVIA

Design and Implementation of a Helical Coil Manufacturing Tool and Evaluation of Impregnating Resin Bond Strength

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Abstract

This thesis was conducted for the R&D Electrical department of ABB IEC LV Motors in Vaasa, with the primary objective of designing and developing a tool capable of producing helical coils in accordance with IEC 61033 specifications. These coils are used to evaluate the bonding strength between enamelled copper wire and resin, which is an essential factor in ensuring the mechanical integrity and performance of electric motors.

The literature in this work focuses on stator insulation in low-voltage electric motors, detailing the main structure and functions of the insulation systems. This part also highlights the role of the impregnation resins in providing mechanical strength, electrical reliability and thermal protection.

The tool was used to produce helical coils by manually winding enamelled copper wire around a mandrel. The coil creation was tested and refined to ensure that the coils met the dimensional and structural requirements of the IEC 61033 standard.

Two impregnation trials were performed to optimize the impregnation process. The first trial revealed challenges such as inconsistent dipping durations and imperfections during curing, leading to resin drippage and uneven surfaces. Improvements in the second trial, such as a removable dipping rack and stricter adherence to the time criteria, provided more reliable results. Different curing orientations, such as horizontal, vertical and hybrid were also explored to assess their impact.

Following the impregnation, bonding strength testing proceeded using a universal testing machine. The test procedures followed IEC 61033 specifications, measuring the force required to break the bond between the resin and wire.

The results confirmed that the tool effectively and consistently produces high-quality coils. Furthermore, the modified impregnation process yielded more reliable and uniform samples. Some originally planned features, such as the long-term aging of the samples, and the usage of winding tension, could not be fully implemented. Details for future plans regarding these improvements are presented in the discussion chapter of this thesis work.

Language: English
Keywords: helical coil, resin, mechanical strength, impregnation, bonding strength test, IEC

EXAMENSARBETE

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Abstrakt

Detta examensarbete utfördes för R&D elektriska avdelningen vid ABB IEC LV Motors i Vasa, med det primära målet att designa och utveckla ett verktyg som kan producera helikala spolar enligt IEC 61033-specifikationerna. Dessa spolar används för att utvärdera vidhäftningsstyrkan mellan emaljerad koppartråd och harts, vilket är en avgörande faktor för att säkerställa elektriska motorers mekaniska integritet och prestanda.

Litteraturgenomgången i detta arbete fokuserar på statorisolering i lågspänningsmotorer och beskriver isolationssystemets huvudsakliga struktur och funktioner. Avsnittet betonar även impregneringshartsernas roll när det gället att tillhandahålla mekanisk styrka, elektrisk tillförlitlighet och värmeskydd.

Verktyget användes för att producera spiralformade spolar genom manuell lindning av emaljerad koppartråd runt ett dorn. Tillverkningsprocessen testades och förbättrades för att säkerställa att spolarna uppfyller kraven för strukturen och dimensionerna som anges i IEC 61033 standarden.

Två impregneringsförsök genomfördes för att optimera impregneringsprocessen. Det första försöket tog fram utmaningar som otillräckliga doppningstider och brister under härdningen, vilket ledde till hartsdroppar samt ojämn hartsyta på spolarna. Förbättringarna i det andra försöket, såsom en avtagbar doppningsställning och striktare efterlevnad av tidskriterierna, gav mer tillförlitliga resultat. Olika härdningsorienteringar såsom horisontell, vertikal och hybrid, undersöktes också för att bedöma deras påverkan.

Efter impregneringen genomfördes vidhäftningstester med en universell provningsmaskin. Testförfarandena följde IEC 61033-specifikationerna och mätte den kraft som krävdes för att bryta vidhäftningen mellan hartset och tråden.

Resultaten bekräftade att verktyget effektivt och konsekvent producerar högkvalitativa spolar. Dessutom resulterade den modifierade impregneringsprocessen i mer tillförlitliga och enhetliga testexemplar. Vissa ursprungligen planerade funktioner, såsom långtidsåldring av spolarna och användning av lindningsspänning, kunde inte implementeras fullt. Förbättringsplaner för dessa aspekter presenteras i diskussionskapitlet i detta arbete.

Språk: engelska
Nyckelord: helikal spole, harts, mekanisk hållfasthet, impregnering, vidhäftningsstyrketest, IEC

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Nimike: Spiraalikelojen valmistustyökalun suunnittelu ja toteutus sekä impregnointihartsin sidontalujuuden arviointi

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Tiivistelmä

Tämä opinnäytetyö toteutettiin ABB IEC LV Motors Vaasan tuotekehitysyksikölle. Ensisijaisena tavoitteena suunnitella ja kehittää työkalu, jolla voidaan valmistaa spiraalikeloja IEC 61033 -standardin mukaisesti. Tässä asiayhteydessä spiraalikeloja käytetään arvioimaan emaloidun kuparilangan ja hartsin välistä sidoslujuutta, mikä on tärkeä tekijä sähkömoottoreiden mekaanisen kestävyyden ja suorituskyvyn varmistamisessa.

Työn kirjallisuuskatsaus keskittyy pienjännitemoottoreiden staattorieristykseen ja kuvaa eristyksen pääasiallista rakennetta ja toimintoja. Osiossa korostetaan myös staattorihartsauksen roolia mekaanisen lujuuden, sähkökäytön luotettavuuden ja lämmönsuojan tarjoamisessa.

Työkalua käytettiin spiraalikelojen valmistamiseen kiertämällä emaloitua kuparilankaa tuurnan ympärille. Valmistusprosessia testattiin ja parannettiin sen varmistamiseksi, että käämit täyttävät IEC 61033 -standardin mukaiset dimensio- ja rakennevaatimukset.

Prosessin optimointia varten tehtiin kaksi hartsauskoetta. Ensimmäisessä kokeessa ilmeni haasteita, kuten näytteiden riittämättömät upotusajat ja haasteet kovetusvaiheessa, mikä johti testikappaleiden epätasaisiin hartsijäämiin ja hartsipintoihin. Toisessa kokeessa prosessia paranneltiin esimerkiksi irrotettavan upotuskehikon avulla, sekä tarkemman ajan mittauksen avulla. Parhaan lopputuloksen saavuttamiseksi testikappaleita kovetettiin hartsauksen jälkeen uunissa eri asennoissa, esimerkiksi vertikaalisesti ja horisontaalisesti. Hartsaustestien jälkeen testikappaleille suoritettiin standardin IEC 61033:n vaatimusten mukaiset sidoslujuustestit.

Tulokset vahvistivat, että työkalun avulla voidaan tuottaa tehokkaasti ja johdonmukaisesti korkealaatuisia spiraalikeloja. Lisäksi paranneltu hartsausprosessi johti luotettavampiin ja yhtenäisempiin testinäytteisiin. Alkuperäisestä suunnitelmasta poiketen vanhennuskokeita tai standardin vaatimaa käämintäjännityksen toteutusta näytteiden valmistuksessa ei ehditty toteuttamaan. Näitä osa-alueita käsitellään työn keskusteluosiossa.

Kieli: englanti
Avainsanat: hartsi, mekaaninen lujuus, hartsaus, sidoslujuus, IEC

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ABBREVIATIONS AND TERMS

IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
ABB	Asea Brown Boveri
R&D	Research and Development
N	Newton
LV	Low-Voltage

1 Introduction

Being a global leader in the electrical and automation industry requires continuous testing and up-to-date documentation in order to ensure that the product quality remains at the highest standard. This role, to a large extent, falls upon the R&D teams within ABB, as the main focus is the continuous improvement and development of ABB products.

In many cases, smaller scale tests are done, in order to mimic parts of the production process and the internal works and components of an electrical motor. This study focuses mainly on what are called helical coils, and resin. The helical coils, which take on a helical shape using wound copper wire, are made in order to resemble the stator windings, which are located inside an electric motor. With the use of resin, these can be impregnated, creating further resemblance regarding the properties of the stator windings in a motor.

The helical coils can then be tested through what is called a bond strength test. The bond strength test makes it possible to check the bond between the resin and the used wire. Sufficient resin bond strength is crucial regarding the performance of the motor, while also providing internal rigidity and stability.

By ensuring a strong bond between the wire and resin, it is possible to better enhance the motor durability, reliability, and efficiency, reducing the overall likelihood of failure.

1.1 Background

The background for this work is based on the need to develop testing capabilities for helical coils at ABB in Vaasa, which are in accordance with the IEC 61033 standard. While the IEC standard provides clear specifications for the helical coils, impregnation process, and testing, there is no pre-existing tool or procedures that can be used to carry out these processes.

Therefore, the background for this work is not only regarding the need for designing and creation of a suitable helical coil manufacturing tool, but also on developing clear procedures and documentation for each part of the process.

1.2 Objective

The objective of this thesis was to initially design and create a helical coil manufacturing tool based on the required IEC 61033 standard criteria.

When the tool is assembled and is capable of producing coils, which follow the given standard specifications, the preparation phase of the coils can be initiated. This includes two trials regarding the impregnation and curing process of the coils, in order to better determine which procedure produces better-suited samples for further testing. The initial trial can be considered mainly as a test, as it is done to better understand the necessary changes needed regarding the setup and steps in order to improve the procedure in the second trial. Once the two trials have been completed, the samples will be visually compared, to determine the impact of the chosen changes considering the flaws or imperfections occurred.

Following the impregnation process, the bonding strength tests take place, which is the foundational reason for the creation and preparation of the helical coils. The bonding strength test itself is done to evaluate the bonding performance between the resin and the wire surface, enabling the comparison of different resins. The setup used in the bonding strength test will be made according to IEC 61033.

Depending on the success of the initial testing, using samples from the impregnation trials will allow for further clarification as to possible future improvements regarding both the preparation of the coils, and the test setup itself. This thesis aims to develop a tool that is easily modifiable, functional, and consistent, adhering to standard specifications. This includes deciding and improving procedures depending on achieved results, to be followed in future tests related to helical coil production.

2 ABB Oy

ABB or Asea Brown Boveri goes back to 1883, when ASEA (Allmänna Svenska Elektriska Aktiebolaget) was founded in Sweden. At this point in time, they started manufacturing electrical lighting and generators. Around 8 years later in Switzerland, Brown Boveri was founded, which specialized in electrical engineering and heavy electrical equipment such as generators, transformers and turbines.

In 1988 the two companies, Asea and Brown Boveri, merged, and formed what is now ABB. This merger allowed them to combine Asea's expertise regarding electrical power with Brown Boveri's heavy electrical machinery capabilities, which made them into what is now a global leader in the electrical and automation industry. ABB's current headquarters is located in Zurich, Switzerland, and employs around 110,000 individuals worldwide (ABB, 2023). In Finland, ABB employs around 5500 people, being one of the most popular employers within the technology industry (ABB, 2024).

ABB's main products and services include:

Table 1. Products and Services (ABB, 2024).

Electrification	Electrical grids, energy management, electric vehicle (EV) charging solutions.
Motion	Motors, drives, and power distribution.
Process Automation	Control systems, Measurement instruments, Programmable logic controllers
Robotics & Discrete Automation	Industrial robots and automation systems.

