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Influence of Abrasive Blasting and Hot Pressing Preparation on the *Pinus taeda* Wood Surface

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Abstract

Metal particles are used in abrasive blasting to provide cleaning, new shapes, or fatigue resistance to surfaces, depending on the format of these particles. However, these particulates constitute large amounts of waste with no proper treatment. In this scenario, this paper aims to compare two surface treatment methods using metallic particles on *Pinus taeda* wood: abrasive blasting and hot pressing. The size and shape of the particles were determined by scanning electron microscopy (SEM) and their chemical constitution by energy-dispersive X-ray spectroscopy (EDX). After each treatment, the wood surface was subjected to wettability and colorimetric tests. The hot pressing treatment and the copper slag particles provided the lowest wettability. The color changes were significant after both methods, highlighting their potential as a new finishing technique.

Keywords: Stainless steel grit, steel grit, copper slag, surface treatment, metallic particles.

1. INTRODUCTION

Metallic abrasives, such as copper slag and both steel and stainless steel grit, are well-known for their use in mechanical cleaning to remove impurities from metal surfaces, although they are not yet applied in wood surface preparation (Grillo & Krewer, 2018). The most common metallic abrasives are steel grit and steel shot. Steel shot is spherical in shape, and it is recommended for surface blasting, enhancing surface resistance of metal sheets, while steel grit has random and angular shape, providing greater impact power on the blasted metal surface, and its major application is to shape metal pieces (Vite-Torres et al., 2013).

An important variant for the steel industry is the stainless steel grit, despite being efficient in abrasive blasting, it can be reused several times, providing a homogeneous metallic surface, and presenting low energy consumption (Sheen et al., 2015). Another commonly used metallic abrasive is copper slag, which can exhibit spherical or angular shape and varied granulometry. It is basically composed of iron oxides and silicates (Fayalite), but it may also contain zinc, sulfur, bismuth, silver, arsenic, antimony, and nickel (Prem et al., 2018).

These metal particles are widely employed in the automotive and steel industries generating large amounts of wastes with no proper disposal (Nazer et al., 2012). However, the civil industry has been investigating ways to reuse these particulate materials as aggregates for concrete, consequently reducing utilization of natural resources (Junca et al., 2015).

The application of granulated or powdered metals for wood treatment by impregnation processes has been studied as an alternative for reusing these materials, based on circular economy concepts (Taghiyari et al., 2015). However, there is no record of studies regarding the use of these particulate metal residues in wood surface treatment in the literature, which is a topic of interest, especially with particulates such as the copper from copper slags and the chromium present in stainless steel which present potential conservative properties when applied on wood surface (Bekhta et al. 2017).

Therefore, this paper presents an approach on wood surface treatment that applies metal particulates on wood by abrasive blasting and hot pressing, which are methods still unexplored by the literature, suitable not only for cleaning and molding sheet metal, with no parameter control, but also to improve the fatigue resistance of sheet metal (Shahid et al., 2017). The effects of abrasive blasting on wood are still unknown, as all studies have focused on the treatment of metal surfaces. On the other hand, hot pressing is commonly used in the production of wood panels and for wood densification, but there are no studies of its application associated with metallic particles on solid wood.

Both abrasive blasting and hot pressing are expected to improve the physical and chemical properties of wood surfaces, especially water repellency and color. Surface treatment systems using metallic residues based on circular economy concepts may result in a low-cost alternative for wood surface finishing and based products. Therefore, this paper investigates the potential of both techniques as an alternative wood surface treatment, using metallic residues. Three metallic wastes; (steel grit, stainless steel grit, and copper slag) were applied on the surface of *Pinus taeda* wood under different conditions. The influence of these treatments on wood surface was determined through morphology, wettability, and colorimetric tests.

2. MATERIALS AND METHODS

2.1. Materials

Steel grit, stainless steel grit, and copper slag were used as raw materials for the surface treatments. These metallic materials are the main solid wastes of the steel industry, especially because of their wide availability. The metallic wastes were used in their original form and composition.

The *Pinus taeda* wood used in this study was felled from a reforestation site located in the state of Santa Catarina. Defect-free wood samples were crafted with dimensions of 30 x 2 x 2 cm (COPANT 30-1:006). The density of the *Pinus taeda* wood used in this study was 0.434 g/cm³.

