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Development of a Winding Mechanism for Amorphous Ribbon Used in Transformer Cores

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1. Introduction

In recent years, the application range of available soft magnetic materials has increased significantly due to the development of amorphous and nano-crystalized systems. Certain ferromagnetic alloys can be obtained as vitreous phases by rapid quenching techniques; some of them partially crystallize by certain heat treatments achieving structures composed by 10 to 40 nanometre long grains surrounded by a vitreous phase. One of these rapid quenching techniques is the melt-spinning, from which it is obtained amorphous metal strips that are, later, wound up into rolls.

The later-use of the wound rolls is the conformation of electric transformer cores showing meaningful improvement in its overall outputs, as well as an increment in the efficiency and fewer environmental impacts. In the past, these cores have been produced with grain-oriented and non-grain-oriented silicon steel sheets, ferrite sheets, Ni-Fe and Co-Fe alloys sheets produced by conventional casting processes, which require several mechanical and thermal processes, which some of them, have a high cost (Gelinas, 2000). The fabrication of nano-structured magnetic packages can be done, in this particular case, by the direct-employment of melt-spinning's strips into different kinds of heat treatments, where it can also be adjusted the hysteresis cycle. Furthermore, its uses can be extended to complex geometries introducing a milling stage after the melt-spinning process, obtaining refined elemental powder particles (Nowacki, 2006; Byoung et al., 2007), which its dimensions can be modified by the control of the milling stage time (Dobrzanskia et al, 2004). The connotations of using soft magnetic alloys affect not only transformer cores but also AC motors (Pagnola et al., 2009; Pagnola, 2009). These new amorphous and nano-crystalized materials are currently sold up to 3 times the price of conventional materials (Condes, 2008).

Magnetic cores lose energy through two independent mechanisms: hysteresis (dissipated energy during the re-orientation cycle of magnetic domains) and Foucault current (eddy or parasitic current). These losses can rise up to 5% and 15% of the entire produced energy, which fluctuates over the manufacturing technique employed. Own research and other authors confirm that these losses can be reduced almost 80 % from those that appear in

devices built with traditional steel (De Cristofaro, 1998; Douglas, 1988; Richardson, 1990). In table 1 and figure 1, it can be seen how much smaller these losses are, and what is more important the amount of energy saved. The LSA implemented Melt-Spinning technique through the project called “Advanced technology magnetic materials production” (PICT-2007-02018), and it aims reducing energy losses to the values given. Amorphous ribbons, similar to FINEMET®, were obtained by preliminary tests, these ribbons were 1mm wide and 20µm thick, and they were quenched straight up on the copper wheel in an air atmosphere, reaching a 10⁶ K/sec cooling rate (Muraca et al., 2009).

Power [kVA]	Core Losses [W]		Saving percentage [%]	Manufacturer
	Fe - Si	Amorphous		
10	40	13,5	66	Osaka Transformer
10	40	11	72	Westinghouse
15	50	14	72	Allied and MIT
25	85	28	67	General Electric
25	85	16	81	Prototype Allied

Table 1. Core losses in regular Fe-Si cores and Amorphous alloys cores refer to Fe-Si (100%).

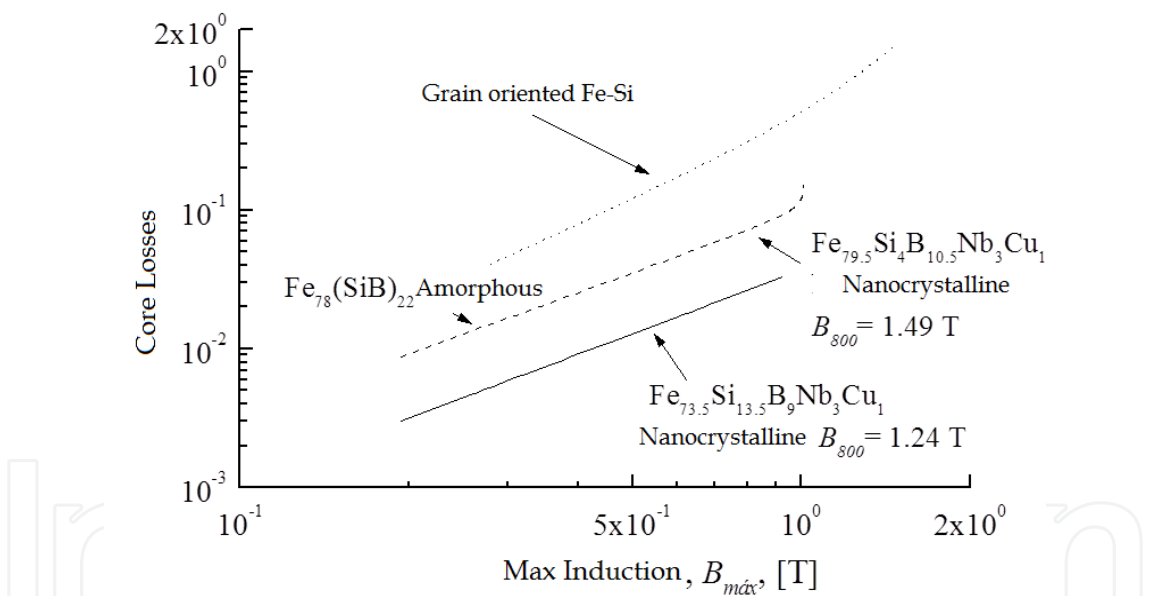


Fig. 1. Core losses with different alloys (Dobrzanskia et al., 2004).