Figure 1. ABB Logo (ABB, Brand Portal, 2025).

2.1 ABB Vaasa IEC LV Motors

In Finland, ABB employs around 5,300 professionals, of which 1,500 work in Vaasa. At Strömberg Park in Vaasa, the manufacturing of electrical motors, transformers and R&D stands out as the most central focus within the area (Vaasa, 2025).

Figure 2. Map of Strömberg Park in Vaasa (ABB, 2025).

During this thesis, the majority of the work has been done at MM, which is the area for IEC LV Motors and an office area for R&D. The insulation lab is located in the KK building, where the preparation of the coils took place, including the impregnation trials and bonding strength test. The KK building serves as a major location regarding the complete production and preparation of electrical motors. These locations can be seen in Figure 2 above.

2.1.1 Winding Workshop

The winding workshop is the place where the winding and insulation are inserted into the stator core. An overview of the materials used during winding can be seen in Figure 6. The winding area can be considered related to the creation of the helical coils, as the helical coils are made to resemble the structure of the wound wire in the stator core. The general area and setup of the working stations related to stator winding can be seen in Figure 3.

Figure 3. Winding workshop.

2.1.2 Impregnation Site

The impregnation site located in KK serves as a major location regarding the preparation of the wound stators. In this area, stators are impregnated using the trickle method, which is described further in Section 3.2. Since this is a dedicated zone for any impregnation related work, the two impregnation trials which are discussed in Chapter 5 were carried out in this space.

This area provides the required ventilation, equipment, and necessary protection when handling resins. It also includes areas where the setup can safely be placed during the impregnation procedure. Following the completion of any impregnation-related tasks, the impregnation zone also includes the ovens used for curing the resin. A part of the zone is shown in Figure 4 below.

Figure 4. Impregnation site.

2.1.3 Insulation Lab

The insulation lab is where most of the sample creation and small-scale testing is done. The insulation lab includes equipment such as a winding machine for tests, including twisted pair samples. It can be retrofitted in order to connect and create other kinds of smaller windings using copper wire. The laboratory also includes a test setup that is used during voltage breakdown testing, which can be used to perform voltage breakdown tests on any kind of prepared samples. It is also the location where the tool and setup used for the bonding strength test can be found.

Figure 5. Insulation laboratory overview.

3 Stator insulation

This chapter focuses on low-voltage electrical insulation systems, with the main focus being on the different components of the insulation process and how they contribute to the overall function of the motor. The impregnation process is also a crucial part of the insulation process, which will also be discussed in this chapter.

3.1 Insulation material of stators

The insulation of today's low-voltage motor stators is the results of several decades of experience and development, focusing on constant optimization and improvement. There are many different kinds of motors, some of which are built to withstand harsh conditions. Because of this, depending on the specific requirements, stators are insulated in various ways using materials selected according to the intended purpose of the motor. These materials are carefully selected for compatibility and suitability regarding the end goal (Chapman, Frost, & Bruetsch, 2008, p. 257). An overview of the material structure commonly found in a stator is illustrated in Figure 6, which includes markings for each component and its corresponding name.

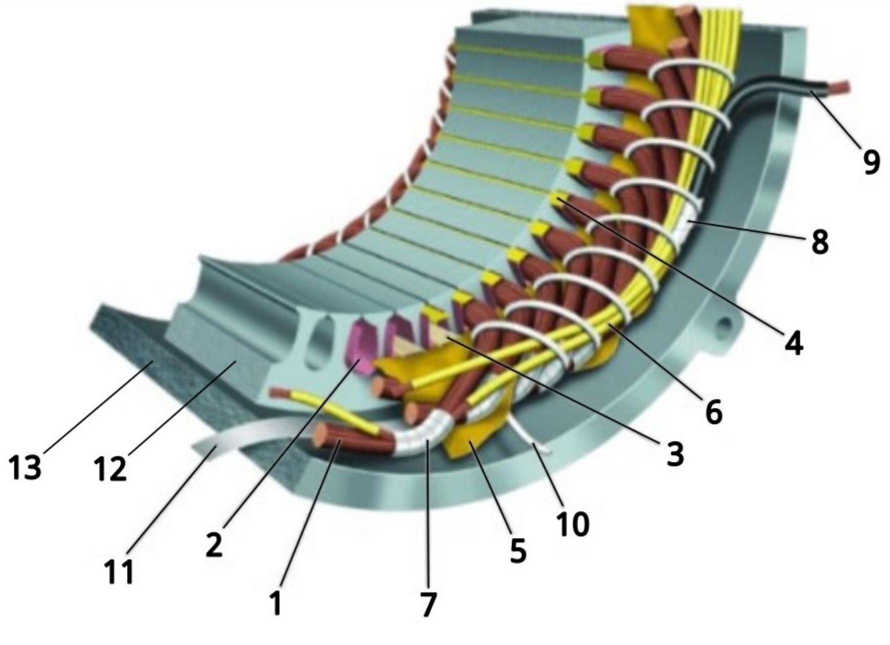


Figure 6. Overview of materials in a low-voltage insulation system.

1 winding wire, 2 slot insulation, 3 slot separator, 4 slot closure, 5 phase insulation, 6 sleeving, 7 coil taping, 8 connection point insulation, 9 cable, 10 tie cord, 11 bracing, 12 stator core, 13 frame. (Adapted from Chapman et., al 2008, p. 257).

The main parts involved in the operation of a rotating electrical machine include the stator and the rotor. The stator serves as the stationary element, while the rotor forms the rotating part. (ABB, 2019). The stator itself can be further divided into three essential sections: the stator core, the conductors, and the insulation system (Stone, Boulter, Culbert, & Dhirani, 2004, p. 7).

In the stator of a low-voltage machine, the insulation system typically consists of two main categories: groundwall and conductor insulation. The groundwall insulation separates the components which may not be in contact with each other. In this case, the groundwall separates the coil from the iron core of the motor. The conductor insulation is a varnishing of the copper wire, which serves the purpose of preventing short circuits from occurring between the different turns of a coil (Pyrhönen, Jokinen, & Hrabovcová, 2014, p. 497).

Besides the groundwall and conductor insulation, the other types of main insulation include slot insulation and the slot wedge, phase insulation and impregnating resin (Pyrhönen, et al., 2014).

The slot insulation, which usually consists of papers, films or flexible laminates, makes up two layers: an outer and an inner layer. These layers line the stator slot walls, providing electrical insulation between the coil assembly and the laminated stator core. The stator slot is then closed at the slot opening using a slot wedge (Stone, et al., 2004, p. 27; Pyrhönen, et al., 2014, p. 511).

The phase insulation separates the wire bundles of different phases in the slot and in the coil overhang (Chapman, et al., 2008, p. 259). One of the most common phase insulations is papers made from the synthetic material aramid (Stone, et al., 2004, p. 108). The phase insulation has to be electronically sound and mechanically resilient, while also being thermally compatible with other insulation system components. The materials used in phase insulation are usually the same as those used in ground and slot insulation. (Chapman, et al., 2008, p. 259).

Beyond these main types of insulation, impregnating resins play a crucial role in connecting each part mentioned together. The purpose and benefits of impregnating resin are further discussed in Section 3.2 below.

3.2 Impregnation Resins

The purpose of the impregnating resin is to fill the stator slot thoroughly. This is necessary, in order to ensure there are no air gaps. With the use of resin, the insulation system is improved by providing mechanical support, removing vibrations that could damage the wire enamel, and providing shielding in end-windings (Sihvo & Pyrhönen, 2007, p. 298; Richnow, Stenzel, Renner, Gerling, & Endisch, 2014). Another benefit of the impregnating agent is the protection against moisture, dirt and chemicals. It can also significantly improve thermal conductivity, when not used in excessive amounts, as resins have ten times higher heat conductivity compared to air (Pyrhönen, et al., 2014, p. 503; Richnow, et al., 2014).

Today, the most common ways, in which the stators are impregnated include dipping, vacuum pressure impregnation and trickling processes (Pyrhönen, et al., 2014, p. 513). The easiest dipping process, which is also called the dip & bake method, is done by submerging a stator in a resin reservoir at atmospheric pressure, which is afterwards cured in an oven at a certain temperature (Richnow, et al., 2014).

Another option is to impregnate the stator using vacuum pressure impregnation (VPI). In this process, the stator is placed in a sealed chamber where a vacuum is first applied to remove air and moisture from the windings. Resin is then introduced under vacuum, improving the resin intrusion into the stator geometry. After the resin has been soaked into the stator, the pressure can temporarily be increased, in order to eliminate any remaining air cavities inside the slots (Richnow, et al., 2014; Stone, et al., 2004, p. 108).

The alternative impregnation method is called trickle impregnation. The trickle impregnation method is a more expensive, but usually more successful method in filling all air spaces (Stone, et al., 2004, p. 108). This method involves coating the windings of electrical components with resin and has become the predominant means of impregnating stators due to the advantages the trickle method has over the conventional “dip and bake” process mentioned above (Thurman, 1989). This process involves preheating the windings, carefully and strategically pouring a measured amount of polyester or epoxy resin on the windings, which is then cured (Pyrhönen, et al., 2014, p. 513; Thurman, 1989, p. 30).

The main advantages of the trickle process are that the resin is only applied where its presence is desired, and the absence of solvent ensures perfect filling of the cavities and improves thermal conductivity. The floor area required during trickling impregnation is also significantly smaller than in dipping processes (Thurman, 1989).

The impregnating resin used in stator impregnation is normally either polyester or epoxy based. Polyester resins are widely used in low-voltage machines, which is due to lower costs, longer life expectancy and the resin characteristics against thermal overload (Thurman, 1989). The polyester resin, however, in some cases may contain styrene which can soften the copper wire enamel. Because of this, the trickle method is usually preferred when using such polyester resin, as the extended contact time is reduced (Sihvo & Pyrhönen, 2007, p. 298; Thurman, 1989, pp. 30-31). Epoxy resin is usually favoured when more requirements are set for the resin performance, as it offers better capabilities in terms of mechanical strength, chemical resistance, and resistance to moisture and radiation (Sihvo & Pyrhönen, 2007, p. 298).

Epoxy resin is less commonly used when dipping stators, as its viscosity is substantially higher than polyester resin (Chapman, et al., 2008, p. 260). This is the reason why the epoxy resin has seen much greater success using the trickle impregnation method, as the strategic pouring and pre-heating of the windings used during the trickle process allow for the resin to better flow efficiently into the windings.

If a stator has been poorly impregnated, it is much more likely to fail due to dirt, pollution, oil, and moisture (Pyrhönen, et al., 2014, p. 503). This can be due to small cracks occurring in the insulation, which in combination with conductive contamination, can cause shorted turns. Insufficient or improper impregnation can also cause excessive vibrations, which leads to abrasion of the magnet wire insulation and to turn shorts. Furthermore, inadequate impregnation can lead to high operating temperatures, leading to thermal deterioration, resulting in further abrasion (Stone, et al., 2004, p. 146).