2.2. Characterization of metallic residues

The morphology and dimensions of the metallic particles were determined by scanning electron microscopy (SEM) in a FEI PHENOM equipment at 5 kV. Complementarily, a TESCAN VEGA 3 LMU SEM equipped with an energy dispersive x-ray spectroscopy (EDX) detector at 15 kV was used to chemically mapping these particles.

After obtaining images, the shape and size of the metal particles were determined using a LEXT OLS4000 Olympus Confocal microscope with a 20x magnification lens. Two samples of each metal particle and 20 measurements per sample were carried out to assess particle size.

2.3. Wood surface treatment

The *Pinus taeda* wood surface was treated with metallic particles using two methods: abrasive blasting and hot pressing. Sixty wood samples with dimensions of 30 x 2 x 2 cm were used per method, following the COPANT 30-1:006 standard, and initial moisture content around 12%.

For the abrasive blasting process, the wood samples were blasted at 100 pounds/inch², 12 cm apart, as suggested by the blasting manufacturer. Specific and separate cabins were used for each type of metal particle.

As for the hot pressing method, the wood samples were initially moistened (50 g water/m² per face) to decrease stress caused by temperature. Then, the wood samples were hot pressed at 70 - 80°C, 52 - 66 kgf/cm², and 1100 g/m² for 15 minutes. After both treatments, the wood samples were conditioned in a climate chamber at 20 ºC and 65% relative humidity for a month.

2.4. Characterization of the treated wood surface

The surface wettability was established with a DSA25 goniometer (Krüss GmbH, Germany) after each surface treatment, using the sessile drop method. Four droplets of distilled water (surface tension 72.80 nN/m) with a volume of 5 µl were deposited on the wood surface in the longitudinal direction of the fibers. The kinetics of the apparent contact angle was assested over 30 seconds.

The effect of the surface treatments was also investigated with the aid of colorimetry with a Konica Minolta CM-5 spectrometer (Konica Minolta, Japan). The colorimetric parameters were determined based on the CIE L*a*b* color space, where L* (lightness), a* (red-green axis), b* (yellow-blue axis), h (hue angle), and C* (chroma).

3. RESULTS

3.1. Morphology and chemical mapping of metallic particles

Table 1 shows the particle diameters of steel grit, stainless steel grit, and copper slag; the Cooper slag showed great variability in size, as well as smaller particle sizes.

Table 1. Diameter of steel grit, stainless steel grit, and copper slag particles.

	Steel grit	Stainless-steel grit	Copper Slag
Min (µm)	270.30	113.32	1.07
Max (µm)	980.76	203.41	97.73
Average (µm)	472.03	143.37	16.58
Coefficient of variation. (%)	42.99	16.70	59.38

Figure 1 displays a high-resolution image of the steel grit particles evaluated, from which were obtained the point and area spectra with their chemical composition. The spectrum 20 in Figure 1a and the graph in Figure 1b refer to the steel grit and showed a predominance of Fe and Si, characterized by a light coloration compared to the other metallic particulate materials.

In the granulometric analysis, steel grit presented irregular surface, angular format, and widely varied dimensions, as well as the chemical composition showed in Figure 1. The bright spots seen in spectrum 21 of Figure 1a and the graph in Figure 1c refer to the element Al and O. In contrast, spectrum 22 of Figure 1a and the graph of Figure 1d, which also refer to the steel grit, highlighted the darkest color point, with a predominance of O, Si, and Al.

The stainless steel grit exhibited a predominance of Fe, Cr, and Ni for all spectra points analyzed. Chromium is the element that characterizes stainless steel according to Figure 2a, the graph in Figure 2b, and Table 2. The spectra highlighted the homogeneity of the samples in terms of constitution and shape, i.e., all spectra showed similar proportions of the chemical elements. Stainless steel grit was the most homogeneous metallic compound in terms of chemical composition, shape, and distribution. Its particles were considered spherical and smaller than the other analyzed compounds, with a predominance of Fe, Cr, O, and Ni.

Copper slag analyses (Figures 3a and 3b) showed heterogeneity of shape, particle size, and chemical composition, with a predominance of Fe, O, S, Si, and Cu, as shown in Table 2 and the graph in Figure 1C. The presence of Zn, Al, Mg, and Ca was also observed. Figure 3a shows the presence of light rounded spots (circled in the image), which indicated magnetite fragments.

