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Investigation of Automating Custom Coil Winding Using Machine Vision and Tension Control

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Abstract. The coil winding industry's demand for automation and accuracy is increasing, particularly in the area of precision electromagnets. Current manufacturing practices do not satisfy some custom wound coil specifications efficiently enough. To meet increasing demand, current automation manufacturing practices must adapt. This research explores automation within the coil winding process in two important and distinct aspects. Firstly, by researching a novel idea of using machine vision for accuracy control and quality assurance. Secondly, using magnetic resistance for tension control on large copper wire spools. In this paper, we utilize machine vision to control the linear pitch of the wire onto the former. This process can be very useful for manufacturers in the coil winding industry, for accuracy and defect control. Significant results show how machine vision can assist the automation process within ($\pm$) 0.15mm. Magnetic resistance added more precise control by 1.16 kg-m/s and reduced the wear on industrial equipment.

Keywords: Elastoplastic Deformation. Compressive Strength. Former. Tensioner. Incrementing.

1 Introduction

Coil winding is used in the manufacturing of electromagnetic coils [18]. Copper coils are generally used in a large variety of applications such as household appliances because of the great material properties it has. Copper allows the high flow of electricity which produces an electromagnetic field when it is wrapped [11]. As electromagnets [1] are becoming smaller, coil winding is becoming more complicated as technology advances [7]. Therefore the manufacturing process to wind the coil has to meet advancing requirements also. Some of these electromagnets are very powerful and have to be designed with ensured quality measures. To gain a better understanding of current coil winding techniques and their problems, a manufacturing company called Buckley Systems participated in an interview [27]. The interview was under a duration of one hour and was answered by the Head Engineer with over 19 years of experience, Wendy Liu. Currently, the wire winders used for the electromagnets require a long and complicated manual process. Specifically, the investigation leads towards the linear winding process because of its common use in industry. Linear winding is the most common automation technique for copper winding because of how versatile it is [10]. With linear winding high speeds can be achieved, increment and tension control can be accurately measured and the allowance of larger wire gauges can be used [5, 24]. A problem found within the linear winding process is that all types of coils are different [10] [6], therefore each winding process needs to be adapted to every new product. As solenoids are getting smaller, coil tolerance is becoming tighter and the requirements are harder to meet. Coincidentally, there is no standardized method for the wire winding process [20] which makes linear winding a challenging process. Currently, there is not a significant amount of research in the coil winding process in increment and custom coils with specific gaps. What is known, is the factors that contribute to the overall wire compactness, quality, and mechanical fill factor [7]. It is how we control that process in linear winding that dictates these factors [5, 24]. It is suggested that for accurate increment control we must control the residual and compressive stresses in the wire [2] [3]. By controlling increment through stress control, the coil can achieve a high fill-factor. A high fill-factor determines how magnetic the coil is [24]. Currently, the fill-factor of the coil-winding process is determined by the pitch of the lead screw and the stress in the wire. Even though the pitch is consistent, the wire gauge is not, and has lots of width variation shown in figure 1. It is suggested that mechanical accuracy control is not accurate enough in today's age for accuracy control. Therefore, exploring the novel idea of using computer vision in an industrial environment to measure the width of the copper wire and to offer quality assurance during the linear winding process is needed. Currently, the process is not measured directly and this paper offers a novel solution to this problem. As coils are being optimized and are

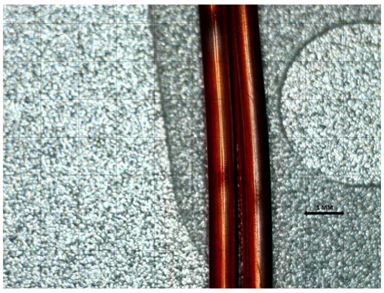

Figure 1: Wire width Variation Under Microscope

becoming more complicated, mechanical tension does not suffice for some complicated winding armatures [5] [9]. When tension in the wire is not controlled properly, or too much force is applied onto the wire, the wire can short within the coil. A short occurs when the turn insulation is broken, leading to puncture of the ground wall [17]. When excessive force, pressure and stress is applied to the wire, deformation occurs [23] [5] . Since elastoplastic deformation of the wire diameter will lead to increased electric resistance in the coil [22] there will be more winds per layer. When examing copper wire under a microscope 1 we can see visually slight width variation. The proposed solution is to create a programmable coil winding machine and tensioning system that is highly accurate. This can be used in one or more applications in the industry when necessary. Currently, there are not many machines that wind complicated former's [28]. With using machine vision, verification of the process can be established in a novel way.