The root causes for poor impregnation include using a resin that is too thin or thick, or otherwise incompatible resin. Additionally, processing a stator in a way that is not in accordance with resin the supplier’s recommendations, such as not preheating the stator during trickle impregnation, inadequate time in the dip tank, or not completely immersing the stator, can be detrimental. Lastly, a temperature, which is too high during curing, or the curing time being too short or too long, can significantly compromise the resin (Stone, et al., 2004, p. 146).

3.3 Bonding Strength Test – IEC 61033

The bonding strength test using helical coils is done according to IEC 61033, test method B. The test specifies the usage of a 1 mm diameter wire, which is made in the form of a helical coil, which is then impregnated with resin and cured. The result of the force required to break the coil is a measurement of the bond strength (IEC, 1991).

The coil is made according to Figure 7, using enamelled copper winding wire by means of suitable winding equipment. In this case, using the helical coil tool created during this work.

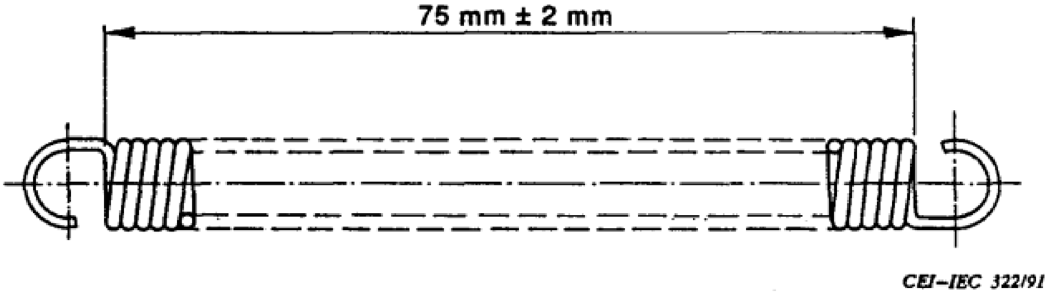


Figure 7. Helical Coil test specimen (IEC, 1991).

For the creation of the coils, the following dimensions apply:

Nominal wire diameter: 1 mm

Mandrel diameter: 6,3 mm ± 0,1 mm

Length of coil: 75 mm ± 2 mm

Winding tension: 10 N ± 1 N

Specimen dimensions (IEC, 1991).

When the coils have been produced, they are to be impregnated in order to proceed with the bonding strength test. According to IEC 61033, the coils are to be treated once with the impregnating agent, where they are immersed vertically in the impregnating agent for 60 ± 10 seconds. Following this, they are slowly and uniformly to be removed at a maximum rate of 1 mm/s. After having been removed, the helical coils are drained horizontally for 10 to 15 minutes, where they are then kept in the same horizontal position during curing (IEC, 1991).

Following the impregnation of the helical coils, the bonding strength test can proceed. The bonding strength test, as outlined in the IEC 61033 standard, requires the specimen to be positioned according to Figure 8. The crosshead speed is then adjusted so that the maximum force is reached in about 1 minute. The results of the bonding strength test are to be documented according to standard instructions found in Table 2.

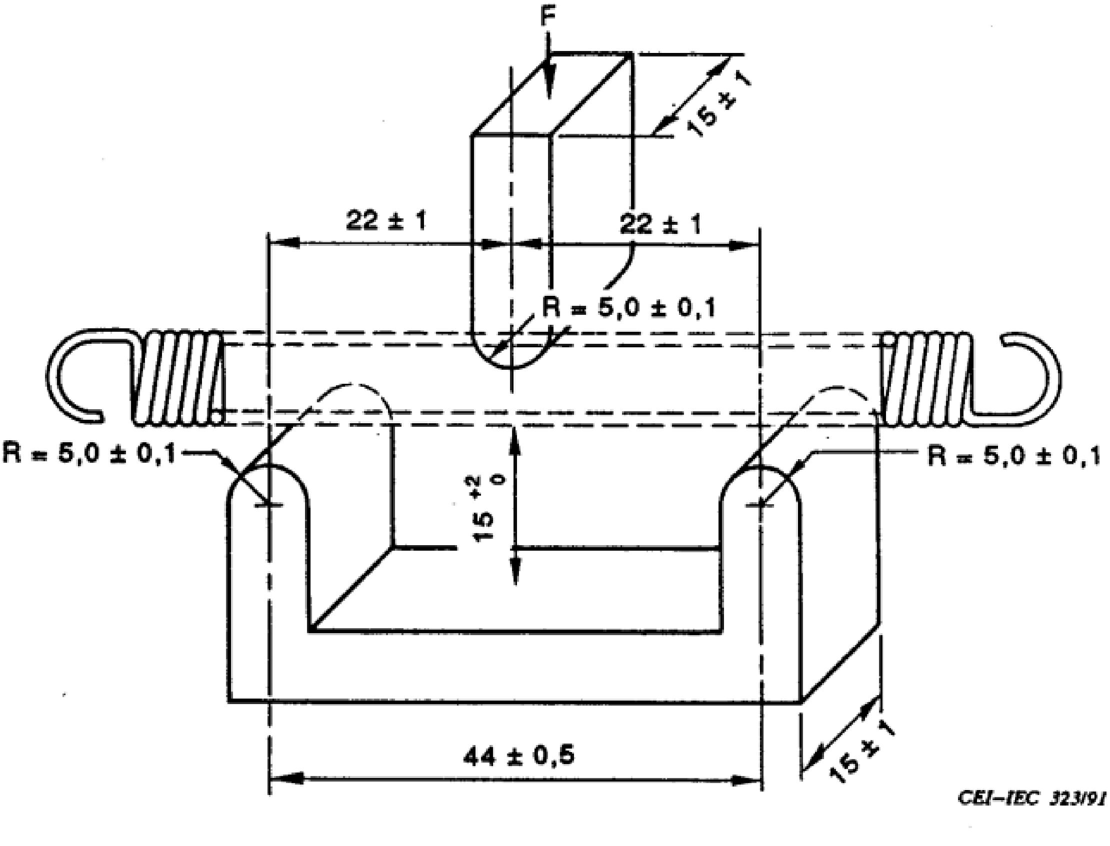


Figure 8. Arrangement of supports (IEC, 1991).

The bonding strength test results are decided as the median value of five measurements in newtons.

After the bond strength tests have been completed, they should be reported as instructed in Table 2 below.

Table 2. Report instructions (IEC, 1991).

Reference to test method B of this standard;
Details of the impregnating agent;
Details of the substrate (type of enamelled winding wire);
Details of specimen impregnation;
Test temperatures;
Bond strength and the minimum and maximum measured values for each test temperature;
If the winding wire or test specimens have been washed in any manner so that they are no longer in an “as received” condition, such procedure shall be noted in the report.

In this case, the test results in Section 6.3 will not be reported as specified in Table 2. This is due to it not being directly relevant to the work. One of the main objectives during the bonding strength tests in this case, as mentioned in Section 1.2, is to determine the success of the procedure and check the force required to break the resin surface. By doing this, it is possible to compare the results and determine if the earlier steps such as the creation of the coils and impregnation process has been successful as well.

4 Tool Creation and Demonstration

This chapter will focus on the planning and design of the helical coil tool, including the final achieved setup and procedure regarding the creation of the helical coils. This will create an initial overview of what was initially planned, compared to what was achieved. Once the tool is complete and initial testing has been done, it is possible to look back at the design and consider what potentially did not turn out as intended, or what still needs to be improved and redesigned. These findings and potential changes are further discussed in Section 4.2 and Chapter 7.

4.1 Tool Design

The design for this tool, which is shown in Figure 9, used the same concept regarding the winding of the coil, which has been previously used in other ABB locations. The reason for this is mainly its simplicity, while also being easily modified to follow the standard specifications, and the possibility of being easily modified further if needed.

The main additions to the concept are the removable handle, the open centre design and the extendable support, enabling the possibility to add the necessary winding tension to the wire using a weight. The mandrel also includes 1,5 mm-sized holes for the wire, taking future tests into consideration, if larger wire is used in the production of helical coils.

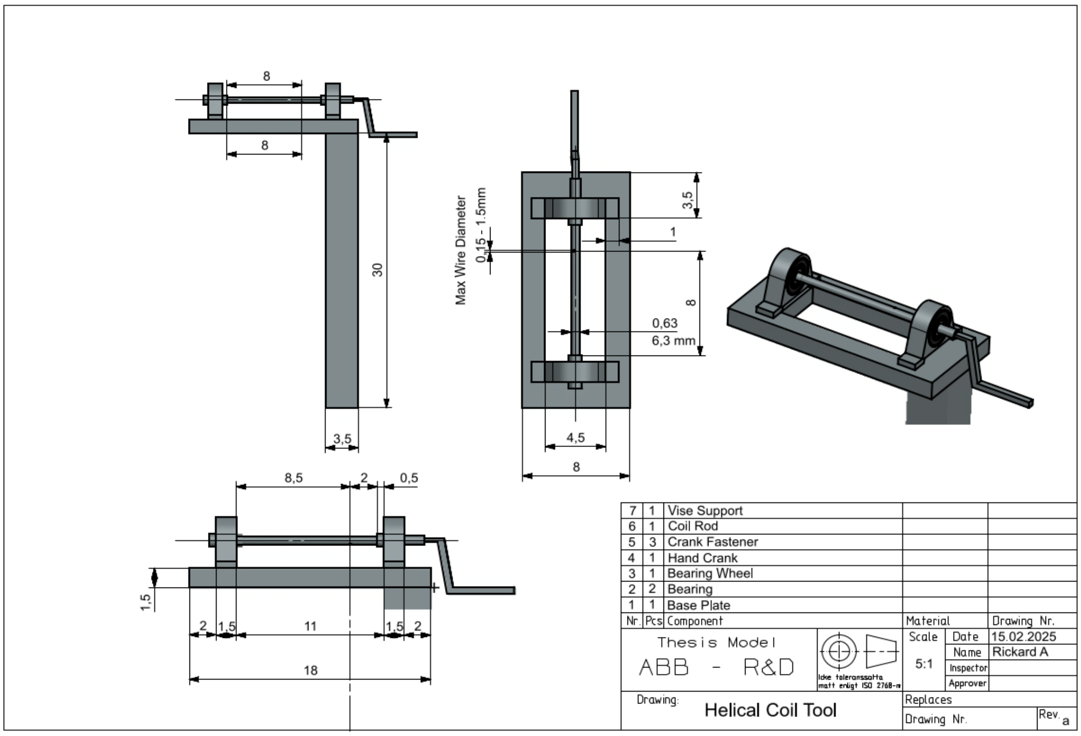


Figure 9. Tool design made in Siemens NX for planning.

4.2 Winding Tension Trials

During the creation of the tool, the design was modified from the original plan. The initially proposed extendable support as shown in Figure 9, was excluded after its limitations were recognized. This is due to the support raising the tool to an impractical height, introducing further difficulties during the creation of the helical coils.

In the original design, the weight was intended to be attached to the end of the wire to provide tension. However, this would have required the wire to remain fully suspended in the air, while being connected to both the tool and the weight, without touching the floor and losing the tension. Due to this, the extendable support would have been necessary, as the length of wire required to create a fully wound coil is substantial, given the wire's diameter of only 1 mm.