The copper slag showed a higher copper content (5%) than what has been observed (0,5 to 1,5%) by Shen & Forssberg (2003), indicating higher purity and relevant antifungal properties. The copper slag particles were heterogeneous in every aspect: shape, distribution, and chemical composition.

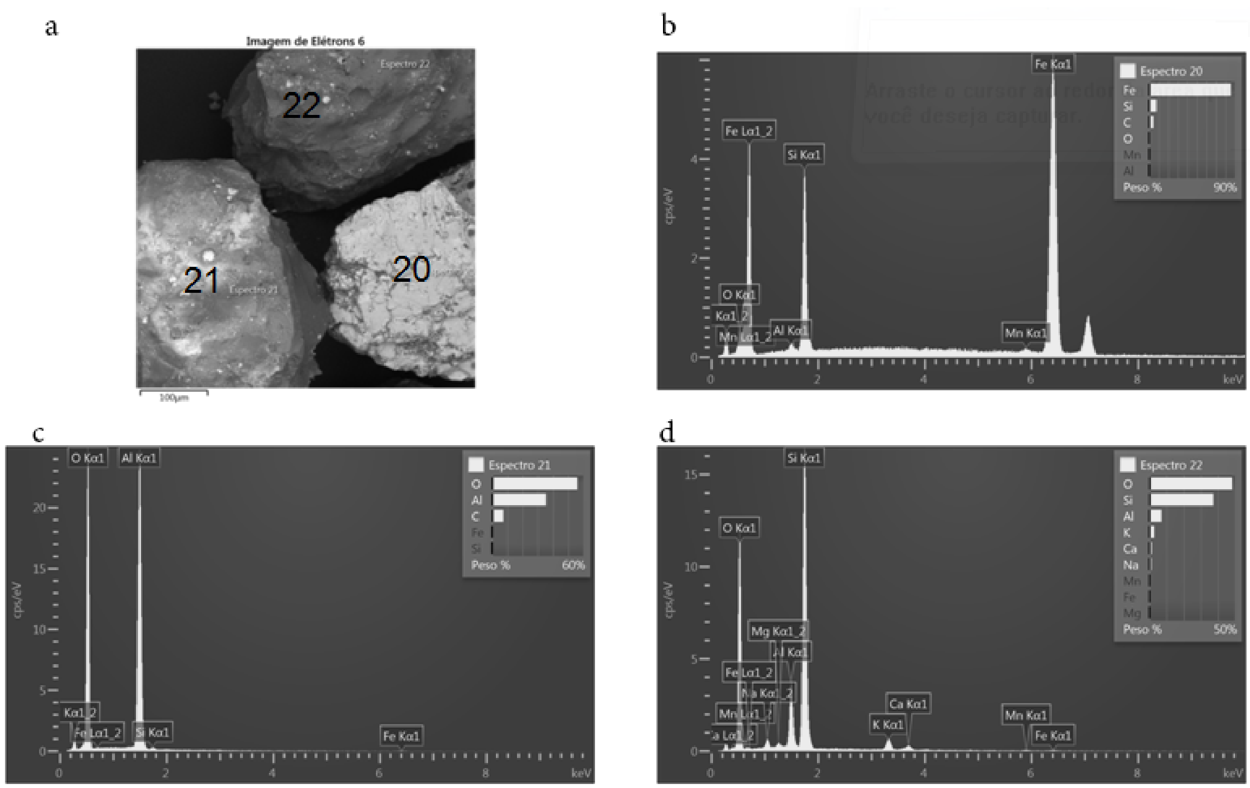

Figure 1. High-resolution images and chemical mapping of the grit
Caption: cps/eV. Counts per second per electron-volt. Kev - kiloelectron-volt. a) spectra of the steel grit. b) EDX test results for spectrum 20 of Figure 1a. c) EDX test results for spectrum 21 of Figure 1a. d) EDX test results for spectrum 22 of Figure 1a. Spectra obtained by Tescan program.