2 Industry Developments

During this interview with Buckley Systems, we observed the operators. We found that the current system implemented resulted in uneven tension, which made the wire winding process difficult for the machine-operator to control. The coil machine I noticed this problem was a machine for rectangular former winding. While winding rectangular coils, the wire tension is not consistent and experiences tension fluctuations. These fluctuations are due to quickly changing wire path length. The varying tension may affect the operation shaft. Excessive forces may cause machine vibrations and non-uniform coil winding. When this happens, the rectification process is extremely time-consuming. It significantly affects the manufacturing productivity rate. Currently, operators are using a soft-headed hammer to force the copper wire to contact to rectify the problem. The wire is firstly purchased on a spool which is then assembled on a free spindle. So it can turn freely. The wire that is stored on the free-spinning spool uses gravity as its main tension force. As the copper wire starts getting used up, the weight of the wheel starts to decrease. The tension force is directly proportional to the mass of the spool, and as the mass of the spool decreases the tension also decreases, This situation is not ideal. "It is quite common that when workers reach the end of the former, the wrapped wire may not be pushed hard against the side. In some cases, it may be too small, or too big within the appropriate amounts of turns," said Wendy Liu. Using excessive force through the soft hammer on an already uneven tensioned system to compact the wire, means that the wire will be slightly deformed. This will potentially damage the insulation layer, therefore produce electrical shorts and deformation of the wire. The copper wire itself has its width tolerance (0.02mm-0.15mm difference). Slightly decreasing the width of the copper wire by force from impact and high tension from the operator means that more turns can be made in each space and increase the resistance of the electromagnet. Damaging the wire can also affect the insulation contact area and create electric shorts in the final product. The machine's guide arm is fixed in one position which feeds through the wire to the bobbin which is then compacted by impact by an operator. The machines are controlled by a pedal. Much like a sewing machine, the operator can wrap the wire into a coil. On one machine, the tensioner arm is on a free moving slider. This means that the operator can adjust where the tensioner arm should be, but it is not very reliable. This slips often and has little to no effect on accuracy. The soft-headed hammer is the only effective equipment that they have currently to rectify it. To assist the operator, the moving tensioner arm is supposed to provide even increments along the width of the former, but it simply is not accurate enough. This can be a problem as it is difficult for the operator to use and the rectification process is time-consuming. It is suggested that a different more accurate mechanism should be put into place to assist operator efficiency and production time. To assist the worker, new methods and techniques are always being made in the coil winding industry. A robot-based coil winding technique combining spindle and fly winding has been developed, to cover a wide range of winds. The method is based on an industrial delta-robot which places the wire on a programmable trajectory around the targeted position [10]. This idea is non-conventional but the handling time and steps times are reduced. It covers a wide variety of possible coils to be wound. The disadvantages of this robot method suggest a decrease in winding speed according to [26]. This suggests linear winding is the fastest method available and the solution proposed above is in the right direction. Some applications don't need this complexity and its very inefficient. A machine recently developed called the 'Linear Flux-Controllable Doubly Salient Machine' has a complicated coil design. The machine consists of HTS-excitation coils. There is a physical separation between the HTS excitation windings and armature windings in this machine. The separation can reduce space conflicts. This means you can fit more coils inside of the machine. Because of the gaps, the temperature on the HTS-excitation coils is regulated better [13]. The cooling is improved and the life span of the machine is increased. The U-shaped HTS-excitation coils work together to get an electromagnetic field. In this example, the coil can only be wound on a specific machine. Unfortunately, coil dimensions can not be found. From the sounds of this coil, fly winding or spindle winding would best suit these complicated applications. A similar coil is wound by Buckley Systems, called the 1800 ROD. Its a solenoid with specific gaps that will be discussed in section 3.1 Table 1. Therefore in complicated applications like this, the linear winding process is circumspect. The reasons for having gaps in the coils benefit the overall functionality of the machine. This in-turn shows the direction the coil winding automation industry should move forward in. A particular method that stood out was using Machine Vision. According to [21] the best method for estimating the ellipticity of steel coils is to use an algorithm. This ensures the quality of the coil before shipping to the customer. This is a method that has not been seen in the linear winding process before. It is suggested that we should follow a similar practice in developing future automated coil winding machines.