Instead, the final tool design included only a compact support, which would be sufficient to properly secure the tool to a vise. The final tool design can be seen in Figure 10 and is further discussed in Section 4.3.

Following this change, clamps were instead used to attach a weight directly to the wire, in order to provide tension. While this showed some initial promising results once a suitable clamp had been found, it also introduced new risks. Because of the weight pulling down on the clamp, it was substantially more likely to either damage the enamelled coating of the copper wire or cause minor bends in the wire being wound. If the wire being supplied to the mandrel is slightly bent, it can cause slight gaps between the coils as they are wound, making them inconsistently wound.

Considering these issues, it was ultimately determined that pursuing further testing regarding temporary wire tension solutions was not viable, in order to proceed with the thesis work. As a result, the decision was made to proceed with the helical coil production and further processes without implementing the winding tension specifications mentioned in Section 3.3.

At the time of this decision, plans regarding proper winding tension solutions had already been found. This, however, would have required substantial planning and time to design and manufacture. These plans are further discussed and described in Section 7.2.

4.3 Tool Completion

The current setup for the tool can be seen in Figure 10. In this picture, each main component of the tool has been marked using letters and numbers. The first part, marked as A, is the base plate which was earlier mentioned in Section 4.1. The base plate acts as the foundation for the entire tool, and includes an open centre, where the wire is wound through.

The mandrel is marked as B and is the piece that the coil is wound around. The mandrel is connected to the bearings marked as C, which are connected to both the mandrel and the handle D, making manual winding of the coil possible. The final part E is the vise support, which is connected to the bottom of the base plate.

The mandrel, which is connected to the handle, is removable using a locking ring. This makes it easy to remove, once the coil is spun, which is much more time efficient than loosening and moving the bearing connected to the front of the mandrel.

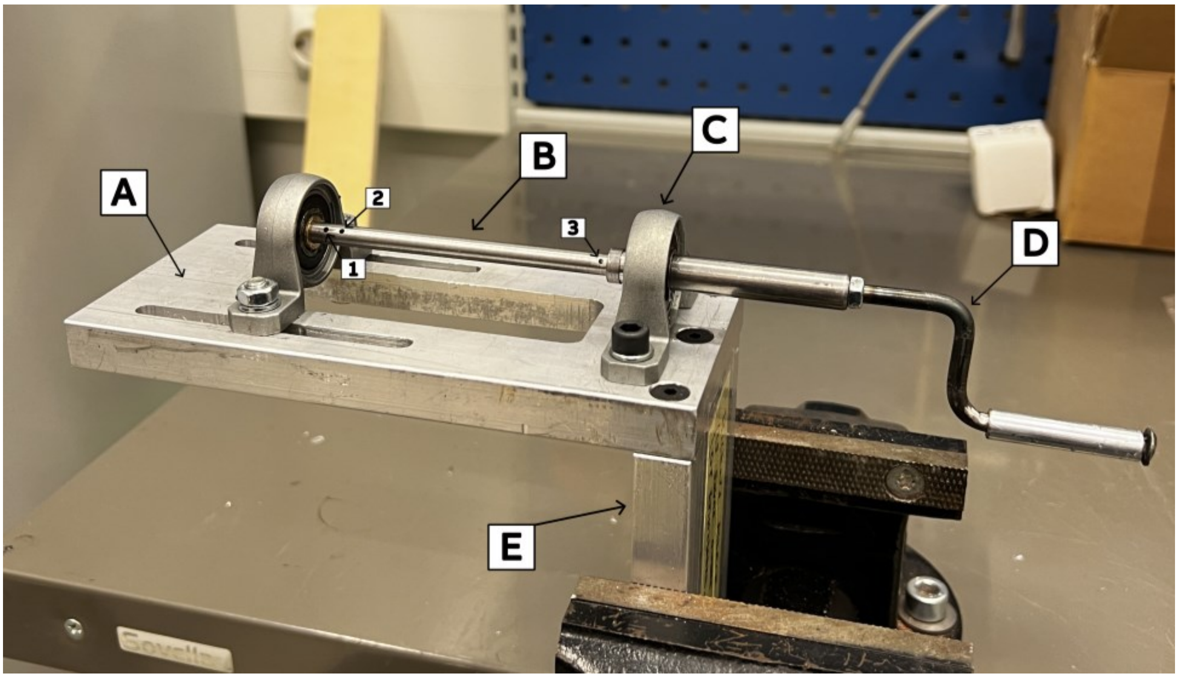


Figure 10. Finished tool and setup with markings.

The mandrel includes 3 different holes sized 1,5 mm each, which are marked 1-3 in Figure 10. These holes are placed at different locations, making it possible to achieve different coil lengths, and being able to wind it from both sides. The outermost holes 1 and 3 are used if the goal is to achieve the maximum length coil possible. This is done, in case excess wire is needed, in order to create larger heads to aid in the impregnation process. The second hole marked as number 2 inwards from the left side of the mandrel causes the coil to end up being around 77,5 mm once fully wound. Using this hole, the coil ends up being within the standard specifications, if only small heads are made, such as can be seen in Figure 7.

4.4 Sample Creation

The wire chosen to be used in the creation of the helical coils is polyimide grade 2 copper wire, with a nominal diameter of 1 mm, which is the specification given in the IEC 61033 standard. The wire is first attached and inserted into the chosen hole in the mandrel, based on the requirements regarding coil length discussed in Section 4.3. Once attached, the mandrel is slightly turned in order to get the initial tension without the wire detaching from the hole. This can be seen in Figure 11, which shows the position the mandrel should be in before continuing with further winding of the wire. After this, the wire can be safely tensioned by hand from underneath the tool, in order to keep it straight and remove slack during the rest of the winding.

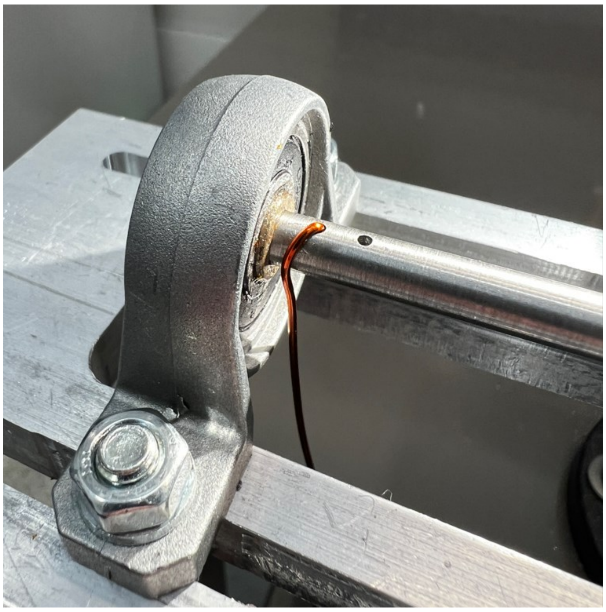


Figure 11. Wire attachment.

When the coil reaches the other end of the mandrel, the tension on the wire can be temporarily released. This is done if the desired outcome of the coil is having a maximum amount of length added. This causes the tension in the coil that has built up during the winding to release, causing the windings to retract by a few centimetres at the end of the mandrel. The tension can then once again be applied to the wire, and the coil can then be wound a few more times to the end of the mandrel once again, giving the coil a bit more final length. An example of how the coils should look like once fully wound, can be seen in Figure 12 below.

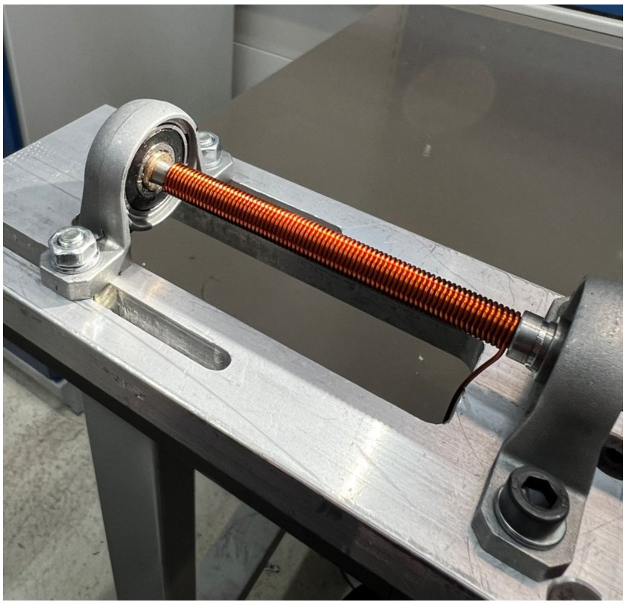


Figure 12. Fully wound coil.

When the coil is fully wound, the connected wire is cut. This part of the wire can also be cut off with more remaining wire than what is shown in Figure 14, if excess wire is needed for the creation of the heads. However, as shown in Figure 16, and as mentioned in Section 4.3, if the coil has been made using the outermost holes, the coil will already be at a length exceeding the standard requirement, making excess wire not necessary in normal procedures.

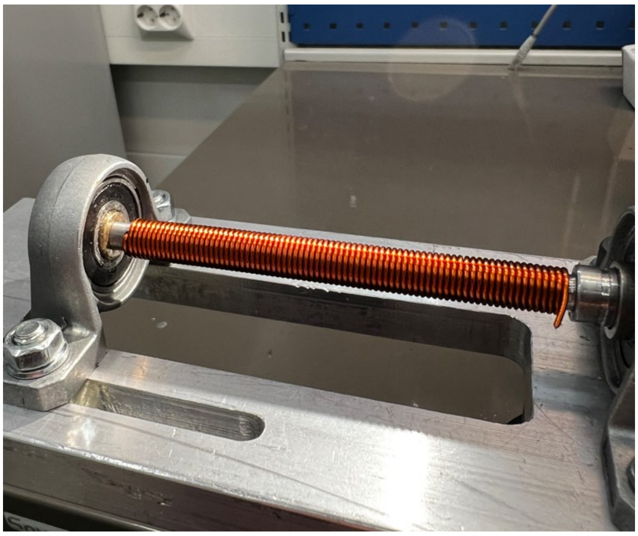


Figure 13. Cutting of right-side wire.

Once the connected wire has been cut, the wire attached to the left side of the mandrel can be carefully removed with a screwdriver. This is done by prying the screwdriver between the windings next to the connection, and slowly bending the screwdriver downwards as demonstrated in Figure 14.

The attached wire will be very securely connected, as it has been tightened during the winding of the coil. Due to this, it is necessary to remove it with great caution, as accidentally prying on the windings next to it can damage the enamel or bend the copper wires, damaging the overall structure of the coil, while also affecting the distances between the windings.