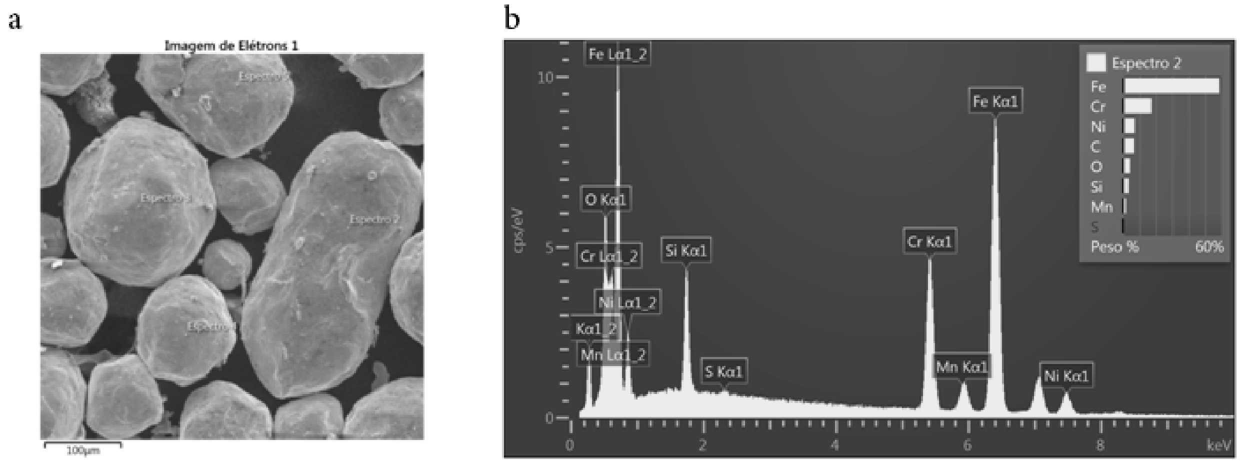

Figure 2. High-resolution images and chemical mapping of the stainless steel grit
Caption: cps/eV. Counts per second per electron-volt. Kev - kiloelectron-volt. a) spectra of stainless steel grit. b) EDX test results for spectrum 2 of Figure 2a. Spectra obtained by Tescan program

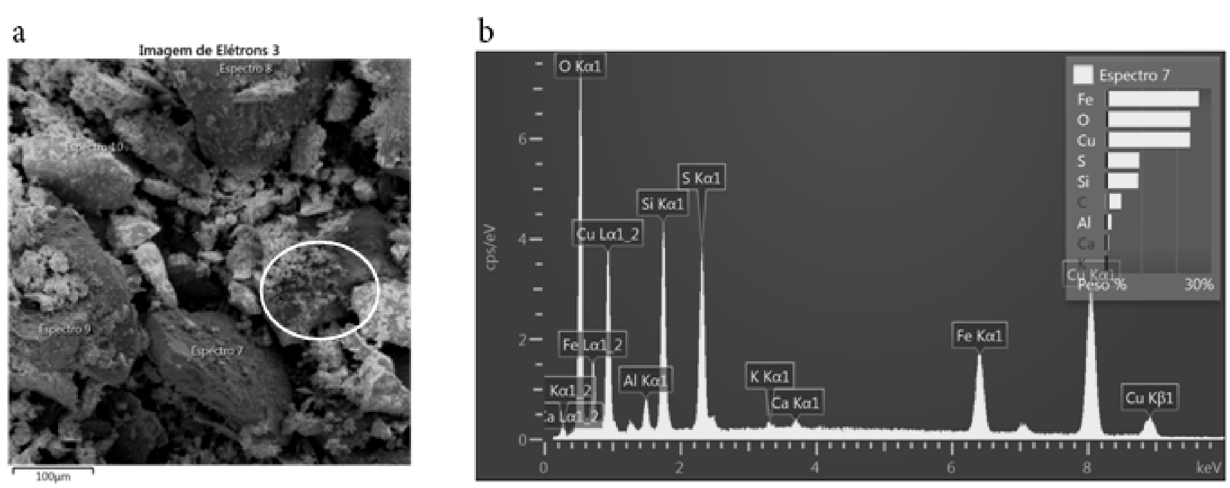

Figure 3. High-resolution images and chemical mapping of copper slag
Caption: cps/ev. Counts per second per electron-volt. Kev - kiloelectron-volt. A) spectra of the stainless steel grit. B) EDX test results for spectrum 2 of Figure 2a. Spectra obtained by Tescan program

Table 2 shows the general chemical composition of the analyzed wood samples. All metallic particles had Fe and O in their constitution, and both the steel grit and the copper slag exhibited a predominance of these elements.

