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Innovative SMC Insulation Technique Applied to Axial Flux Machine Prototypes

Emir Pošković, Federico Carosio, Fausto Franchini, Luca Ferraris

Abstract – **The paper describes in detail the realization of an axial flux machine prototype adopting an innovative Soft Magnetic Composite (SMC) material. The novel technique here presented regards a Layer-by-Layer deposition adopted to insulate pure iron powder grains previously selected. The obtained material is then used to prepare the machine's stator parts. The activity steps are detailed: from the powder preparation to the molding phase, the consequent milling for the final shape, and the consequent magnetic, energetic and mechanical characterization. The prototype design and assembly imply the realization of the stator with the adopted innovative material, and the Authors also realized the preparation of the rotor equipped with bonded magnets. The preliminary experimental results are presented at the end, and considering the machine to be the first trial with the presented material, the efficiency of 77% should be viewed as a promising result for the future development of the activity.**

Index Terms-- Axial flux machines, Bonded magnets, Insulating process, Magnetic characterization, Soft Magnetic Composites (SMC)

I. INTRODUCTION

THE paper describes the activity related to the realization of an axial flux machine whose stator is made with a Soft Magnetic Composite (SMC) material [1-3]. Nowadays, SMC is a viable alternative to ferromagnetic sheets for the realization of magnetic circuits or part of electrical machines [4-9], particularly when the proposed shapes become complicated to be traditionally realized [10].

The novelty presented in the paper lies in the innovative procedure adopted to insulate the magnetic grains of the iron powder with a layer-by-layer deposition which allows for obtaining a very thin layer in the order of nano-meters [11]. The material's preparation is described in detail in the paper, starting from the coating formulation, the magnetic iron powder selection and the deposition process.

The obtained insulated material is then adopted to realize the stator of an axial flux machine (Fig. 1), whose particular shape represents a significant example where SMC materials can replace laminated steels [12].

Recently axial flux machines have become very popular for several advantages they offer with respect to "traditional" motors [13-15]; one of the most significant is the high efficiency achieved by these machines [16], [17]. Such behavior is complemented by a very compact machine with a high power density, that is to say, a convenient weight/volume ratio [18]. Moreover, the motor shape allows a facilitated installation in a wide range of applications: automotive [19-23], aerospace [24], household [25], biomedical, etc. [26-29].

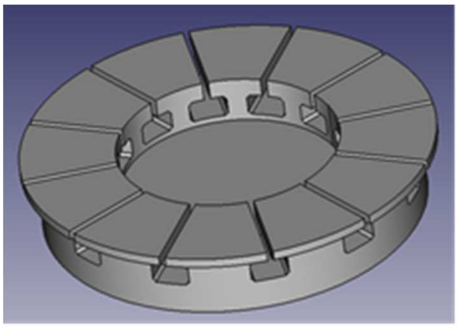

Fig. 1. Stator of an axial flux machine

On the other hand, some drawbacks afflict these machines [30]. The first consists of high axial force produced when strong permanent magnets are adopted [31]. This force produces mechanical unbalance and instability, mainly in the single rotor/single stator stage [32]. A possible alternative solution consists in the use of multistage arrangements, such as double rotors, double stators, etc. [33], [34]. However, the same axial force requires the use of particular bearings, more expensive than those used in radial flux machines. Also, obtaining a thin air gap is more challenging.

Other disadvantages concern the production process: it is possible to realize stator cores with laminated steel, but it necessitates a complicated punching process. Such a process is more expensive, and the tools wear and tear faster than a traditional punching process. Furthermore, the use of electrical sheets with the conventional process is not possible due to significant leakage fluxes that would be present. Other techniques, for example, laser cutting, are still under investigation [35], [36]. For these reasons, a viable alternative solution is represented by the use of SMC materials [37]. The stator core and pole expansions prepared by SMCs permit to conduct the magnetic flux easier than the same components designed with laminated steels. Furthermore, some parts are impossible to produce with electrical sheets.

Axial flux rotors are generally equipped with ferrites, NdFeB bonded magnets, or NdFeB sintered magnets. In general, particular shapes are not required, but to reduce the cogging torque, specific arrangements can be implemented favouring the use of bonded magnets [38].