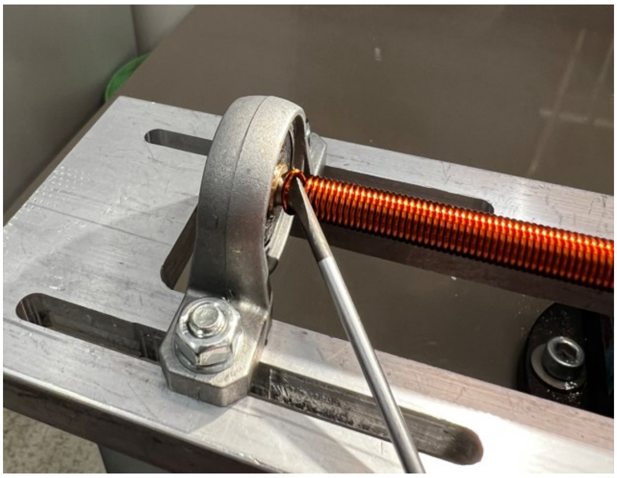


Figure 14. Removal of left side attached wire.

When both ends of the coil have been cut, the handle can easily be pulled out of the bearings by disconnecting the locking ring that is attached to the right-side bearing, as depicted in Figure 15. While pulling out the mandrel, the coil can be grabbed and carefully pulled off the mandrel at the same time.

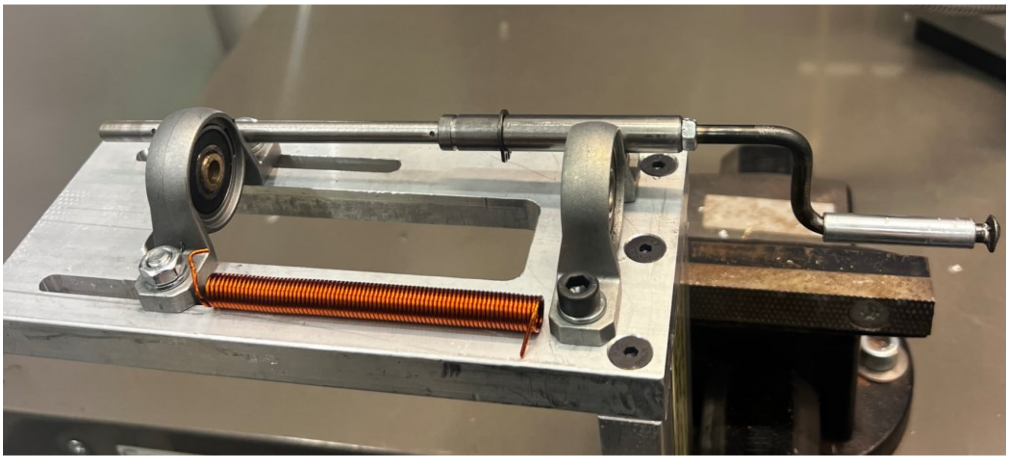


Figure 15. Removal of the handle and coil.

4.5 Prepared Helical Coil

A fully wound coil using one of the outermost holes as discussed in Section 4.3 and shown in Figure 10, ends up with a total length of 83,20 mm. This includes having had the tension temporarily released, and wire wound further, as explained in Section 4.4.

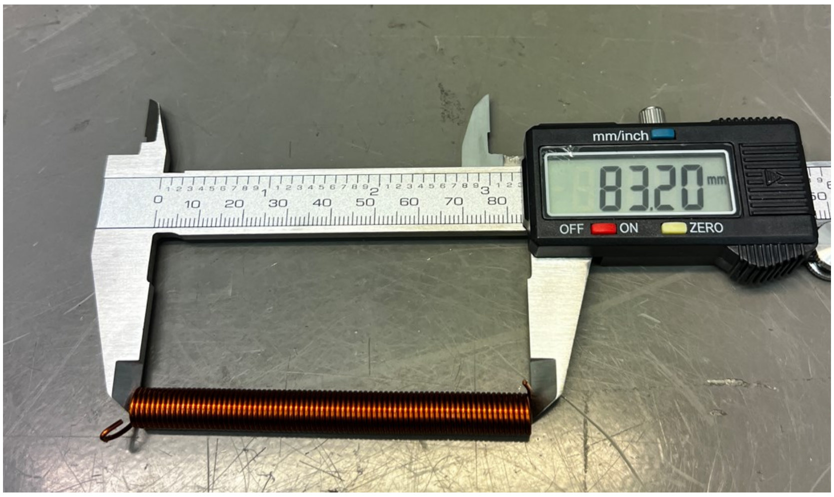


Figure 16. Fully wound coil measurement.

If the coil has been properly tensioned and wound according to the earlier steps in Section 4.4, the inner diameter of the helical coil should turn out to be 6,3mm (Figure 17). According to the IEC 61033 standard, described in Section 3.3, the required inner diameter is 6,3 mm ± 0,1 mm.

Figure 17. Fully wound coil inner diameter.

When the coil has been made, and the dimensions have been checked, the heads of the coils can be carefully opened by bending the head as shown in Figure 18. This is done to both have the length of the coil be within the standard criteria, but also in order to get extra wire, used to create heads for the coils.

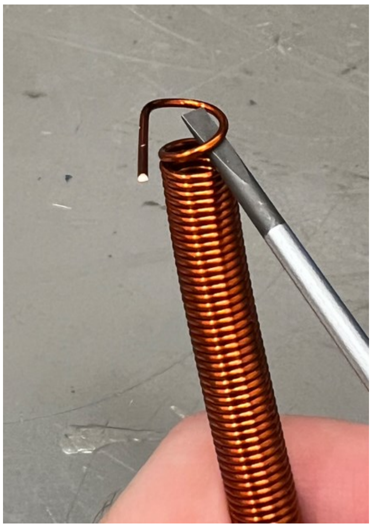


Figure 18. Opening of the coil head.

While opening and straightening out the wire of the opened windings, the coil length can reliably be made to be around 75,85 mm or 74,60 mm, depending on how many of the windings are opened. However, both of these measurements are well within the standard criteria as specified in Section 3.3, so the length used can be freely chosen. Shown below is a coil made with one of the outermost holes, shown in Figure 10, leaving plenty of excess wire to make the desired heads necessary.

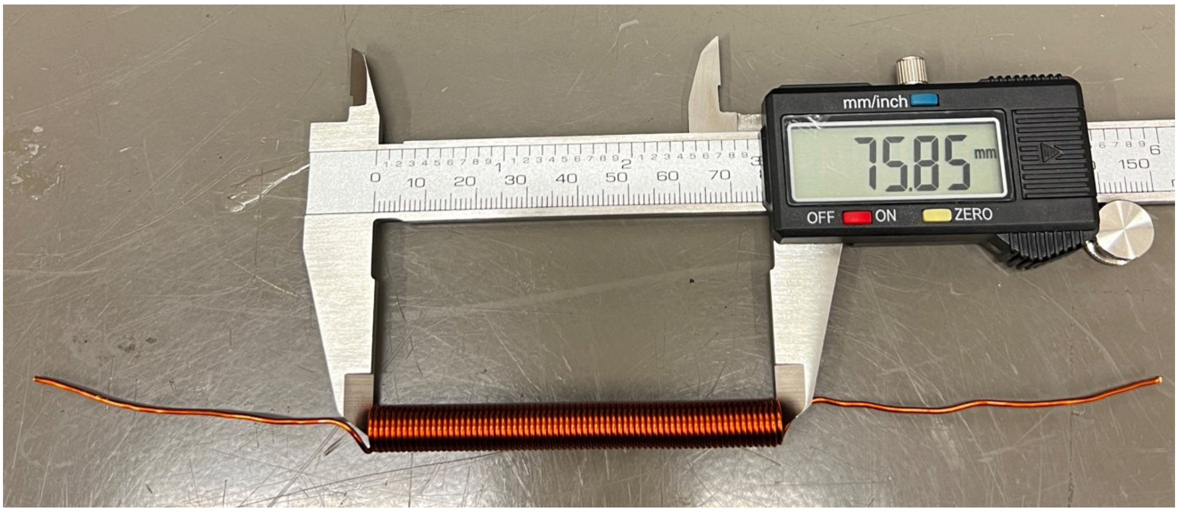


Figure 19. Shortened coil measurement.

When the windings have been opened to the desired length, which in this case is 75,85 mm, the excess wire can be used to create heads depending on in what way the coils will be impregnated and cured. This is done in order to aid in the handling of the coils during the impregnation procedures, but also depending on what equipment is used during the draining and curing of the coils. The impregnation process and its related procedures are further discussed in Sections 5.1 and 5.2, and in this case, a rack as seen in Figure 23 is used.

As the rack mentioned uses twisted copper wire as a suspension wire, there is a risk of slack occurring. In order to combat this, larger and wider heads are made, in order to fit larger hooks, ensuring a stable and secure connection. An example of how these heads can be made is seen in Figure 20. This is especially important when the coils are being cured in an oven, as vibrations and movement of the rack can cause the coils to detach from the hooks.

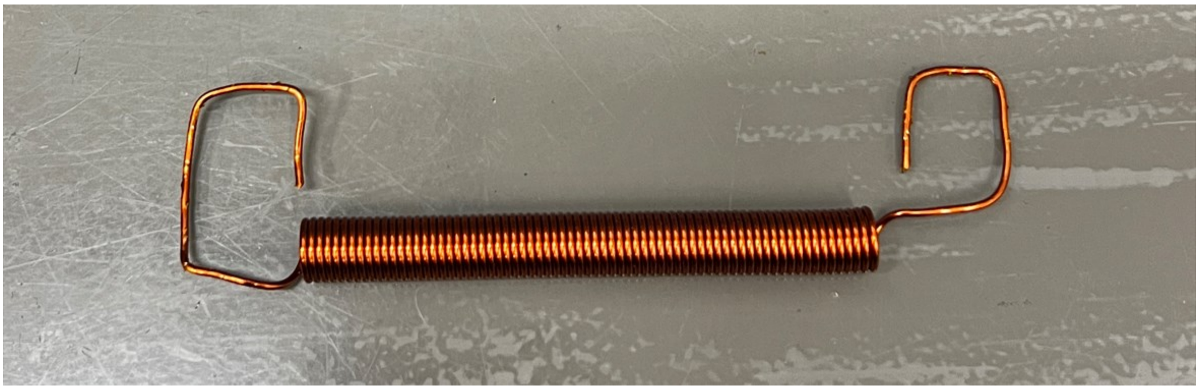


Figure 20. Fully prepared coil with suitable heads.

5 Impregnation

In this chapter the impregnation process of the coils will be discussed. Due to there not being earlier documentation regarding procedures, it has been decided that the impregnation process will be done to as far an extent as possible, to what is mentioned in IEC 61033. The impregnated helical coils discussed in this chapter are cured according to the production process temperatures and times in both trials.

During this process, two different trials regarding the impregnation of the helical coils were done. The first trial was done in order to initially see and check every part of the how the process turned out, in order to be better informed and prepared for the second trial. Another focus was to be able to compare the results of the trials, which include slightly different procedures regarding the dipping time, draining time, and the curing positions of the coils. As mentioned above, the main purpose of this is to find out what procedure regarding the impregnation process yields the best results, while also following the standard to the maximum extent of what is possible.

When this procedure is decided, it can be implemented as the standard way the impregnation of the coils is done henceforth at ABB in Vaasa, while also continuing investigations regarding potential improvements during future impregnations.