Some secondary elements found in steel grit were: Si, Al, Mn, Ti, Ca, and K. The stainless steel grit samples presented a substantial amount of Fe and Cr. The stainless steel grit in the study presented a spherical shape, which could lead to less friction in wood surface treatment processes, preserving the fibers during the abrasive blasting or hot pressing. Copper slag showed a predominance of Fe and O, as well as steel grit (Table 2).

Table 2. Chemical composition of the metallic particles obtained by EDX.

Element	Mass (%)		
	Steel grit	Stainless steel grit	Copper slag
Al	3.82	0.17	1.68
C	5.04	4.84	3.90
Ca	0.17	-	0.70
Cr	-	17.77	-
Fe	49.23	60.30	34.25
Mn	0.59	2.13	-
Mo	-	0.18	-
Mg	0.07	-	0.62
K	0.19		0.58
Cu	-	-	5.89
Ni		7.06	-
Na	0.07	-	-

Table 2. Continued...

Element	Mass (%)		
	Steel grit	Stainless steel grit	Copper slag
O	33.12	4.29	35.22
S	-	0.03	2.37
P	0.07	-	-
Si	7.41	3.21	14.07
Ti	0.22	-	0.61
Zn	-	-	0.65
Other elements	-	0.02	0.11

3.2. Surface wettability of treated wood

Table 3 displays the behavior of the apparent contact angle of the wood treated by abrasive blasting and hot pressing. For the blasting process, some occurrences of no droplet formation were registered, i.e., the droplet completely dissolved, characterizing the surface as hydrophilic.

The metallic particles used in grit blasting differed greatly in behavior, given that the stainless steel grit particles presented the highest average sessile drop contact angle compared to the other particles, and thus the highest overall wettability.

Table 3. Apparent contact angle of wood treated by blasting and hot pressing with metal particles.

	Blasting		Hot pressing	
Time (s)	Average (°)	Maximum (°)	Average (°)	Maximum (°)
5	58.31a (10.05)	125.20	81.61a (9.73)	137.50
15	43.63b (8.80)	124.00	74,14b (13.34)	137.40
25	6.50c (6.76)	103.70	71.24b (16.71)	137.40
Particle	Average (°)	Maximum (°)	Average (°)	Maximum (°)
Steel grit	37.12b (11.96)	109.70	66.94b (12.75)	124.70
Copper slag	33.08b (7.35)	112.30	97.69a (4.82)	137.50
Stainless steel grit	40.40a (7.48)	125.20	60,82b (17.06)	115.60
Application	Average (°)		Maximum (°)	
Blasting	36.85c (9.41)		125,20	
Hot pressing	75.83a (13.50)		137.50	
Control samples	54.28b (6.98)		121.30	

Caption: Different letters refer to statistical differences. Values in parentheses refer to coefficients of variation. Normality (Shapiro-Wilk test) and residue homogeneity tests were carried out at 5% significance level and the analysis of variance (ANOVA) was performed along the Tukey test.

In the hot pressing method, the droplet did not dissolve as observed in the blasting process, indicating a surface with hydrophobic potential Importantly, the limit angle for dissolution was 40°. This behavior is due to the greater impact of abrasive blasting, which breaks the fibers in the amorphous zone of cellulose and creates openings that allow adsortion of moisture content. In contrast, hot pressing uses steam injection causing the expansion of cell walls (Song et al., 2018), fixating the metallic particles on the wood surface without breaking the fibers.

Comparing both methods, hot pressing presented the highest average angle (75.83°) and possibly the lowest liquid absorption, while grit blasting showed the lowest average angle (36.85°) and the highest wettability. The latter presented a lower average angle(36.85°) than the control samples (54.28°), as a result of the impact of the metallic particles shot against the wood surface, causing the wood to show frayed fibers and openings for adsortion of moisture content. On the other hand, observing visually wood porosity of the samples subjected to hot pressing was lower compared with the ones subjected to the blasting process, due to the simultaneous application of temperature and pressure, which reduced water absorption by the wood surface (Bekhta & Krystofiak, 2016; Carvalho, 2020).