2. Melt-spinning

One of the most common rapid quenching techniques to produce amorphous metals is the one called melt-spinning. Using this technique, the molten alloy is jetted on the surface of a high speed spinning copper wheel through a nozzle. The casting wheel acts as a heat sink reaching one million degrees per second cooling rate (Praisner et al., 1995) necessary to achieve the vitreous phase instead of a crystalline structure (see figure 2). In figure 3 it is shown a diagram of the melt-spinning apparatus, where it can be seen the small and weak linkage between the ribbon and the casting wheel.

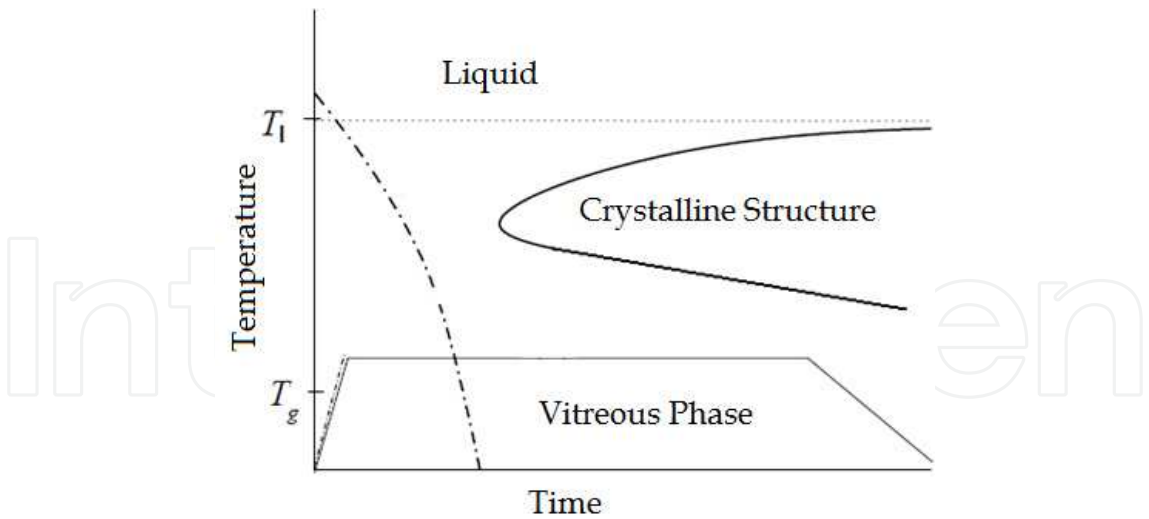


Fig. 2. Cooling procedure to avoid crystalline structure. (Moya, 2009).

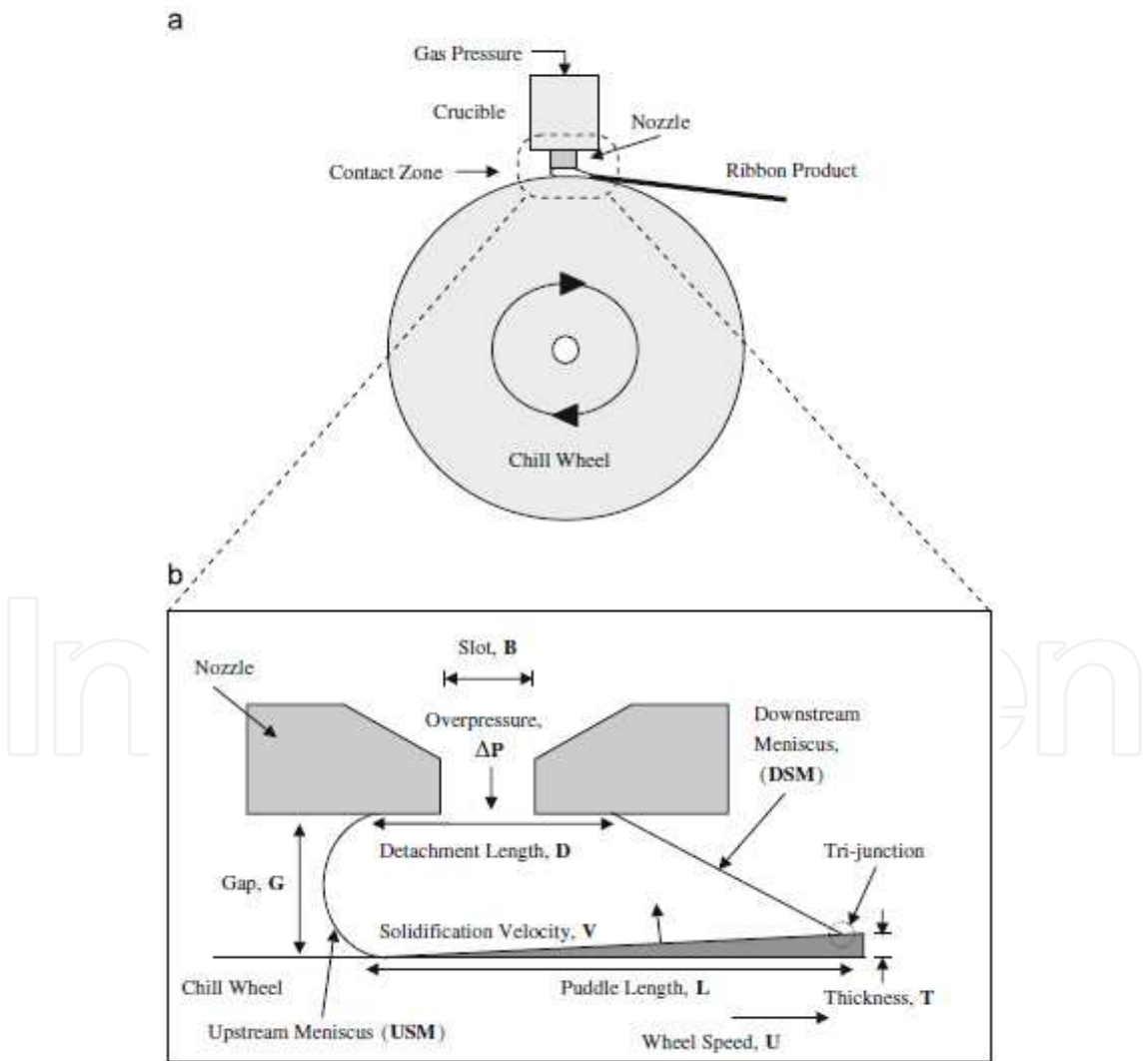


Fig. 3. (a) Schematic of a melt-spinning apparatus, (b) Blow up of the contact zone. (Theisen et al., 2010).