5.1 First impregnation trial

During the first trial, a simple rack was first made out of copper wire, which is attached to a bucket. The coils are then attached to a second pair of small hooks connected to the suspension wires, which will remain above the resin surface.

These small hooks were added, so that the coils can easily be removed from the resin, without the risk of accidentally touching the resin coating. A picture of the complete setup before adding the resin can be seen in Figure 21.

Figure 21. First impregnation setup.

Following this, the bucket is then filled with the impregnating resin, making sure that the coils are fully submerged in the resin as seen in Figure 22. According to IEC 61033, the coils are to be vertically submerged in the impregnating agent for 60 seconds ± 10 seconds.

In this case, due to the copper wire rack on the bucket not being removable, there were issues regarding following the required time submerging the coils. This was largely due to the amount of coils, but also due to having to be cautious when removing them, so as to not let the coated coil come into contact with other surfaces.

As a result, this caused uncertainty regarding the exact times each of the coils had been submerged, as the time submerged had been started when the first coil was submerged in the resin.

Figure 22. Coils submerged in resin.

According to IEC 61033, the coils are to be removed from the impregnating agent at a speed of 1 mm/s. Due to this being at such a low rate, this specification was not possible to fulfil with the equipment available.

As compensation, vertical draining was implemented after having removed the coils from the impregnating agent. This was calculated according to the specification regarding the speed of which the coils should be removed from the resin during dipping. Since the length of a fully wound coil is around 75 mm, this would require a vertical draining time of 75 seconds, considering the 1 mm/s specification.

The vertical draining process of the coils can be seen in Figure 23.

Figure 23. Coils being drained vertically.

While the vertical draining process was done, it was not carried out adequately, as the time each coil was drained, could not be confirmed. This is due to the difficulties of transferring all of the dipped coils, to the curing rack, as mentioned earlier in the chapter.

Furthermore, the quantity of dipped coils in each trial was around 20, causing it to take an exceedingly long time to transfer all of the coils after having been drained. During the first trial, the timing was also started as the first coil was transferred. The end result for this, meant that while some of the samples could have been draining vertically for 75 seconds, some were also drained for extended times, such as 5 minutes or above.

Once all the samples had been drained vertically for at least 75 seconds, the next step is to carefully change the coils into a horizontal position as seen in Figure 24. This is easiest done by grabbing the lower head of the coil, keeping the top head attached, and carefully securing the lower head to a second hook. During this process, it is important to be careful not to touch the surface of the wound structure of the coils, as this could affect resin coating, thereby compromising the testing phase.

Unlike the horizontal draining process, which is specified in IEC 61033, vertical draining is not mentioned in the standard. It was instead implemented to mimic the draining that would have taken place during the removal of the dipped coils.

According to the standard, horizontal draining should be carried out for 10 to 15 minutes. In order to ensure that all of the coils followed the necessary time criteria, they were all kept and drained horizontally for 15 minutes, measured from the moment the final coil was repositioned.

Figure 24. Coils being drained horizontally.

Following the horizontal draining time of the coils, the rack is then moved to the oven to proceed with final adjustments. As can be seen in Figure 24, the coils are not completely horizontal. This needs to be adjusted, in order to follow the IEC 61033 standard specifications for horizontal curing.

If the coils that are cured are not properly set horizontally, they are prone to give inconsistent results, as the resin will still have time to reposition once put in the oven. This is especially important considering the resin's viscosity changes when heated, making it less viscous.

The coils, however, can easily be adjusted by bending the hooks on the rack that are attached to the heads of the coils, until both sides are as horizontal as possible. The final and adjusted positioning of the coils can be seen in Figure 25.

Figure 25. Adjusted coils.

5.2 Second impregnation trial

The second impregnation trial was done in a similar procedure to the first one, however, this time a removable rack was made for the coils, as can be seen in Figure 26. This made it possible to ensure that all of the coils were dipped and drained vertically for an equal amount of time, by removing all of them from the resin at once.

In this trial, the coils were timed to be transferred to an empty bucket after being submerged in the resin for 60 seconds. Once they had been transferred, the timing for the vertical drainage was immediately started.

The vertical drainage addition was also revised, extending the duration to a total of 5 minutes. This was done considering the first trial which included a 75-second vertical drainage period, did not follow any existing specifications regarding the IEC 61033 standard.

As mentioned in Section 5.1, this had been implemented as compensation for not being able to remove the coil from the impregnating agent at a rate of 1 mm/s. However, as shown in Figure 27, the impregnated coils from the first trial still had a lot of resin drippage, including an uneven resin surface.

As a result, the decision was made to increase the vertical drainage time to 5 minutes, in hopes of the second trial achieving better drainage before being cured.

Figure 26. Transferring the dipped coils.

In order to get a better understanding of how to achieve the best possible outcome for the samples, some coils were cured in the oven in different orientations. The first set of six coils was processed as described in IEC 61033. A second set of six coils was kept in the vertical position for an additional 15 minutes after the initial 5-minute drainage and then cured vertically in the oven. Lastly, a third hybrid set of three coils was drained vertically for 5 minutes, drained horizontally for 15 minutes, and then repositioned into the vertical position before being cured in the oven.

5.3 Impregnation trials comparison

The main differences between the two trials of impregnated helical coils are the improved setup and the revised time adherence strategy implemented in the second trial. As described in Section 5.2, the time for both vertical draining and horizontal draining in the second trial was only timed after each coil had been correctly positioned on the curing rack. This adjustment, unlike in the first trial, ensured that every coil underwent draining for the durations specified in the IEC 61033 standard.

The dipping issues mentioned in Section 5.1 were resolved in the second trial by using the removable rack. This allowed all samples to be removed after exactly 60 seconds and simultaneously drained when transferred to an empty bucket as seen in Figure 26. The visual comparisons between the trials are further discussed in Section 5.4 below.

5.4 Post Impregnation Inspection

The first trial regarding the impregnation process, which included some immediate challenges as outlined in previous sections, resulted in a significant variability in the way the resin had cured. Around half of the coils, which had been successfully cured while remaining perfectly horizontal, showed a surprising amount of drippage. An example of this can be seen in Figure 27.

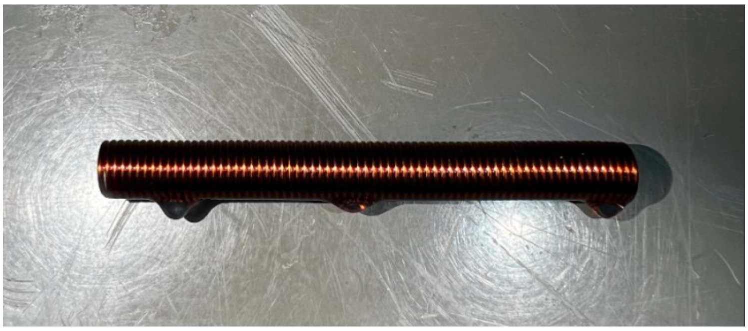


Figure 27. Horizontally cured coil.

The second half of the coils mentioned above, while positioned to be as horizontal as possible, were found to have developed a slight lean when collected after curing. This was noticeable in almost every coil that had been cured in a similar manner, since there was no excess resin found in the central area of the coils. Almost all of the coils which had not remained perfectly horizontal showed a similar outcome as to what can be seen in Figure 28, resulting in only a single area at the end of the coil having drippage.

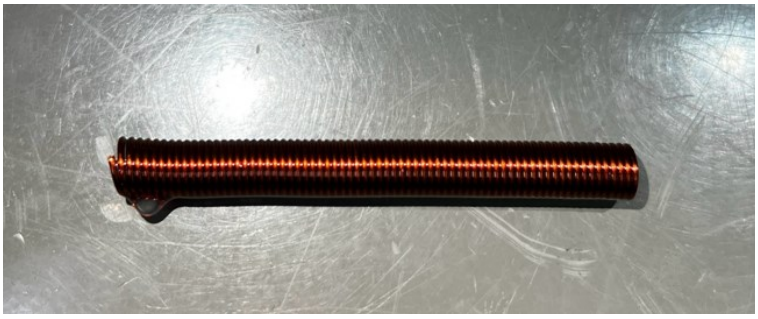


Figure 28. Horizontally cured coil affected by a slight lean.

The second trial regarding the impregnation of the helical coils, as mentioned in Section 5.2, was done using an improved setup and extended draining, including better time adherence. Another focus for which results will also be discussed further below is the three different orientations in which the coils were cured.

The outcome of the horizontally cured samples in the second trial, using the new procedures, can be seen in Figure 29. These samples, compared to the first impregnation trial, show a significant decrease in the occurred excess resin, specifically in the central area of the coils. While drippage had still occurred at the end of the coils, the coils followed a consistent pattern in the way the resin had cured, compared to the inconsistency found in the first trial. In this case, the better time adherence during both the dipping process, and the extended draining, has proven to aid in the overall outcome of the impregnated coil resin surface.

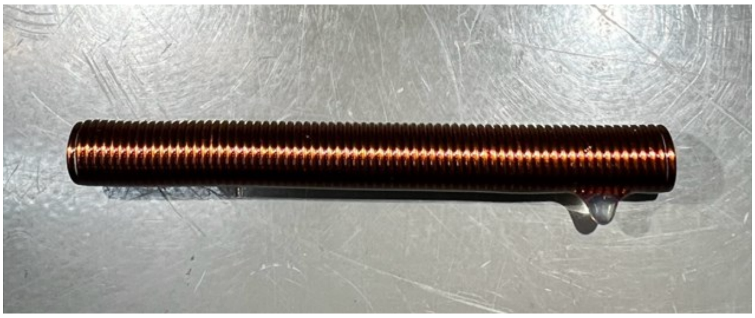


Figure 29. Horizontally cured coil with extended draining.

As mentioned at the end of Section 5.2, in the second trial six coils were selected to be cured in a vertical position. These coils followed a procedure similar to that of the horizontally cured coils, with the key difference being the draining orientation. Instead of being horizontally drained after the initial 5-minute vertical drainage, these samples remained in the vertical draining position for an additional 15 minutes. After the combined 20-minute vertical draining, these samples were transferred to the oven rack and cured in the same vertical orientation.

The resin outcome of these samples proved to be significantly better in comparison to the horizontally cured ones. This can be seen in Figure 30, which shows one of the vertically cured coils having no excess resin or drippage.

While a vertical curing method is not specified in IEC 61033, as mentioned above, the results were visually favourable. This is due to the vertical orientation preventing excess resin and potential uneven spots that could affect the results during testing and complicate coil positioning during the testing phase. The uncertainty and potential drawbacks of this are discussed in Section 7.2.

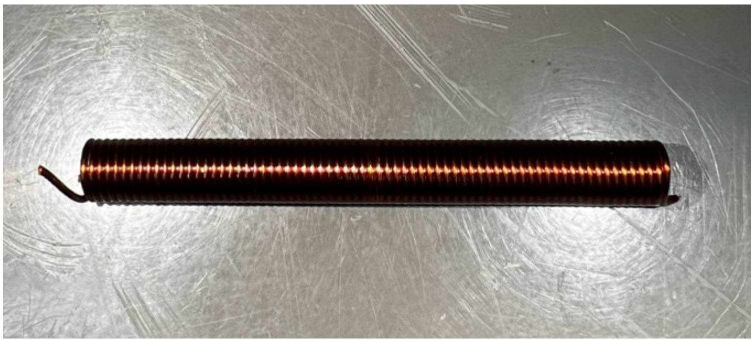


Figure 30. Vertically cured coil with extended draining.