Figure 4a compares the sessile drop angle values obtained in both methods. However, droplet absorption by the surface was faster in the wood samples treated with abrasive blasting, due to a combination of the blast pressure of the spherical particles and the shape of the particles (especially the angular ones), leading the wood to erode, and causing small ruptures on its surface.

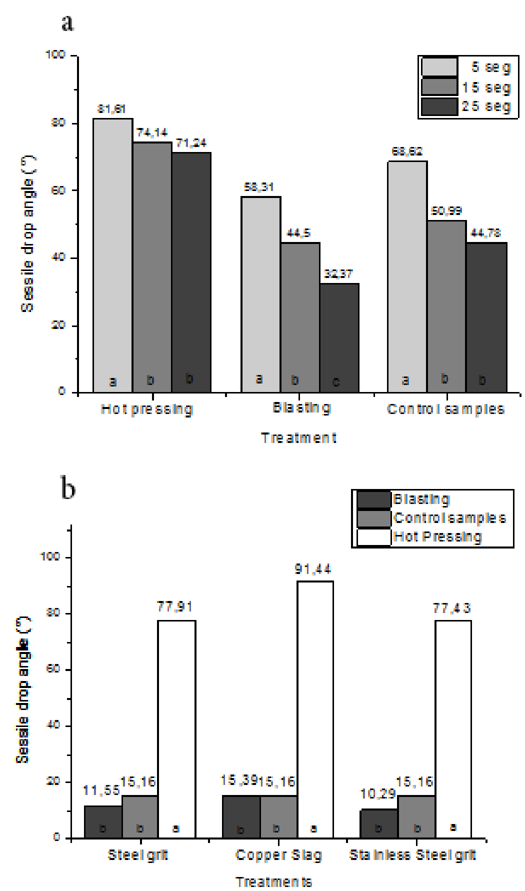

Figure 4. Effect of wettability on the method of application of metal particles.

Caption: a) contact angle of the three treatments (5,15 and 25 s). b) analysis of the contact angle of the three metallic particles applied through three treatments.Graphic obtained by Origin 8.5 program. Different letters refer to statistical differences.

Figure 4b compares the application methods on *Pinus taeda* wood, and the sessile drop contact angles for steel grit, stainless steel grit, and copper slag. Hot pressing exhibited the lowest wettability, and the sessile drop contact angle was higher for copper slag (91.44°), possibly due to the high amounts of Fe, O, Si, and Cu. In contrast, the three metallic particles showed similar performance for both the control samples and the blasting method, with no statistical differences between steel and stainless steel grit.

3.3. Colorimetric parameters of the treated wood

Table 4 presents a comparison between the wood surface treatment methods. The highest values and lightness (+L*) were always observed in the control samples. The samples treated by abrasive blasting, presented critical color changes, with the largest difference compared to the control samples, resulting in darker wood color. This is because the blasting process wears down the wood and the color of the metallic particles on its surface, simultaneously with the surface treatment. The color obtained by hot pressing was similar to the one obtained by blasting.

Table 4. Colorimetric parameters of wood treated with metal particles, by blasting and hot pressing.

Treatment	L*	a*	b*	C	h
Abrasive blasting	64.58c (8.71)	3.16c (50.93)	15.70c (24.61)	15.97c (23.97)	78.33a (5.45)
Hot pressing	65.40b (18.84)	3.90b (41.10)	17.64b (28.64)	18.09b (29.07)	77.96a (3.91)
Control Samples	68.28a (5.29)	5.58a (24.89)	19.04a (12.60)	19.86a (15.13)	73.75b (3.77)

Caption: Different letters refer to statistical differences. The values in parentheses are coefficients of variation

4. DISCUSSIONS

4.1. Morphology and chemical mapping of metallic particles

These findings of morphology of metallic particles are in accordance with what Vidilli et al. (2016) and Goldstein et al. (2018) described regarding the relationship between the atomic number and color observed in SEM images. The higher the energy required for the electrons to strike the surface, the higher its atomic number and the lighter the tone seen in the images. These fragments like light rounded spots were also found in copper slag by Panda et al, (2015). The grit presented a predominance of angular-shaped fayalite and magnetite with de-standardized particle sizes.