The amorphous alloy is obtained from a crystalline alloy, called mother alloy, which has the same chemical composition as the amorphous one. The way to get to the mother alloy is melting the proper quantity of the different components into an induction heater several times in order to insure a homogeneous alloy. Afterwards, the alloy is introduced into a quartz crucible with an induction coil which heats the alloy over the melting point; then, an argon over-pressure expulses the alloy through the nozzle on the high speed spinning wheel. As a result, a continuous amorphous ribbon is obtained; its thickness ($\approx 20 - 100 \mu\text{m}$) is a function of the injection pressure, the gap between the nozzle and the wheel and the cooling rate. Depending on the alloy and its corrosion susceptibility, the process should be in a controlled atmosphere, in a vacuum chamber or even in environmental conditions.

3. Winding system

The winding mechanism designed is capable of working at high winding speeds (an order of magnitude higher than those used in paper winding and steel-making, see table 2), it also insures the quality of the product as it's has been solidified at the wheel without changing its surface roughness generated in the previous stage, since any aspect that has influence on its surface integrity during this stage has a direct impact on the magnetic package's performance. This winding system is assembled next to the cylindrical sleeve by the casting wheel seen in Figure 4.

Two problems hold the design back at the first stage of the process:

1. Thread of the strip into the winding reel.
2. Tension control of the roll.

Both of these issues mainly appear because of the intrinsic characteristics of the melt-spinning technique. Due to the speed of the process and the fact that the strip has no fixed point at the casting wheel the solutions given are rarely similar to those found in regular winding machines. First of all, an automatic threading system was designed due to the impossibility to count on the proper time to thread the strip into the winding reel by a human (~ 5 to 10 seconds). This time implies an excessive collection of material (250 to 500m) by the casting wheel that can be wrecked by its own weight or successive folding.

With regard of the tension control, it's critical not only because of the typical problems in every wound roll, but also because an over-tension can separate the strip from the casting wheel where the material is still in a liquid state. Therefore, two zones were established in the machine, a free-tension zone and another one where it is controlled up to a set-point determined by the tension profile.

Figure 5 and 6 shows the proposed design, where it can be seen a set of guiding belts (1), that generate an air flow capable of dragging the strip from the casting wheel up to the pinch rollers (2). These rollers are powered by an asynchronous motor and variable frequency drive, where the strip purely rolls over them; the control of their speed and the winding velocity of the reel are the manipulated variables of the tension control system. Between the guiding belts and the pinch rollers, there are a set of idle rollers (8 & 9), which provide the system a stock of material in order to prevent an unwanted detachment of it at the solidification meniscus. Next to the pinch rollers there is a deflector (4) that simply

guides the strip towards the winding reel (5). At last, the winding reel is surrounded by a wrapping belt that ensures the thread of the strip into the reel during the startup.