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II. MATERIALS DEVELOPMENT AND PREPARATION

SMC materials are composed of ferromagnetic powder where every ferromagnetic grain is electrically insulated with a material that should be organic or inorganic [39], [40]. Producing these materials means adopting particular binders to provide the required mechanical robustness to mix the compound, which will be compacted and heat treated.

The choice and selection of the materials are described in the present Section.

A. Layer formulation

The LbL deposition was performed in order to deposit a multilayered nanostructured and insulating coating on each particle [11]. The coating composition comprised organic polyelectrolytes bearing either positive or negative charge and anionic inorganic nanoplatelets. The selected components were employed to produce positively or negatively charged solutions/suspensions baths to be employed for the LbL deposition. In a typical deposition procedure, the metal powder of choice is alternatively exposed to the positive and negative bath in order to allow for the adsorption of the selected components. This produces a nanostructured coating comprising multiple layers held together by electrostatic interactions. After each deposition step, the particles were washed with deionized water. Centrifugal forces were employed to separate the particles from the deposition/washing baths. The procedure is repeated until the desired number of deposited layers is achieved (Fig. 2). At the end of the procedure, the coated powders were dried in a vacuum oven at 80°C.

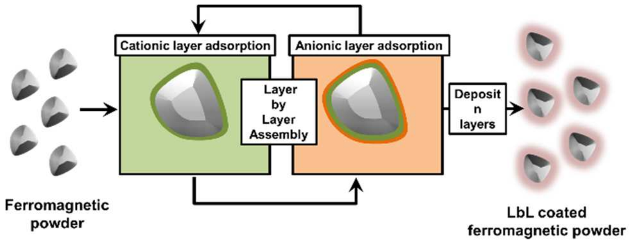

Fig. 2 Schematization of the adopted LbL deposition procedure

The LbL deposition is unique in that the layer constituents can be selected from a wide range of chemicals such as natural and synthetic polyelectrolytes as well as nanoparticles with different shapes and compositions. In addition, the deposition procedure is also controlled by parameters such as solution/suspension concentration, pH, ionic strength and temperature. This opens up to tunable coating compositions and thicknesses, allowing targeting the deposition of multilayers bearing multifunctional properties. For example, the proposed approach could potentially allow to coat each particle with a nanostructured coating, providing electrical insulation and conferring additional features like improved mechanical properties and the possibility for high-temperature post-treatments [11].

B. Ferromagnetic powder formulation

The selection of the ferromagnetic powder has a fundamental importance in obtaining the expected results, and there is no unique way to choose it, as the final application requirements must be considered [41]. Electrical machines or parts of electrical machines, chokes, and parts of magnetic circuits are possible examples of SMC adoption. Together with the operating frequency range [42], [43], the proper ferromagnetic powder must be selected to comply with the specific requirements.

A large variety of ferromagnetic powders, together with different grain dimensions, has been evaluated to get the composition most suitable for the intended purposes. Particular importance is addressed to the final density of the compacted material, the coercivity at low frequency, and the maximum permeability.

Several powder typologies have been considered:

- high purity iron with a spongy form (Fig. 3)
- iron and silicon alloy with a spherical shape (Fig. 4)
- a mix of the previous materials
- high purity iron with morphology modified with mechanical processes (lamellar, pseudospheric)

Fig. 3 and Fig. 4 show two different morphologies that have been evaluated for the final selection of the material to be adopted in the present case.

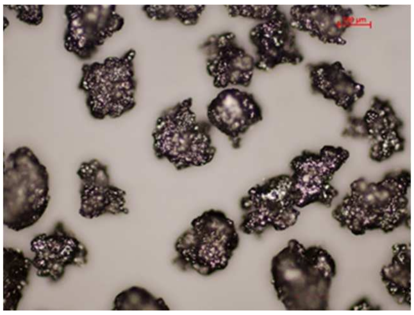

Fig. 3. Iron with spongy form

Fig. 4. Iron and silicon alloy with a spherical shape

The preliminary phase of characterization brought to select the high purity iron, as it resulted the best for the low coercive field H_c (due to the purity and the absence of mechanical treatments) and high final density of the compacted material. Furthermore, the spongy form that commonly causes the formation of excessive accumulation of binder in the dust inlets is compatible thanks to the thinness of the adopted insulating process and material, making it possible to exploit the high compressibility due to its morphology without penalizing magnetic and mechanical properties.