According to Bracconi & Nyborg (1998) and Midander et al. (2006), the lighter shade and points observed in the steel grit particles (Figure 1) indicate the presence of manganese (or iron) oxide, as observed in the EDX test performed in this study.

The same predominance of Fe and O in steel grit was also observed by Yildirim & Prezzi (2011), whose obtained a similar reading of the chemical composition of these metallic abrasives, this demonstrates a standardized constitution of these components. Meneguel (2017) identified mainly Fe and Mn when studying steel grit , with the amount of Fe similar to what was observed in this study. In the other hand, Chun et al. (2016) studied the composition of copper slag and observed a predominance of Fe and Si oxides, e.g. fayalite and magnetite. According to Panda et al., 2015 copper slag should present at least 0.5% Cu – usually between 0.5 and 1.5% –, and higher values indicate high purity, as verified in this study.

4.2. Surface wettability of treated wood

The hot pressing treatment presented the lowest wettability in all measurements, due to the ability of this method to preserve the wood surface by compression, which hinders the passage of liquids. This pattern is a result of the viscoelastic nature of wood, which softens its structure (Kutnar & Sernek, 2007). According to Kutnar & Sernek (2007), when exposed to a temperature of 54 to 56°C, wood cell walls – especially hemicelluloses – soften, allowing the fibers to be molded by the metallic particles, as seen in this study. However, when exposed to a temperature of 72 to 128°C, lignin softens, allowing for greater mobility of the middle lamella.

Papp & Csiha (2017) investigated the relation between roughness of wood and surface wettability with sanding application with different grit sizes, it was observed that higher the surface roughness the lower the contact angle and higher the liquid absorption, this behavior was repeated in relation to the application of abrasive blasting.

4.3. Colorimetric parameters of the treated wood

Besides the other assays, the study observed statistical differences in colorimetric parameters (a*,b*,L*,C and h). However, its can be classified according to its coloration and in this aspect the values of the present study were compared with the results of Camargos & Gonçalez (2001) and Bonfatti Junior & Lengoswki (2018) by the cluster method, where it was observed that regardless of the application method or the presence or absence of surface treatment (abrasive blasting and hot pressing), the wood was classified as pinkish-gray.

From a commercial point of view, it becomes attractive, as it means that the wood has not altered to the point of changing its aesthetic appearance.

5. CONCLUSIONS

According to the results obtained:

- Both metal particles interacted with the wood, i.e., the wood surface was successfully treated regardless of the application method used;
- Hot pressing resulted in a surface with higher hydrophobicity compared to abrasive blasting and the control samples;
- Both treatment methods changed the original color of the samples, darkening them, regardless of the nature of the metal used;
- Copper slag showed the greatest total alterations in color of the wood samples;
- Both treatments can be used as new wood finishing methods, due to the aesthetic changes that can be achieved through them, especially when associated with copper slag;
- Abrasive blasting and hot pressing with metal particles can also be used as a finishing method to change the aesthetics of the wood.

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All Authors Contributions: CRediT Taxonomy

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Márcio Rocha: Conceptualization (Lead); Formal analysis (Lead); Investigation (Lead); Methodology (Lead); Supervision (Lead); Writing – review & editing.

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REFERENCES

Bekhta P, Krystofiak T. The influence of short-term thermo-mechanical densification on the surface wettability of wood veneers. Maderas, Ciencia y tecnologia, Concepción 18(1): 79-90. 2016.

Bekhta, P.; Proszyk, S.; Krystofiak,. T.; Sedliacik, J.; Novak, I.; Mamonova, M. Effects of short-term thermomechanical densification on the structure and properties of wood veneers. Wood material science & engineering, 12(1): 40-54, 2017.

Bonfatti Júnior EA, Lengowski EC. Colorimetria aplicada à ciência e tecnologia da madeira. Pesquisa Florestal Brasileira. 38. 2018.

Bracconi P, Nyborg L. Quantitative phase analysis and thickness measurement of surface-oxide layers in metal and alloy powders by the chemical-granular method. Applied Surface Science. 133(1/2):129-147. 1998.

Camargos, J. A. A. & Gonçalez, J. C. A colorimetria aplicada como instrumento na elaboração de uma tabela de cores de madeira. Brasil Florestal, n. 71, p. 30-41, 2001.