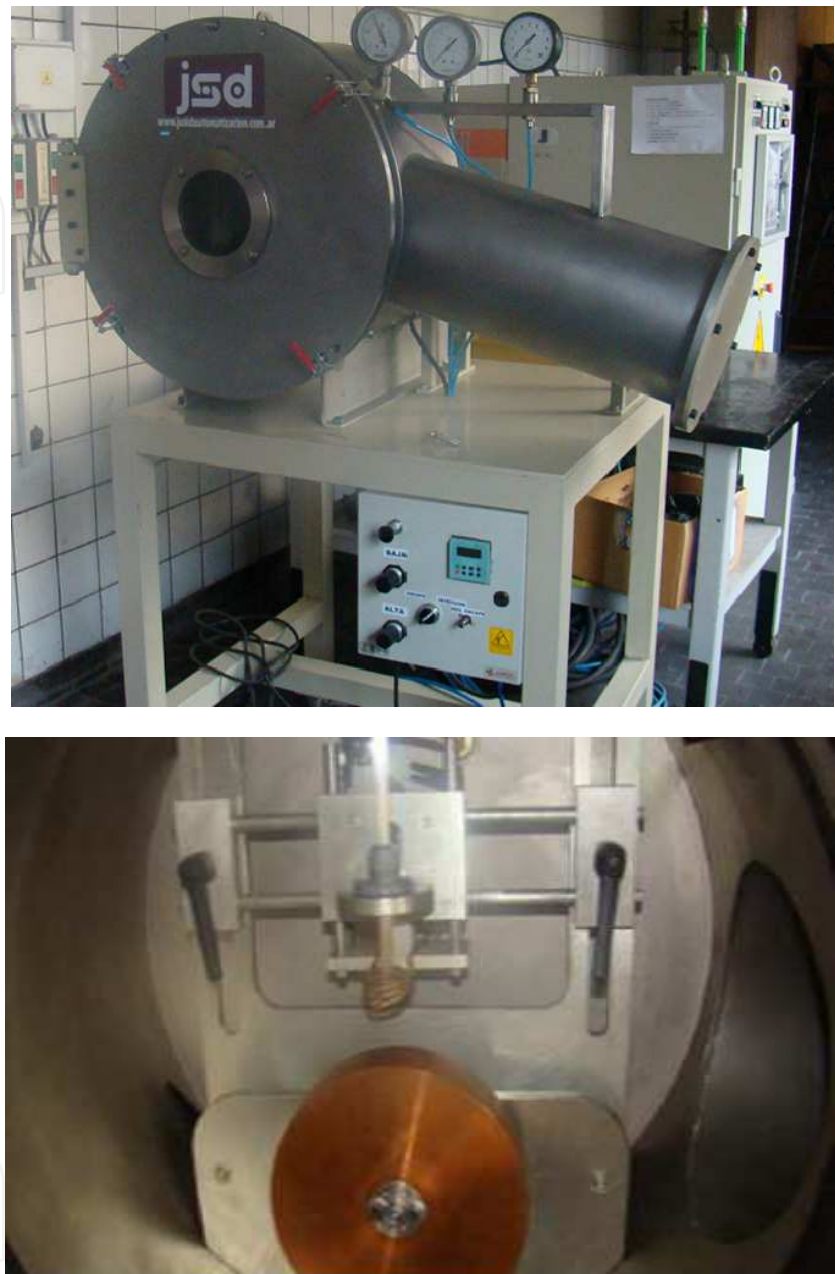


Fig. 4. Melt-spinning Equipment developed at LSA. Crucible and copper wheel.

Material	Winding Speed [m/s]	Winding Tension [Mpa]	Source
Paper	≈ 8	< 10	Liu, 2009
Steel	≈ 8	15 - 75	Liu, 2009
Plastic Films	≈ 15	< 4	Lee et al., 2002
Magnetic Tape	< 5	< 4	Liu, 2009
Amorphous strip	25 - 50	15 - 30	Own development

Table 2. State of the art - Winding parameters found in different industries.

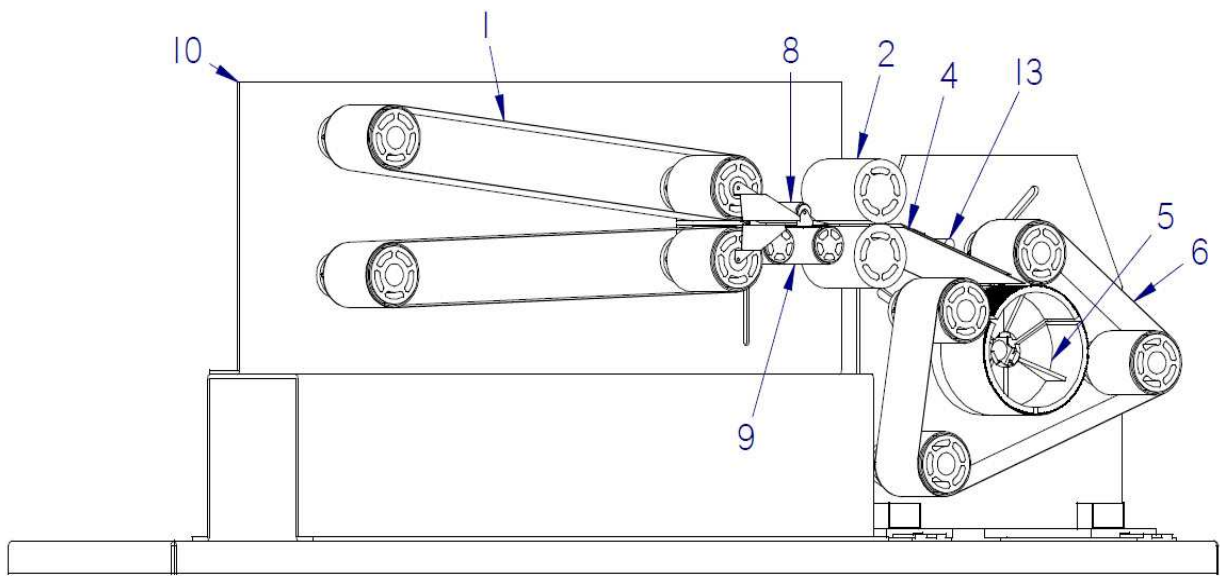


Fig. 5. Winding machine at startup: 1. Guiding belts; 2. Pinch rollers; 3. Initial deflector; 4. Main deflector; 5. Winding reel; 6. Wrapping belts; 7. Crossslide; 8. Stocking system - dancer roller; 9. Stocking system - Fixed roller; 10. Chassis; 11. Main motor; 12. Slide guides; 13. Tension sensor.