3 Methodology

For this research, a solenoid called the 1800 Rod solenoid made by Buckley Systems will be used as the testing coil. This solenoid has high specifications, so much that up to 40 percent fail quality inspection. It consists of complicated winding gaps which are not currently automated. The 1800 Rod solenoid has four variations for it is specified application. The 1800 Rod special has a 25, 50, 75 and 100 percent field strength wind. This former has special gaps which are represented by the 0's in table 1 below. The gaps are located on the final layer. Adding in the gaps is a manual task and requires a manual input that slows production. In this case, increasing accuracy during production would best suit this linear winding application. The unique shape of the former, rectangular with rounded edges makes tension and winding a challenging issue. The manufacturers are currently using mechanical tension. The wire does not receive consistent tension to consider the change of shape on the former. The increment is controlled by a soft headed hammer and does not suffice. Due to time restraints, the 1800 Rod solenoid type with 25 percent field strength will be wound with 1 layer for testing. This will be discussed more in the methodology.

3.1 Solenoid Coil

Table 1: 1800 ROD Winding Scheme

1800 ROD Winding Guide				
Coil Type	**Field strength (%)**	**Gauge (mm)**	**Turns Per Layer**	**Total Turns**
1800	25	1.29mm	21 20 21 20 21 19 9 10 0 0 0 0	270
1800	50	1.29mm	41 40 41 40 41 40 0 0 0 0 0 0	243
1800	75	1.29mm	62 61 62 61 62 56 8 10 10 10 10 8	420
1800	100	1.29mm	82 81 82 81 82 78 19 20 20 19 0 0	564

According to sources referenced above [30] and the industry interview, it is suggested that a different more accurate mechanism should be put into place. Specifically, to assist operator efficiency and production time [2]. Noticeably, the area of tension control and incrementing is well behind, comparing to standard industry equipment. It is proposed that a method for tension control and machine vision should be put in place to assist production in a positive aspect.

3.2 Tension control

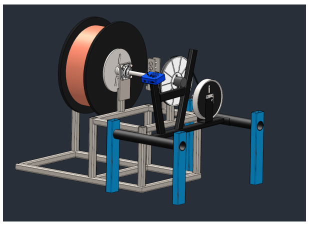

Figure 2: Final Magnetic Resistance Tensioner

The equipment used is a magnetic flywheel like the one used in patent [14]. This design shown in figure 2 is used in current applications such as magnetic resistance bikes. The magnetic resistance bike uses a flywheel with magnets to create a consistent resistance [12]. The most challenging parameter to control is the relationship between tension and speed [25]. These parameters will require micro-controllers with fast feedback. This will allow the spool to constantly un-spool at a consistent rate no matter the weight or size. A simple control system can be implemented into the servo motor. This will control the position of the flywheels distance to the magnets. As the speed changes, the distance of the flywheel to the magnet will adjust to the correct resistance level. Directly controlling the tension in the wire shown in figure 3. The way the magnetic resistance was measured was by using a pull force sensor. The pull force sensor measured to two decimal places, up to 150kg.Pull force meters are common practice measurement instruments for measuring tension. To make results consistent, a spring was used and extended to 80mm each time for accurate readings on the wire. As each level was increased on the magnetic resistance unit, one or more winds would occur before measuring. This ensured that the system was consistent with the level of tension [29]. Three trial measurements were made at random places along the middle of the wire shown in figure 4. Results were averaged out.

Figure 3: Tension System

Figure 4: Tension Measuring Method

3.3 Machine Vision

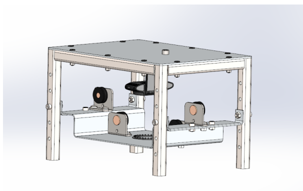

Figure 5: Vision Rig

The wire from figure 3 is designed to run through a measuring apparatus shown in figure 5, through a series of pulleys. As the wire gets fed through, the camera above it measures the wire. It does this by an algorithm shown in figure 6. Firstly, the wire is filtered in the HSV Scale. It filters the image in the orange and brown scale as this is the color of copper wire. The image is then median blurred, to find the edges of the copper wire using a canny image filter. To improve the filtered image quality a kernel is added. The final image is dilated. Adding Dilation improved image quality in this algorithm. Two bounding box contours are used to find the boundary of the wire's parameters shown on the computer screen in figure 8. The width of the two bounding boxes is subtracted and an accurate pixel width is then outputted to the user. To make this estimation more accurate and efficient, a Region of Interest(ROI) is located directly underneath the camera. To convert the pixel to useful measurements, we must use a ratio to convert pixels to millimeters but consider other factors such as height and focal length. The output is shown in figure 12.