III. MATERIALS CHARACTERIZATION

The magnetic and energetic characterization of the powder represents a crucial point as it allows to verify the compliance of the powder to the technical specifications required by the application.

It is not possible to characterize the powder by itself, but it is necessary to realize devoted specimens as described in the following sections. In particular, the more accurate magnetic characterization tests involve the use of toroidal-shaped samples, while the preliminary tests, characterized by a lower degree of precision but still such as to ensure complete reliability and repeatability, use samples in the form of thin parallelepipeds [44].

The manufacturing phases of the toroidal samples can be summarized as follows:

- compression of the powder in the mold
- heat treatment at 150 ° C
- milling of the solid disk to create the desired shape
- realization of the excitation and measurement windings

A. Powder compaction in the mold

The powder compaction is obtained by means of a 200 tons press (Fig. 5) available in the Authors' laboratories: the powder is placed in the mold chamber, and a cylindrical specimen is obtained (Fig. 6).

Fig. 5. 200 tons press adopted to realize the specimens

Fig. 6. Powder deposition in the mold and cylindrical sample

B. Heat treatment

The selected mixture contains a small percentage of a thermosetting resin, which has required a crosslinking heat treatment in order to give the finished piece the desired mechanical properties. The heat treatment consisted in placing the specimens at 150 °C in an oven (Fig. 7) in the air for 6 and a half hours.

Fig. 7. Specimens of heat treatment in the oven

C. Milling to the desired shape

In order to obtain the toroidal sample, the pressed and heat-treated specimens are worked with a numerical control milling machine (Fig. 8), getting the sample shown in Fig. 9.

Fig. 8. Milling machine operation to shape the specimens in toroidal form

Fig. 9. Toroidal specimens after milling

D. Excitation and pick-up coils

The device to be characterized will, in effect, be an electromagnetic transformer, and therefore it is necessary to provide an excitation winding and a winding to measure the magnetic flux on the toroidal magnetic circuit, as described in the standards IEC 60404-6 and IEC 60404-4. Usually, the Epstein frame is the most common method applied to electrical steel sheets; this test methodology can be performed for various values of frequency, but for high-frequency applications, the toroidal magnetic tests are preferable. And also, the Epstein frame cannot be used for SMCs because the standard sizes of the equipment, the particular dimensions, and shapes are complicated to be prepared with the powder metallurgy technology. The final sample is depicted in Fig. 10 and is ready to be characterized.

Fig. 10. Toroidal specimens with the windings required for testing

E. Magnetic and energetic preliminary characterization

A preliminary evaluation of the properties of the material can be performed with samples in the form of thin parallelepipeds, much simpler to produce by pressing in a particular rectangular mold is sufficient (Fig. 11). The obtained specimens are used in the single sheet tester (SST) method, which permits magnetic characterization both for laminated steel and SMC materials. The samples thus obtained can be directly tested with the device depicted in Fig. 12, in which the specimen constitutes the closure of the magnetic circuit necessary for the measurements. This device allows a rapid characterization, with reliable results from the point of view of the classification of materials [44]. Based on the experience gained and the results obtained, threshold values were defined, exceeding which resulted in the execution of tests on toroidal samples, characterized by longer and more expensive preparation.

Fig. 11. Sample in the form of a parallelepiped for Single Sheet Test

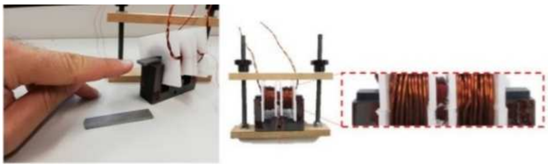

Fig. 12. Single sheet tester for preliminary quick magnetic characterization

F. *Complete characterization of the selected material*

Both types of samples produced are characterized by the same measurement system, refined ad hoc for the needs of the work. This system allows the generation of any periodic waveforms by checking, deleting or adding appropriate harmonics. In particular, it is possible to obtain perfectly sinusoidal waveforms (with the harmonic distortion factor of less than 1%) in a frequency range from 0.2 Hz up to a few kHz, which allows a complete magnetic characterization.