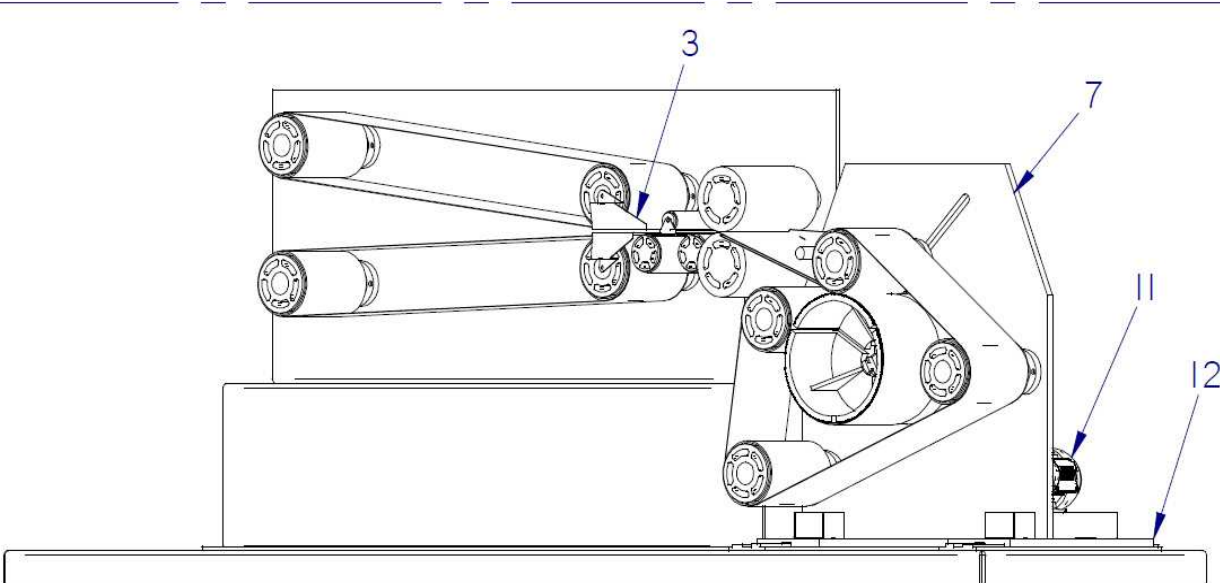


Fig. 6. Winding machine at startup.

3.1 Winding tension profile

Several winding stress models have been developed in order to find the proper winding tension profile (Li et al., 2009; Liu, 2009; Lee et al., 2002). Following the model proposed by Liu, every new wound lap is considered a collection of concentric laps of web material. In every one of them it is formulated the differential equations of internal equilibrium to find out stress, strain, displacement and pressures developed during the winding. Finally, the profiles shown in figure 7 were obtained.

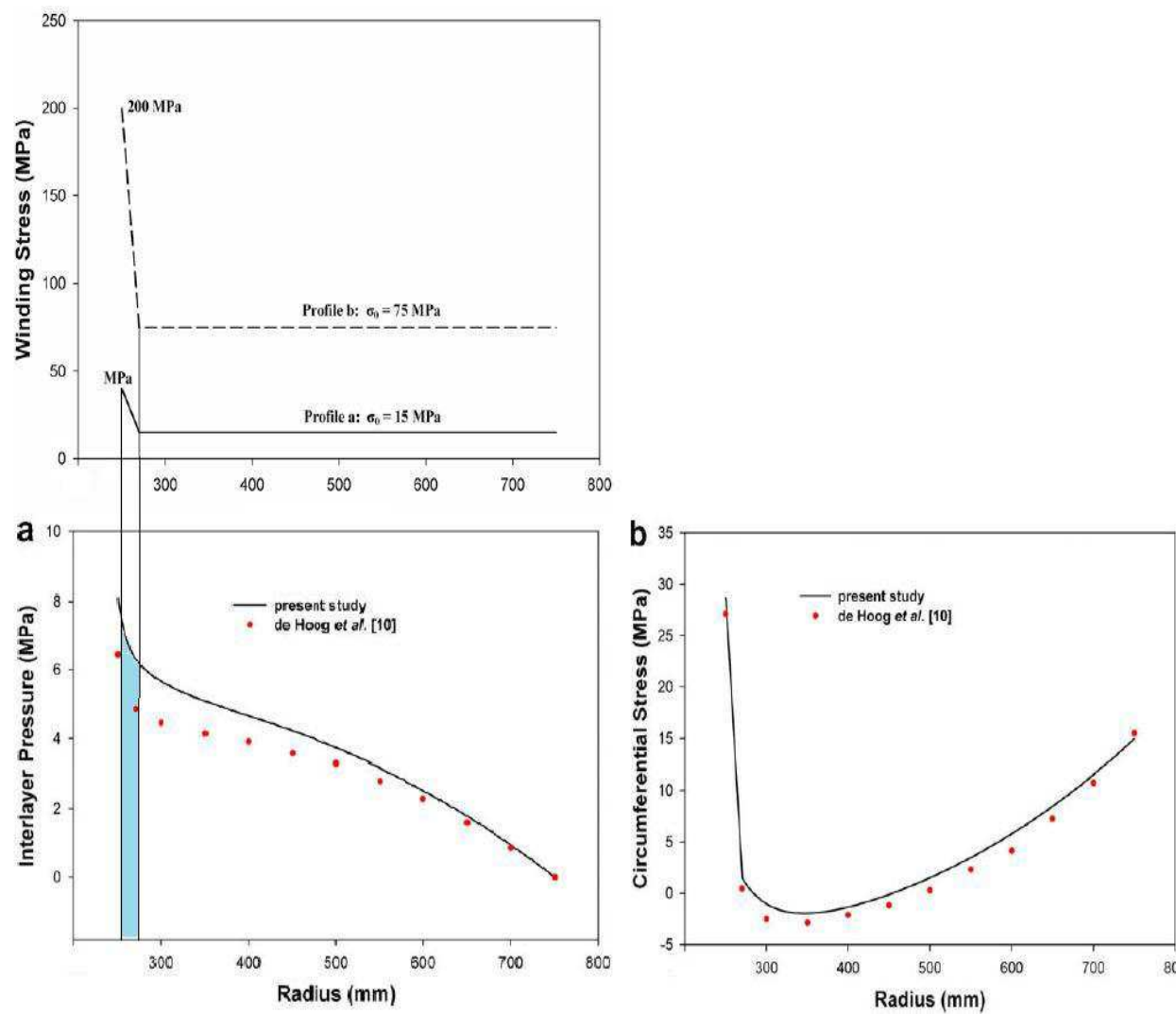


Fig. 7. Interlayer pressure (a) and circumferential stress (b) for the winding stress profile in the above figure (Liu, 2009).