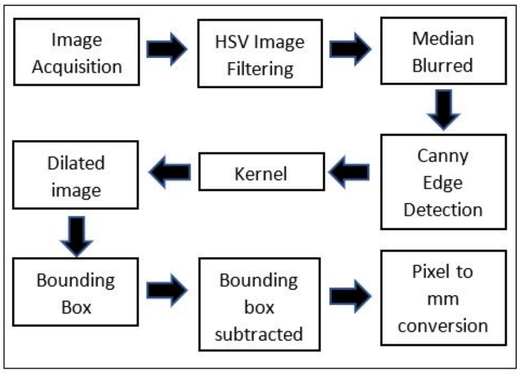

Figure 6: Copper Wire Measurement Algorithm

3.4 Linear Guide

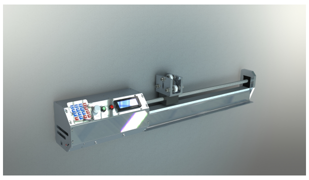

Figure 7: Linear Rail

After the camera processes the algorithm, it starts a TCP server. The NVidia Jetson Nano acts as a server and the Arduino Uno acts as the client. The server and client communicate with the use of an Ethernet cable. This is a common industrial practice for sending information over short distances. The linear guide has a stepper motor that moves the carriage up to an accuracy of 0.0125 mm shown in figure 7. The set up is shown in figure 8. The code is shown in my GitHub repository [16]. To test out if the algorithm is correct, we must run an experiment. The experiment consists of wrapping a wire around an 1800 Rod coil for one layer. When the layer is wound, we compare it to a hand-wound 1800 Rod coil which is the control coil. The control coil is compared to one made with the automated coil winding machine using the algorithm. The variables being measured are the Winding Gap, the Inductance and the Ohmic Resistance. A good result of a well-made coil,

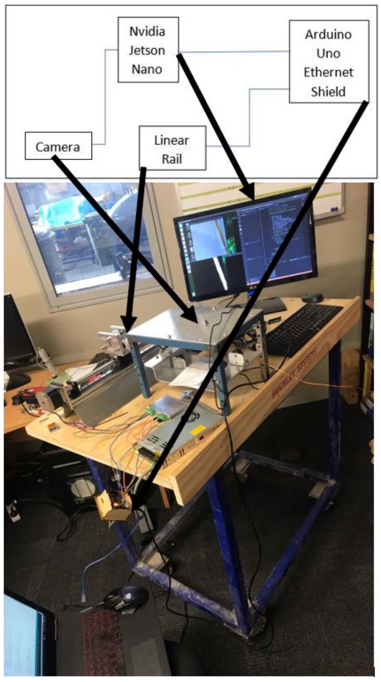

Figure 8: Hardware System

would have the correct full factor and be optimized for the device it is used in. Often equipment manufacturers optimize their winding machines based on experiments and expert knowledge [4]. A good result would pass Buckley Systems' rigorous quality assurance test. The coil would get a resistance reading which would be approved by a Quality Inspector. There would be no shorts in the finished coil. There would be an increased production rate of coils from the current average output per day, once the machine has been implemented. To measure if the increment control is accurate, we must compare the total winding error using visual inspection. This will give an estimate to see how well the machine fulfilled the fill factor variable. The more compact the wire the higher the magnetism. To verify results, resistance and the inductance need to be measured. To figure out if the coil is shorting, the actual resistance minus the Target Resistance using a Four-Wire Measurement must be verified.