The hysteresis cycles, the B (H) characteristic, the trend of material losses, and their breakdown into the different contributions are detected; all of this is repeated for all frequencies allowing a highly detailed analysis of the magnetic and energetic behavior of the material.

Fig. 13 shows an example of a synthetic representation of the results that can be obtained by means of the implemented measurement system.

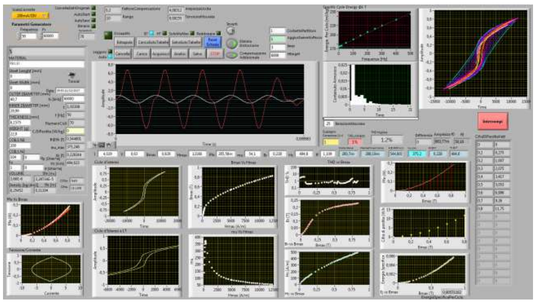

Fig. 13. Measurement system

The obtained results are compared with those of a commercial Insulated Iron Powder Compounds (I.I.P.C.) taken as reference and the most widespread on the market.

In the following Fig. 14 ÷ Fig. 18, the graphs of the complete characterization of the material are presented as a function of the frequency: magnetization curve B(H), relative magnetic permeability, specific losses, and hysteresis cycles. The results show lower specific iron losses compared to reference SMC materials, as reported in Fig. 17, only the magnetic permeability is worse than the more popular commercial product, as shown in Fig. 15.

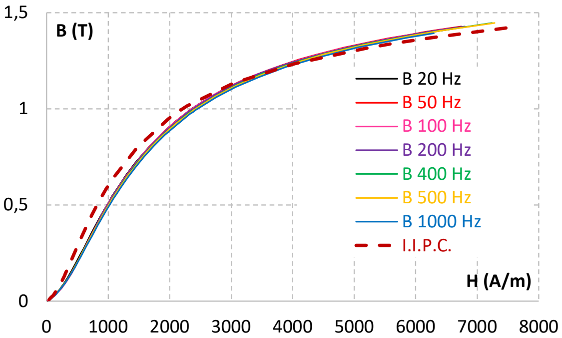

Fig. 14. Magnetization curves at different frequencies and compared to the most widespread SMC on the market

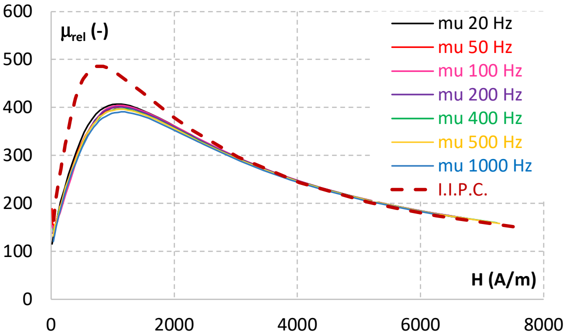

Fig. 15. Magnetic permeability of the selected material and compared to the most widespread SMC on the market

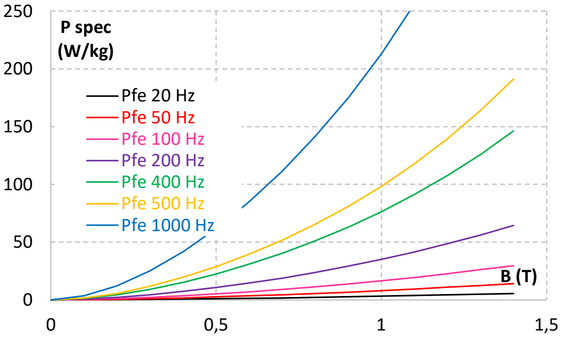

Fig. 16. Specific losses of the selected material

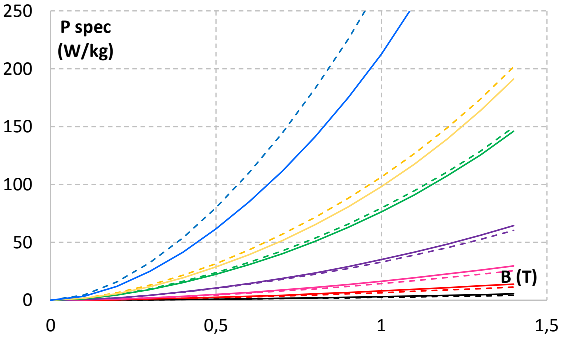

Fig. 17. Specific losses of the selected material compared to reference SMC material available on the market