As it can be seen, the winding stress profile starts at a higher value and then it starts decreasing through a ramp towards the regime value. During this ramp the roll is setting up its linkage with the winding reel, which will determine the end of the startup stage and the beginning of the working regime stage. To insure that the threading is complete the friction force generated by the internal pressure times the surface of every wound lap must be higher than the inertial force plus the winding tension. From now on, the roll is fixed to the winding reel and no slip between them will be found.

$$\mu_s \cdot \int_{r_o}^{r'} (p_i \cdot S) \cdot dr = F_{friction} > F_{inertia} + T_{winding} \tag{1}$$

Once established the tension profile, it can be calculated the power necessary for the winding reel motor and for the pinch rollers motor. On one hand, the winding reel motor

(main motor) is going to take most of the torque necessary for the winding, on the other hand the pinch rollers motor will be working almost as a brake because upstream it is a free-tension zone and downstream the tension is provided by the main motor. This is why the power of the main motor is considered to take this torque times a service factor to make up for the startup situation. Taking into account these considerations and the dimensions of the strip and the reel, it is needed a 5HP AC motor for the winding reel.

3.2 Startup

When the casting wheel starts throwing the first cuts of amorphous strip, the guiding belts (1) drag it towards the pinch rollers (2) where a first thread is done. At this point, it's the first contact with the winding machine and it is found pure rolling friction between the strip and the pinch rollers, where these jog the strip forward with its own tangential speed. As a consequence, it is needed a high precision in the mounting of this rollers in order to preserve the clearance between them; if it is bigger than the designed one the strip would slip between them. But if it is smaller, the material would be damage by an operation similar to a laminate. Due to the constant contact between the strip and these rollers, it is recommended to pay close attention to the hardness during the material selection of the rollers in order not to damage the surface quality of the strip; several options appear like copper, brass or even PTFE (TEFLON®) inserts. Next to the pinch rollers (2) the strip is guided towards the winding reel (5) by the main deflector (4). The winding reel is spinning to a higher tangential speed than the speed of the strip in order to ensure the threaded. Additionally, the reel is surrounded by a wrapping belt (6) which guarantees the strip to follow the profile of the reel until there is enough friction between the successive wounds of strip, so to create a bond within the reel and the strip, but this won't happen until several wounds of ribbon had already been rolled over the reel.

3.3 Working regime

Once insured the threaded, the wrapping belts are completely removed, as can be seen in Figure 8, to look after the surface integrity of the strip. This action is performed by a pneumatic actuated scissor mechanism. Meanwhile, the spinning speed of the reel is reduced because during the threaded it was significantly higher; also, from this moment on, the dancer roller (8) can freely move in the vertical axis, and the tension sensor (13) is disposed as it is shown in Figure 8. From now on, the winder is at a working regime and we must proceed to the tension control of the roll.

The basic principle of the tension control is the small difference between the pinch roller's speed and winding speed (represented by the tangential speed of the reel) which is slightly higher (He et al., 2010). The structure of the device for controlling the tension is shown in Figure 10. The tension measurement is used to tune up the spinning speed of the reel, by an asynchronous motor, variable frequency drive and encoder. The control set point establishes a tighter roll at the beginning and looser at the end, known as taper tension control (Good et al., 2008). With this system it is intended to obtain an optimum tension of the roll without inflicting any damage to the material.

A storage system is incorporated in order to prevent flaws on the tension control system, such as response time, slipping of the strip on the pinch rollers, lack of precision on electric

and electronic components. Every difference between the pinch rollers and the casting wheel speed, overcomes into an over-tension of the strip or an excessive storage of material, which may cause a possible detachment of the solidification meniscus.

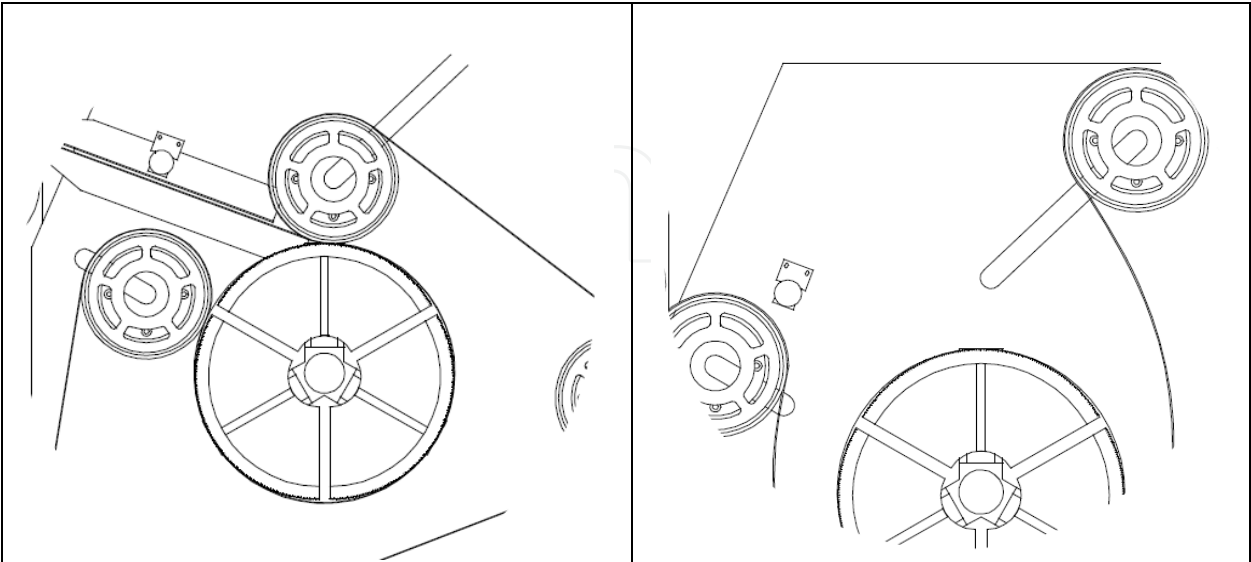


Fig. 8. Wrapping belts and tension sensor at startup condition (3.1) in working regime (3.2).