4 Results

4.1 Machine Vision Result

Figure 9: Solenoid Winding Results
The reference solenoid is Manual Wound (Top Left), Automatic 1 (Top Middle), Automatic 2 (Top Right) , Automatic 3 (Bottom left), Automatic 4 (Bottom Middle) and Automatic 5 (Bottom Right)

To compare the results reliably, we treat one coil that is hand-wound by an experienced operator to be the control coil. This will be used as a control coil for comparison. To make sure results are accurate, five coils were wound using automation and results were averaged out. The findings were that the first(Auto 1) and fourth coil (Auto 4) automatically wound were the best found in 9. These were the closest to the control coil. These results were significantly close. Because the machine sometimes throws out large values the total winding error reached up to a maximum of 7.5mm in the fifth coil wound (Automatic 5) shown in figure 9. This is due to sudden changes in lighting. The coils were wound using the same set up as in 8 The resistance in the automated coil was found to be 81.185 (average of readings) compare to the manual baseline of 82.19(Manual Wound) found in figure 11. The inductance was 322.5 (Average) compared to the manual baseline of 318 which is considerably better. Having a higher inductance means that the coil is outputting the proportional current to the magnetic flux meaning that the coil is operating at its optimum. While comparing the winding error the findings, we found hardly any difference compared to a baseline of 1.26 mm and an automated result of 1.35mm(Average of Auto 1, Auto 4 and Auto 5) found in figure 9.

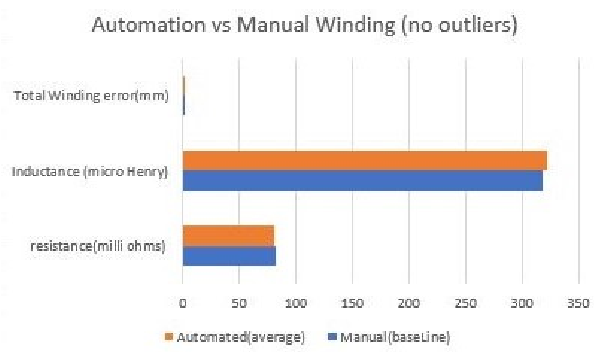

Figure 10: Machine Vision System Results

Furthermore, comparing the fill factor from current coil winding machines will indicate how good the machine is performing to achieve a tight winding gap. Looking into sources [22] we can see that a good example of a machine, called the tw-2 machine, achieves a gap of less than 0.1mm. other sources such as [6] found a 0.075mm gap but it rises to a 0.2mm gap on the last layer. No research reports use a camera. Using a camera should improve the results of the system. What was common through other research was that an effective brake system is necessary on a coil winding machine. Because there is so much starting and stopping in the coil winding rectification process, the tension is rarely constant. Adding in a tension system decreases tension disturbances [22] therefore decreasing winding gap error.

4.2 Tension Results

The max 20.2 N. The min was 8.8 N found in figure 11. The tension system has an effective tension of 1.16 kg-m/s on a 120.2 kg coil. It was producing 11.37 watts at 40 RPM. The system is rated for (570 Watt) 58.12 kg-m/s at 130 RPM. While examining other research results, PLC-based Tension Control System [19] found tension control to vary between 5N-10N. Explicit Dynamics Process Simulation of Linear Coil Winding, [5] was found to be 90N. Thomas A. Mannin found that [15] When they equipped a tensioner on a multi-spindle machine their price can add another 30 -35 percent to the cost to the machine.Another source, [24] look at around 50N to 200N at 800 RPM. All these results are comparable to my magnetic resistance system even at