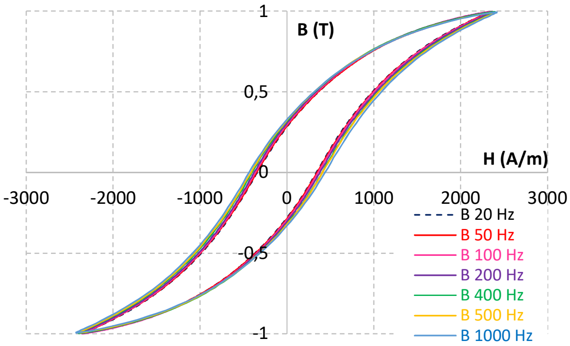

Fig. 18. Hysteresis cycles of the selected material

G. *Mechanical characterization*

The verification of the mechanical resistance of the material passes through the realization of specific specimens and their characterization by means of a transverse rupture strength, or TRS, which consists in subjecting the specimen to a gradually increasing stress, measuring the value of load for which the specimen breaks. The characterization system is shown in Fig. 19. The tested materials have reached a TRS average value greater than 100 MPa.

Fig. 19. Transversal break test device (TRS)

IV. PROTOTYPE REALIZATION AND TESTING

A. *Prototype realization*

The analytical model of the machine has been developed in Matlab environment, considering as fixed constraints the torque, the speed and the bus voltage. More detailed information related to the model is reported in previous work [32].

The resulting design data of the machine are reported in Table I.

TABLE I - DESIGN DATA OF THE MACHINE

Number of pole pairs	4
Number of slots	12
Stack length	19.5 mm
Stator outer diameter	105 mm
Stator inner diameter	59.85 mm
Rotor outer diameter	105 mm
Rotor inner diameter	59.85 mm
Airgap	0.7 mm
Bus Voltage	14 V
Rated speed	2000 RPM
Rated current	12 A
Rated torque	0.74 Nm

Once the selected material has been completely characterized, it is possible to proceed to the realization of the prototype obtained by making 12 blocks and their subsequent milling. Fig. 20 illustrates some of the construction phases of the prototype: from the processing of the blocks obtained with the mold, to the combination of the first semi-finished products, up to the milling of the parts to obtain the structures of the "teeth" of the stator around which to realize the relative windings.

In Fig. 21, a phase of preparation of the rotor prototype is shown, with the specially made bonded magnets, while in Fig. 22, the complete prototype is visible.

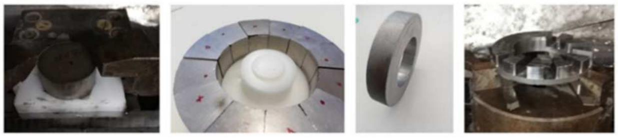

Fig. 20. Stator prototype realization

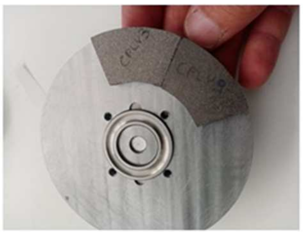

Fig. 21. Prototype rotor realization

Fig. 22. Prototype realization

B. *Prototype testing*

The assembled prototype has then been tested on a dedicated test bench (Fig. 23), designed and realized for the project purpose, where a Pasqualini/eddy-current brake allows for varying the resistant torque in a wide range and with small steps. The torque is measured with a 2 Nm torquemeter, while the motor is supplied and controlled by means of a sensorless, field-oriented control type inverter which varies the supply conditions to reach the desired imposed speed.

Fig. 23. Experimental setup for the prototype characterization

The data collected during the tests have been analyzed and organized; in Fig. 24, the torque values are reported as a function of the absorbed stator current. The linear correspondence is evident and allows for to calculate the torque constant of the machine.

The torque-speed plane has been deeply explored, detecting mechanical and electrical quantities, and obtaining a map of the efficiency, as reported in Fig. 25 and Fig. 26.