Carvalho DE. Caracterização tecnológica e densificação termomecânica da madeira de *Gmelina arborea* Roxb. PhD Thesis, Dept. of Engineering Forestry, Federal University of Paraná, Brazil. 2020.

Chun T, Ning C, Long H, Li J, Yang J. Mineralogical characterization of copper slag from tongling nonferrous metals group China. Jom 68(9):2332-2340. 2016.

Grillo G, Krewer EJ. Produção mais limpa: um comparativo entre os processos de jato de escória de cobre e jato de granalha de aço. Revista Global Manager Acadêmica 7(1). 2018.

Goldstein JI, Newbury DE, Michael JR, Ritchie NW, Scott JHJ, Joy DC. Scanning electron microscopy and X-ray microanalysis. 554pp. Fourth Ed. Springer. 2018.

Junca E, Oliveira JR, Espinosa DCR, Tenório JAS. Iron recovery from the waste generated during the cutting of granite. International Journal of Environmental Science and Technology 12(2): 465-472. 2015.

Kutnar A, Šernek M. Densification of wood. Zbornik gozdarstva in lesarstva, 82: 53-62. 2007.

Meneguel L. Aproveitamento de resíduos de granalha de aço-carbono por metalurgia do pó. M.S. Thesis, Dept. of Engineering and Material Science, Caxias do Sul University. Caxias do Sul. 2017.

Midander K, Pan J, Leygraf C. Elaboration of a test method for the study of metal release from stainless steel particles in artificial biological media. Corrosion Science. 48(9): 2855-2866. 2006.

Nazer AS, Pavez O, Rojas F. Use of copper slag in cement mortar. Rem: Revista Escola de Minas. 65(1): 87-91. 2012.

Panda S, Mishra S, Rao DS, Pradhan N, Mohapatra U, Angadi S et al. Extraction of copper from copper slag: Mineralogical insights, physical beneficiation and bioleaching studies. Korean Journal of Chemical Engineering 32(4): 667-676. 2015.

Papp, E. A., Csiha, C. Contact angle as function of surface roughness of different wood species. Surfaces and Interfaces, 8: 54–59. 2017.

Prem PR, Verma M, Ambily PS. Sustainable cleaner production of concrete with high volume copper slag. Journal of Cleaner Production 193: 43-58. 2018.

Shahid L, Janabi-Sharifi F, Keenan P. Image segmentation techniques for real-time coverage measurement in shot peening processes. The International Journal of Advanced Manufacturing Technology 91(1-4): 859-867. 2017.

Sheen Y, Le D, Sun T. Innovative usages of stainless steel slags in developing self-compacting concrete. Construction and Building Materials 101: 268-276. 2015.

Shen, H.; Forssberg, E. An overview of recovery of metals from slags. Waste Manag. 23: 933–949. 2003.

Song, J.; Chen, C.; Zhu, S.; Zhu, M.; Dai, J.; Ray, U.; Li, Y., Kuang, Y.; Li, Y; Quispe, N.; Yao, Y.; Gong, A.; Leiste, U. H.; Bruck, H. A.; Zhu, J. Y. Vellore, A.; Li, H.; Minus, M. L.; Jia, Zheng.; Martini, A.; Li, T.; Hu, L. Processing bulk natural wood into a high-performance structural material. Nature, 554(7691): 224-228, 2018.

Vidilli AL, Afonso CRM, Amigó VB, Amigó AM, Riva R, Kiminami CS. Laser cladding de pós obtidos por moagem de alta energia de ligas nanocristalinas Ti-Nb-Fe-Sn In: 22º CBECiMat - Congresso Brasileiro de Engenharia e Ciência dos Materiais, Natal, RN, Brasil. 2016.

Vite-Torres M, Laguna-Camacho JR, Baldenebro-Castillo RE, Gallardo-Hernandez EA, Vera-Cárdenas EE, Vite-Torres J (2013) Study of solid particle erosion on AISI 420 stainless steel using angular silicon carbide and steel round grit particles. Wear 301(1-2): 383-389, 2013.

Yildirim IZ, Prezzi M. Chemical, mineralogical, and morphological properties of steel slag. Advances in Civil Engineering. 2011.