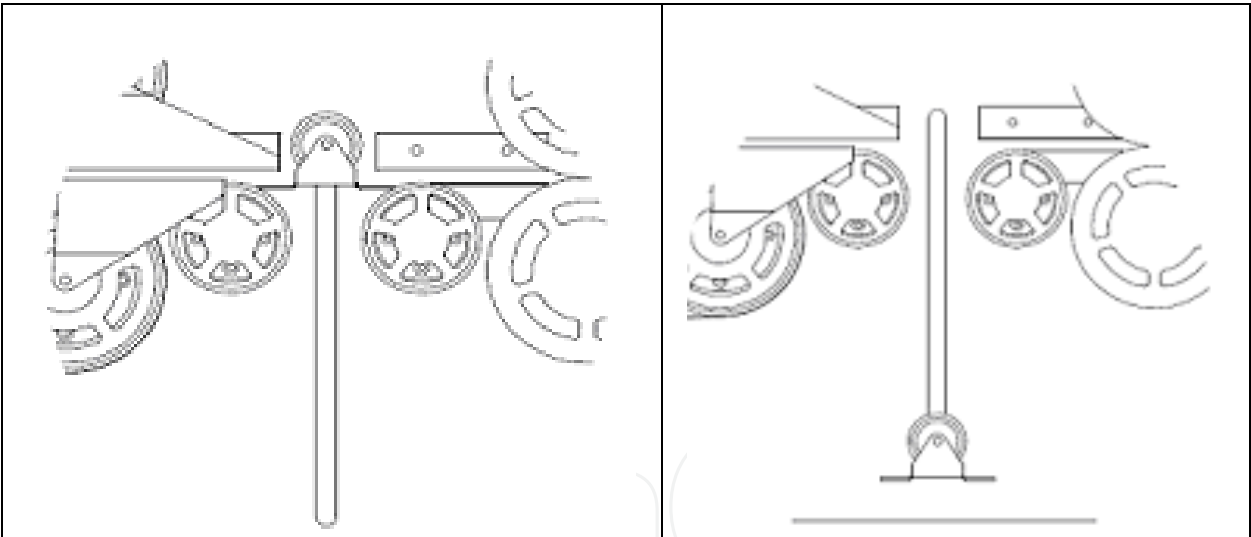


Fig. 9. Stocking system at startup and during the working regime.

The mechanism is composed by 3 idle rollers (Figure 9), two of them (9) are fixed, while the centered one (8) can move along the vertical axis forcing the strip to take a larger profile instead of the straight line from the startup. Sensing the position of this roller, it is tuned up the pinch rollers speed, only when the stock is excessive or insufficient. So, this variation will be considered as a transitory regime for the tension control system, in order to assume the pinch rollers’ speed as a constant. With this system a little stock of ribbon is created in order to absorb every produced over-tension.

The winding reel (5) is provided with a mandrel for a quick demounting of the finished roll. Moreover, the reel along with the wrapping belt is mounted on a cross slide (7) which can be

moved over the sliding guides (12) in a cross direction, as can be seen in Figure 5 and 6. With this system several angular defects during the tuned-up before the startup of the equipment are corrected.