The last few samples in the second trial included a hybrid procedure incorporating elements from both the vertically and horizontally cured coil processes. In this case, each coil was first drained for 5 minutes after having been submerged in the impregnating agent for 60 seconds, then horizontally drained for an additional 15 minutes. After the horizontal draining, the coils were repositioned vertically on the oven rack, where they remained in a vertical orientation during the curing process.

Combining vertical and horizontal draining phases, while then proceeding to cure it vertically, aids in the overall draining process. This is because including more orientations causes the resin to flow out of potential spots where it is likely to gather. The end result of this procedure can be seen in Figure 31, which is almost identical in appearance to the vertically cured coil in Figure 30.

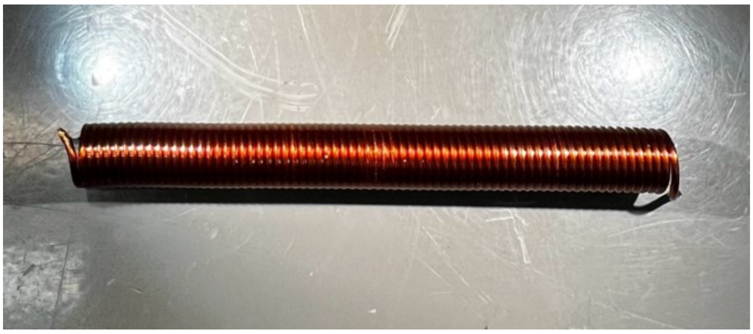


Figure 31. Hybrid horizontally drained, vertically cured coil.

When comparing the first and second impregnation trials, a clear improvement in the resin surface is noticeable. One of the reasons for this is the better handling of the coils during the dipping process, which is primarily due to the extended draining times and different orientations in which the coils were both drained and cured.

While IEC 61033 specifies horizontal curing as the standard method, the visibly inferior results regarding the resin surface on the horizontally cured coils suggest that vertical curing should be considered as a viable alternative. Vertical curing may help ensure more consistent test results by minimizing the risk of irregularities regarding the resin surface or other imperfections that could otherwise influence the outcome. This, however, will require further testing, using bond strength tests in order to compare if the different resin surfaces impact the test results. The first test results using coils from the second trial can be found in Section 6.3, while future testing regarding the resin surfaces are discussed in Section 7.2.

6 Bonding Strength Test

This chapter will be focused on the testing phase of the project. This will include information as to what equipment was used and how the setup was done, while also looking into how the specifications regarding the IEC 61033 standard are incorporated. The tests will use impregnated helical coils from the second trial, looking at the results achieved and considering how the differences in the appearance and structure of the coils could potentially affect the results.

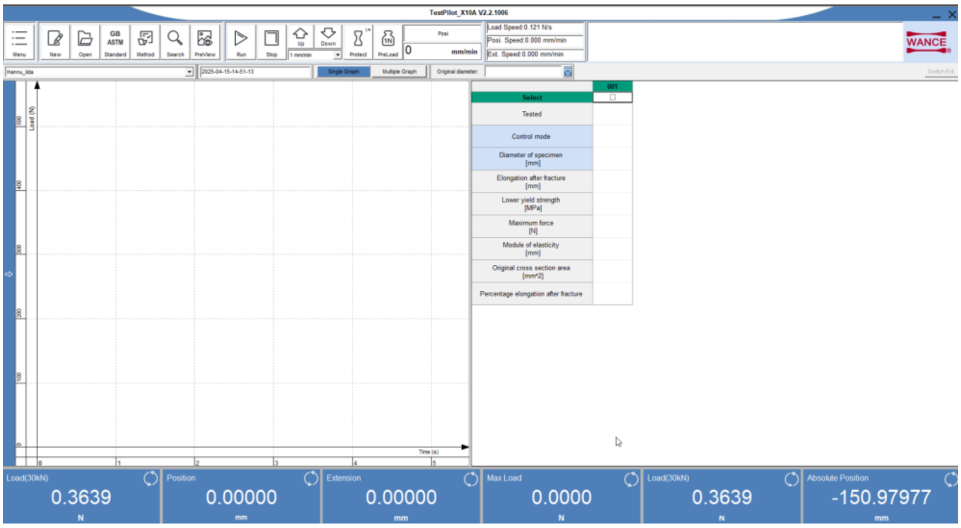
6.1 Testing Equipment

The machine used during testing is located in the insulation laboratory, as previously mentioned in Section 2.1.3, and is an electromechanical universal testing machine manufactured by Wance. The machine is capable of either measuring tension in attached materials or applying force, and in this case, the machine will use force to perform the bond strength tests. The setup made to perform the bonding strength test is further discussed in Section 6.2.

According to IEC 61033, the equipment used must comply with the relevant requirements in ISO 178, particularly regarding test speed control. This machine fulfils these requirements, which in this case is a test speed of 1 mm for specimens with thicknesses between 1 mm and 3,5 mm (SIS, 2019).

Figure 32. Electromechanical Universal Testing Machine.

The machine can be controlled by using the TestPilot software, which is shown in Figure 33. The software can be used to manually or automatically adjust the crosshead speed and positioning, which can be seen in Figure 35. When used during the testing phase, the crosshead is initially moved into position close to the positioned helical coil. The speed is set at 1 mm / minute, which as mentioned above is the speed used for specimens with a thickness between 1 mm and 3,5 mm ISO 178 (SIS, 2019). Following this, the software is then run until the resin surface cracks. After having initiated the test, the software shows a live graph regarding the position of the crosshead, and the current applied load. This can be seen in Figure 33 at the bottom row, which also includes additional live data.



1 mm/min

0 mm/min

Load Speed:0.121 N/s

Posi. Speed:0.000 mm/min

Ext. Speed:0.000 mm/min

Hannu_Ida

2025-04-15-14-51-13

Original diameter:

Load(30kN) 0.3639 N

Position 0.00000 mm

Extension 0.00000 mm

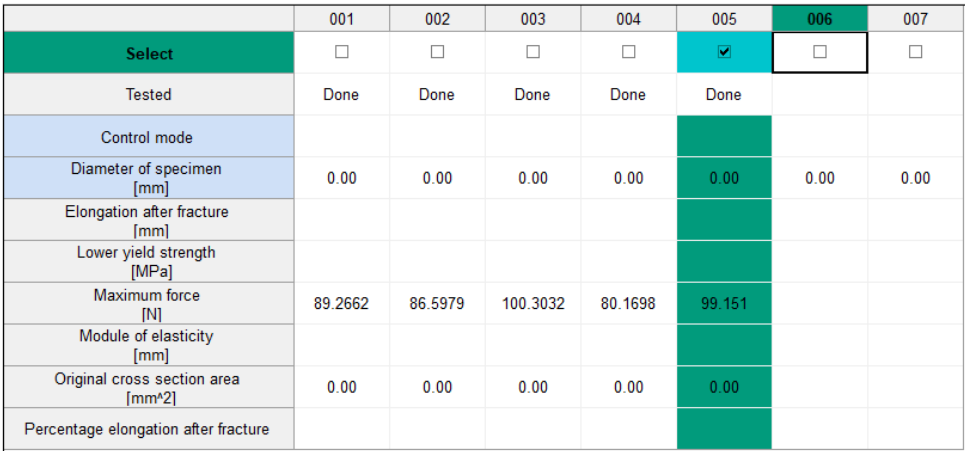
Max Load 0.0000 N

Load(30kN) 0.3639 N

Absolute Position -150.97977 mm

Figure 33. Overview of TestPilot.

Once the resin surface cracks, the crosshead automatically returns to its set starting position. The test results are shown as a table, which include the exact force that was applied when the resin surface cracked. An example of this can be seen in Figure 34 below.



	001	002	003	004	005	006	007
Select	☐	☐	☐	☐	☑	☐	☐
Tested	Done	Done	Done	Done	Done		
Control mode							
Diameter of specimen [mm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elongation after fracture [mm]							
Lower yield strength [MPa]							
Maximum force [N]	89.2662	86.5979	100.3032	80.1698	99.151		
Module of elasticity [mm]							
Original cross section area [mm^2]	0.00	0.00	0.00	0.00	0.00		
Percentage elongation after fracture							

Figure 34. Example of test results.

6.2 Test Setup

The test setup includes parts made according to Figure 8, which were made according to the dimensions specified in the IEC 61033 standard. This can be seen in Figure 35, which illustrates the main parts used in the setup. Each feature of interest has been marked using letters for clarification.

The crosshead A is opened, and the attachment B is inserted. Since the lower crosshead has been removed, a flat cylindrical area is exposed, which serves as a suitable platform for the support fixture C. Due to the weight of the individual components, the bottom support fixture does not need to be attached as long as it is placed on a surface of sufficient area for it to remain completely straight and secure. The crosshead can then be lowered, to ensure that the attachment lines up perfectly with the support fixture. This is done to make sure that the attachment presses down on the coil at the centre-most point of the coil during the test.

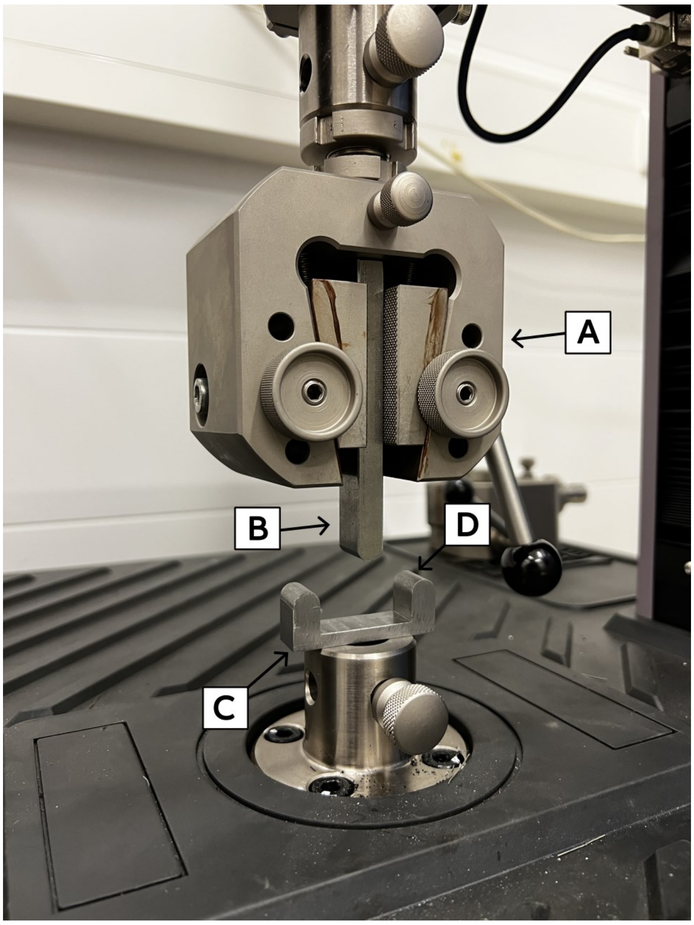


Figure 35. Crosshead attachment and bottom support fixture.