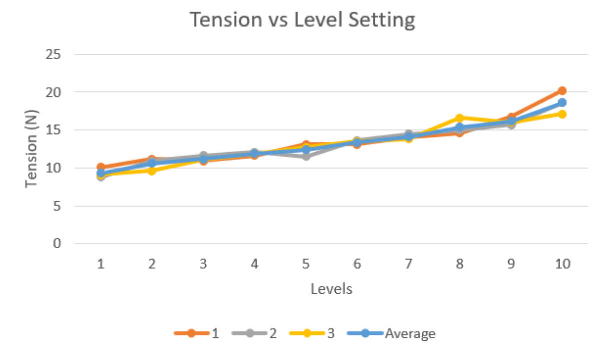

Figure 11: Tensioning System Results

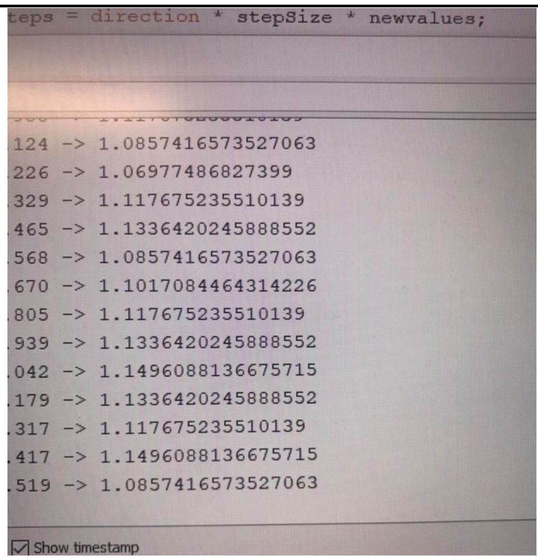

Figure 12: Algorithm Output

higher speeds.

5 Discussion

While disregarding outliers, machine- vision automation is seen to be very useful for improving industrial coil winding shortfalls. Referring back to section 2, we achieved a positive result in increased accuracy in the linear coil winding process by providing a solution to the problem in section 3. It achieves high compactness, a low total winding error and a high inductance for solenoids. While regarding outliers, it is very dependent on lighting conditions, the algorithm used to convert pixels to millimeters and the color of the copper wire. Noticeably a lot of the times the readings would jump to a measurement almost 0.15mm from the actual measurement of the wire as seen in figure 12. This would cause the winding to reach the end of the former before the correct amount of winds were reached, causing these outliers. To fix this issue, a better lighting rig must be designed and a change in the HSV scaling must occur. If a better camera was used, and more parameters were set regarding zoom and optical parameters then there would be more accurate reading and fewer outliers. Having tension benefits automation by making it easier for the worker. As little as 1 kilogram is enough to make the system taunt or loose. A brake system would be more useful for manual-operated production according to feedback from an operator. As automation becomes more profound in industry, magnetic resistance will be more useful, but manual over-ride is still needed. Due to time restrictions and accessibility, increase speeds were not measured for tension control. The maximum speed ever reached by the tension system was less than 40 rpm per minute. This was because the custom coil measured during the process was done manually. The coil needed to be compacted and incremented correctly, as this coil was intended for a customer. If speeds were increased, then the maximum field-effect would be outputted by the magnets. This is expected to be around kg-m/s at 130 rpm according to theory. This would be hard to verify with the method currently used and an alternative method would need to be implemented. For example, using a better pull force sensor that allows the copper to be fed through.

6 Conclusion

The results highlighted, showed that machine vision can increase accuracy in the coil winding process within ($\pm$) 0.15mm and assist the automation process. The biggest weakness found was that the measurements are highly affected by lighting, distance and optical focus. An industrial camera would suit this application best with consistent and steady lighting. Using more cameras would also increase accuracy and quality assurance by measuring the width from a different orientation. This is a common industry practice. Conditions were not controlled well as lighting could have an effect of up to .5mm on the width of the wire which is very inaccurate. An assumption that was made was that the linear rail had an accuracy of up 0.0125 mm. If there was a bigger budget, an industrial camera and gear-driven stepper motor for higher accuracy control would have been used. Magnetic resistance added more precise control by 1.16 kg-m/s and reduced the wear on industrial equipment. A weakness found in the tension control was that still, some physical force had to be applied because the magnets were not strong enough. With stronger magnets and using a break, we can verify that magnetic resistance is the best option for tension control. It is suggested, with a higher budget, a magnet particle clutch for better industrial practice should be implemented for optimum tension control [18], [8], [12], [25]. Research may continue in this area but it is highly recommended that tension control should be fine-tuned with the use of a PID [25]. It is also suggested that machine learning should lean towards quality assurance inspection rather than use to control the pitch of the lead screw. Since technology still needs to become cheaper for higher quality equipment, machine learning is useful for final coil inspection on the final layer of copper winds. The final layer is where most variation in winding gaps occur [6].

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8 Definitions

- Elastoplastic Deformation - The relationship between stress and the elastic limit of a material and its breaking strength.
- Compressive Strength - The resistance of a material to breaking point under compression.
- Former - Another name for a bobbin.
- Tensioner - A device used to direct the copper wire onto a former.
- Incrementing - Increasing the turns of copper wire on the former.

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