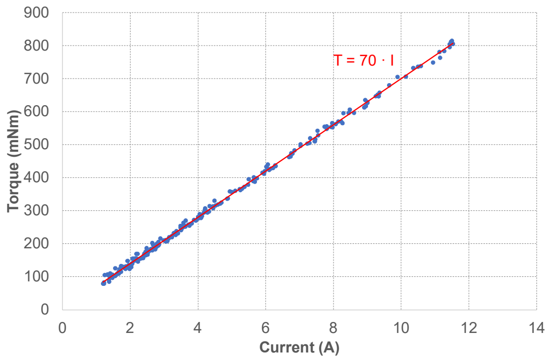

Fig. 24. Torque as a function of the current

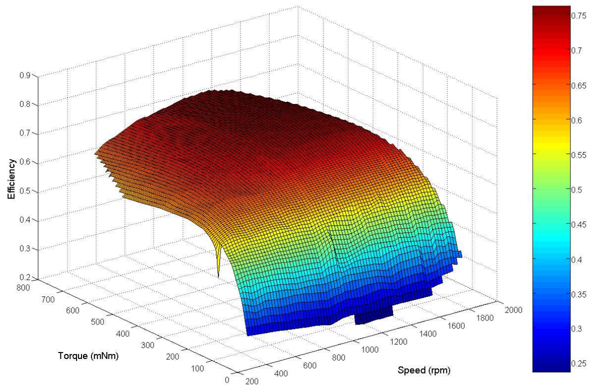

Fig. 25. 3D efficiency map of the prototype under test

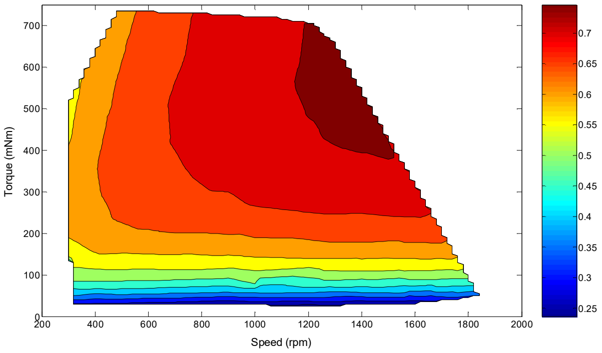

Fig. 26. 2D efficiency map of the prototype under test

V. CONCLUSIONS

The huge experimental activity reported in the paper represents a first application case of the Layer-by-Layer insulation technology that the Authors have patented.

The case presented and discussed in detail is an innovative SMC material adopted to realize the magnetic circuit of a fractional axial flux machine.

The characteristics of the materials are considered more than satisfactory from different points of view: the magnetic properties, in terms of maximum permeability, should still be improved but represents a good starting point, while the energetic behavior, explored in a wide frequency range, is excellent (specific losses at 50 Hz around 7 W/kg). Also, the mechanical properties represent a significant obtained result, with TRS greater than 100 MPa, but above all, the material's resistance to the stress while milling resulted extraordinary. In addition, the comparison with the most popular SMC material shows promising results.

The obtained results have to be considered of "preliminary" value due to some limitations from the available supply source. Nevertheless, efficiency greater than 77% for this first prototype must be considered satisfactory, with promising future perspectives.

The future activities that will be carried on are related to the prototype and coating material. For what concerns the motor, which is currently presenting a significant cogging torque, some modifications of the magnetic circuit will be implemented; specific polar shoes will be designed, produced and added to the stator in order to reduce the reluctance resulting ripple [45-48]. On the material side, its already evaluated capability to support thermal treatments at higher temperatures will be further investigated to improve the hysteresis losses and the mechanical resistance. This contribution allows for the design of novel hybrid systems capable of delivering SMC materials where energy parameters and mechanical properties are maximized as a function of the selected application field.

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Federico Carosio took his PhD (2012) in Materials Science and Technology at Politecnico di Torino with a thesis entitled: "Layer by Layer assembly of nanostructured coatings for flame retardancy and barrier properties". At present he is Associate Professor at the Department of Applied Science and Tecnology of Politecnico di Torino, Italy. His research is focused on polymers, nanostructures, smart fibres/textiles and nanocellulose-based materials (thin films and foams) with particular attention to their surface modification achieved through water-based deposition techniques. He has coauthored more than 100 scientific papers (total citations: 6317, H-index 45, source google scholar) published on international peer review journals and he has attended several national and international congresses and workshops.

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