Once the preparations regarding the setup have been completed, the prepared helical coil can be placed between the crosshead attachment and the support fixture as seen in Figure 36. Before proceeding with the test, it is essential to ensure that the coil is centred on the support fixture. Both sides should extend equally, in order to ensure a centred point of applied force as shown in Figure 8.

In the case of there being an excess or uneven amount of resin on the coil surface, it should be documented, as its effect on the results are currently uncertain. If the coil has excess resin or drippage in the central area, the coil should be rotated so that the flattest possible surface is aligned under the crosshead attachment. In the case that excess resin or drippage has occurred at the support points, which are marked as D in Figure 35, the coil should similarly be rotated to achieve a flat and stable position.

Helical coils with drippage at the end points of the coils were in this case also rotated, so that the areas suffering from drippage are faced downwards. A combination of these adjustments can be seen in Figure 36.

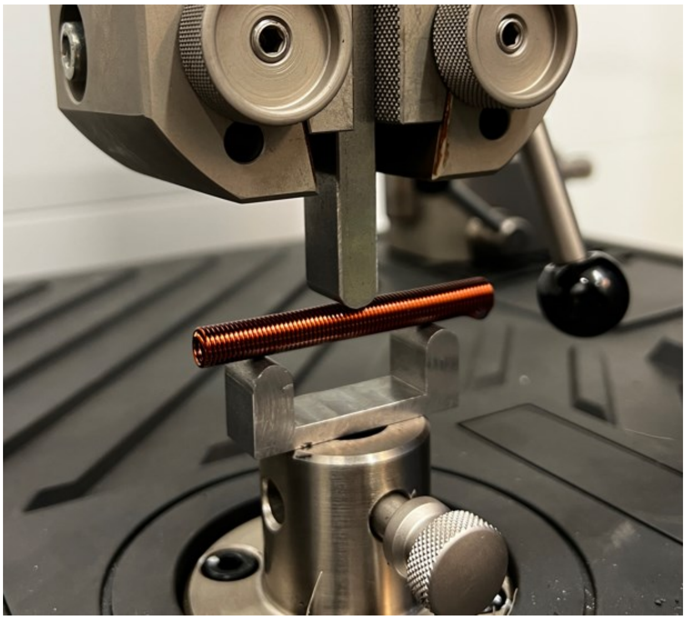


Figure 36. A prepared helical coil in testing position.

6.3 Test Results

According to IEC 61033, 5 samples made using the same resin and orientation are to be tested. The bond strength is expressed as the median of the five measurements in Newtons.

During the testing phase, only the second trial of impregnated coils was tested. This was decided, considering the second trial included a much more planned out and reliable procedure for each step. From this batch, 5 were chosen that had been horizontally cured, 5 that were vertically cured, and 2 hybrid coils which were horizontally drained prior to being vertically cured.

The initial bond strength tests were conducted using the horizontally cured coils. Due to the horizontally cured coils from the seconds trial still showing some signs of drippage, there were some minor difficulties regarding achieving correct and balanced positioning. The test results from the horizontally cured coils can be seen in Table 3 below.

Table 3. Horizontally cured helical coils.

Sample Number	1	2	3	4	5
Maximum force [N]	89,2662	86,979	100,3032	80,1689	99,151
Median Value	91,173				

The vertically cured coils, which had a smooth and even surface, provided no difficulties during the testing. The results from the vertically cured coils are shown in Table 4 below.

Table 4. Vertically cured helical coils.

Sample Number	1	2	3	4	5
Maximum force [N]	71,8617	91,5706	107,4591	93,0261	90,1759
Median Value	90,818				

The final set of coils tested were the hybrid coils that had been initially drained horizontally for 15 minutes but then repositioned vertically during curing. These samples were impregnated at the end of the second trial, when a few unimpregnated samples remained, and this was considered as a potential alternative procedure worth exploring.

However, since only two samples were made, it was not possible to meet the standard requirement of five test samples, making it difficult to draw a reliable conclusion regarding the results of this approach. The results of the two samples tested can be seen in Table 5.

Table 5. Hybrid horizontally drained, vertically cured helical coils.

Sample Number	1	2	3	4	5
Maximum force [N]	85,3244	87,9321	N/A	N/A	N/A
Median Value	86,628				

When looking at and comparing the median results achieved, the variation between the positions drained and cured seems minimal. The difference in the median between the horizontally and vertically cured is as low as 0,355 N, indicating that the curing orientation had little impact on the overall bond strength. This suggests that under the tested conditions, both curing orientations may be equally viable in terms of bonding performance.

These test results have provided a strong foundation regarding the impregnation procedure’s effectiveness. The future plans related to these results are further discussed in Section 7.2.

7 Discussion

The aim of this thesis work was to design, develop and test a helical coil manufacturing tool capable of producing samples according to the IEC 61033 standard, specifically for bonding strength tests between enamelled copper wire and resin. This work included the tool's design, initial functionality testing, sample creation, impregnation process, and the bonding strength test.

7.1 Limitations and Issues

At the initial planning phase of this thesis, some additional features and tests were planned that could not be achieved within the time frame of the work. One of the early challenges was the manufacturing timeline for the tool components. When the design had been created, the parts necessary in order to assemble the tool took more time to be manufactured than had been expected.

During this time, as mentioned above, including ageing of the impregnated helical coils was still considered. This would have required finding a suitable oven for long-term testing and planning how the coils would be cured in the oven, while also having to consider the times that would be used. Short term ageing was also considered, as this would already provide some insight into how the ageing of the impregnated coils affects the results during bonding strength tests.

This plan, however, was no longer an option at the time since as mentioned above, the time to manufacture the tool took longer than expected. There were also uncertainties regarding finding available ovens suitable for such tests during this time period. Because of this, the plans regarding ageing of the samples were dropped, in order to focus on the main processes mentioned in IEC 61033 related to the bonding strength test. The plans for future ageing tests are discussed further in Section 7.2.

Another part of the earlier trials regarding the investigation of the tool functionality that had to be reconsidered, was the implementation of the winding tension. The winding tension itself plays a crucial role regarding future tests, that will be used within ABB in Vaasa. This is important, as the setup has to follow all specifications regarding IEC 61033, for the results to be considered valid. As mentioned in Section 4.2, there was initial testing done regarding potentially being able to simply attach the weight to the copper wire using clamps. This, however, was deemed to be both inefficient and potentially damaging regarding the wire surface. Following this, the planning for a more complete setup in order to implement the winding tension was done, but it was deemed too time-consuming to be done during the scope of the thesis work. Due to this, the focus on implementing the winding tension during this work was dropped. The future plans for the implementation of the winding tension are discussed in Section 7.2.

7.2 Future Testing and Improvements

At this stage, the main priority following the completion of this thesis work will be to implement the winding tension, ensuring that all future coils can be made according to the IEC 61033 specifications. As mentioned in Section 4.2, the use of an extendable support or clamps to achieve the winding tension of 10 N, was deemed to be impractical and unreliable.

After reconsideration and further planning, the next steps regarding achieving the implementation of the wire tension, will be done by implementing a brake system to the copper wire spool which is the source of the wire during winding. In this case, a rack will be designed and created which the spool is attached to, in order to allow it to freely spin. This will allow the spool to be placed directly beneath the fastened tool, where the wire can then be attached to the mandrel and wound into coils.

When the winding tension has been implemented, every part of the tool and helical coil creation process will follow each specification found in the IEC 61033 standard. When this is done, further tests and the corresponding results can be considered valid for use in company documentation. When this is achieved, each step and procedure in this thesis will be redone, on a larger scale.

This time, however, aging of the impregnated helical coils will also be included. The aging process of the coils will still only be short term, such as 7, 14 and 30 days. This is done in order to be able to achieve a base procedure for how this will be done, and how the aged coils affect the results during the bonding strength test.

When each process discussed in this thesis work has been documented, it is possible to continue with investigations as to how to further improve each procedure, and what during these procedures can affect the end results in different ways.

Regarding this, the main questions are how the impregnation procedures, different timing and orientation affect the curing of the coils. This is checked in combination with how the final resin surface affects the bond strength test results. As previously discussed in Section 5.4, there was found to be a substantial difference in the resin surfaces based on the durations the coils were drained, and in what orientation they were cured.

This raises questions, such as how the resin surface actually affects the results during the bonding strength test. It is not possible to simply conclude that the horizontally cured coil with an uneven resin surface and dripping as seen in Figure 27, is going to perform worse than a vertically cured coil with no visual flaws in Figure 30. These need to be tested further, as if the resin surface proves to not be a significant factor in the outcome of the results during the bonding strength test, it needs to be documented for future impregnation procedures.

The reason for this as a whole is to remove any doubts and speculation regarding what potentially could affect the results of the impregnation procedures and bond strength testing. As mentioned above, this is expected to take place after the winding tension has been implemented.

This will be achieved by recreating similar samples using the improved time adherence and orientations, but on a much larger scale. This will allow sufficient testing of each procedure, in order to get valid results and confirm if any current visual flaws do indeed affect the bonding strength test results.

7.3 Summary and conclusions

The outcome of this thesis can be considered to be successful. As outlined in Section 1.2, the tool design proved to be effective and reliable in producing helical coils. The tool, as was planned during the design phase, can be easily modified for future additions, without compromising the implementations made regarding the IEC 61033 standard specifications.

At this stage the coil manufacturing process follows all the necessary specifications in the standard except the use of winding tension, and the produced samples can be replicated at a high degree of consistency. As the tool allows for the creation of coils that exceed the standard-length requirements, it is also flexible, enabling the creation of any kind of heads that could be needed during the impregnation process.

One of the foundational parts regarding the preparation of the coils, which is the impregnation process, was carefully planned out and was done in two different trials. Because of this, the issues and flaws that occurred during the first trial have been eliminated.

This has made it the possible to use the second impregnation trial procedure as a solid basis for future testing. Using this procedure will aid in the continued deeper investigations regarding the differences in the outcomes that can occur during the impregnation process.

By further documenting the differences and results between the cured samples, the impregnation procedure can be further tweaked based on the findings, until a final procedure can be chosen and used in official testing henceforth.

During the testing phase, a procedure for setting up the machine regarding the bonding strength testing was done after having confirmed the suitability of the manufactured attachment and support fixture. The testing phase allowed for confirmation regarding the success of both properly produced helical coils, and the impregnation process. These initial test results were compared to previously done tests at other locations within ABB, where the results were deemed similar and acceptable.

As the bonding strength test ended up providing good results, it further confirms that each part of the process done during thesis has allowed for a solid foundation regarding future sample creation and impregnation procedures.

Each step that has followed the structure of the planned objectives in Section 1.2 has been achieved successfully. As mentioned in Section 7.2, continuous investigations regarding improvements of all processes will continue until a procedure for each phase has been documented and can be used in the future creation, preparation and testing of helical coils.

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