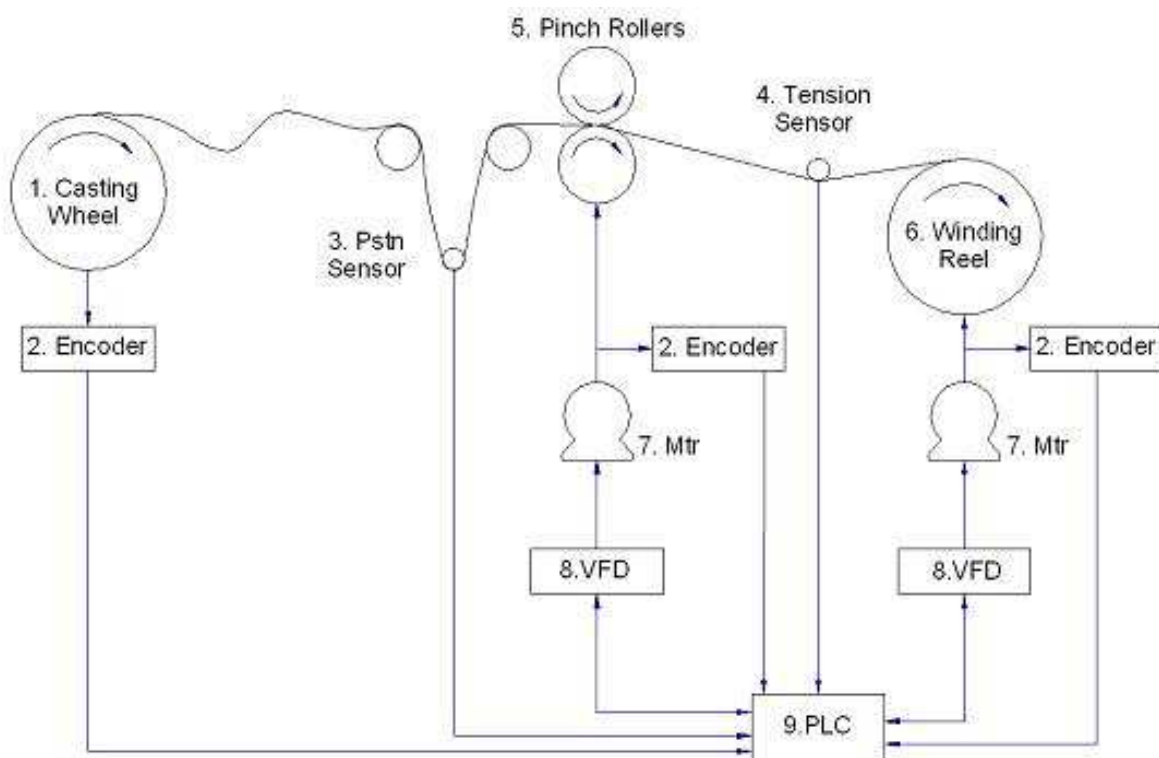


Fig. 10. Control System Structure: 1. Casting Wheel; 2. Encoder; 3. Position Sensor; 4. Tension Sensor; 5. Pinch Rollers; 6. Winding Reel; 7. Asynchronous Motor; 8. Variable Frequency Drive; 9. PLC.

4. Results and discussion

The initial investment and operating cost for the 25-30 lifetime-years of the transformer will be called Total Cost of Ownership. Within the Operating Cost of the device is included the cost of the dissipated electric energy at the windings (Cu) and at the core (Fe). Consequently, had the core losses been diminished (by using amorphous metal cores), the Total Cost of Ownership of a device produced by this technology would be reduced in comparison to those produced by traditional technology; and would profit a considerable economic gain to the owner of this machine. From this point of view, the implementation of an accurate winding system as the one proposed, presents an optimum solution to the formerly described process, not only to behoove the handling of the final product, but also to simplify the post-melt spinning heat treatments, such as isothermic annealing which is used to obtain nano-crystalized ribbons (Muraca . et al. 2009).

An accurate control of the material and design of the nozzle's orifices (Saito, 2010; Kurokawa, et al. 1999), working pressures of the chamber and ejection temperature are

crucial to prevent unwanted flaws (Saito, 2010; Marashi et al 2009) which include the absence of the formation of the strip on the casting wheel as can be seen in Figure 11. For this reason it is highly recommended to ensure the working conditions described along this article.



(a)



(b)

Fig. 11. (a) Ejection of molten material on the wheel in a non-operational regime, (b) Ejection of molten material on the wheel in a operational regime; both photos on its own equipment in LSA.

5. Conclusion

It is proposed in this paper the design of a winding mechanism for amorphous strips used in magnetic transformer’s cores, its general dimensions are specified in the drawing in Figure 12, and it’s assemble with the personally designed equipment is completely possible.

The components and parts designs are based on our own experience in building these equipments and on our investigations on the production of micro and nano-materials (Ozols et al., 1999; Pagnola, 2009; Muraca et al., 2009), as well as other author’s technical considerations in the fabrication of different products for industrial magnetic packages as shown in Figure N. 13. (Croat, 1992; Kurokawa, et al. 1999) were considered.

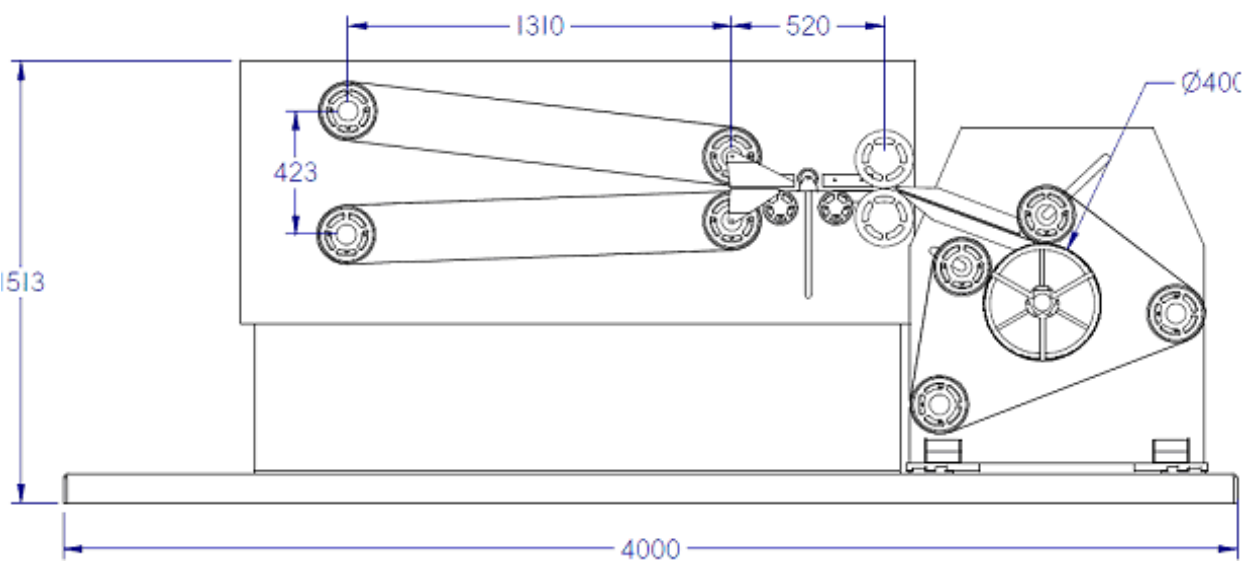


Fig. 12. General drawing of mechanical parts.



Fig. 13. $\text{Fe}_{78}\text{Si}_{13}\text{B}_9$ amorphous strips used in magnetic cores, and industrial magnetic package.

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