

Limeira, July 10, 2023



Dear Editors;

Please, the revised version of the manuscript is attached. All Reviewers' suggestions/comments are provided and solved. In this opportunity, the Authors are very grateful with suggestions/comments. All modification and new sentences included are yellow highlighted. A compilation of the modifications/improvements correlated with each one of the Reviewers' comments are followed:

Best Regards;

A handwritten signature in black ink, appearing to be 'W. Riuper Osório', is located below the 'Best Regards;' text.

Wislei Riuper Osório
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Reviewer(s)' Comments to Author:

Reviewer: 1

"The paper is devoted to the important problem in the field of material science. This topic is very well investigated so the authors need to emphasize their novelty and real new results because it seems that we've read something like that."

AUTHORS: At first at all, the authors are very grateful with your comments and suggestions provided. Based on the Reviewers' comments, a new sentence containing NOVELTY is included, as yellow highlighted. No previous results or similar have been previously published. The effect of the resulting dendrite arm spacings in powder and consequently into compaction and anisotropic tensile and compressive strengths have not yet published. Considering that it was also suggested: "...The paper must be shortened.", and based on the suggestions provided by Reviewer #2, the manuscript was possibly revised and improved. It is also remarked that the Reviewer #2 has also suggested some improvements, which were totality adopted and included into the revised version. Modifications are also yellow highlighted.

Reviewer: 2

"The paper can be accepted, but it is necessary to carry out certain refinements in order to improve the quality of the work and its application for subsequent tests."

AUTHORS: The Reviewer is correct. Authors are very grateful with your contributions provided. All modifications are yellow highlighted.

- Aluminum and aluminum alloys are increasingly used in various fields of technology, means of transport and various branches of industry. They are applied in the manufacturing, aircraft, space, military, automotive and electronic industries. In order to improve the tribological and mechanical characteristics of aluminum alloys, various reinforcers and additives are added and appropriate composites are formed. This further improves the working characteristics of the obtained aluminum alloys. It is necessary to explain in more detail the areas of application of aluminum and aluminum composites. It is necessary to review the paper: 10.1088/1742-6596/2212/1/012029

AUTHORS: Again, it is appreciated the comments provided. The suggested references were analyzed and included into the revised version. Modifications are yellow highlighted. These are included into Introduction, i.e. at first paragraphs and at the last two paragraphs. Please, see into the revised version.

- Expand the introduction with papers from this field.

AUTHORS: The Reviewer is correct. The Introduction was revised and more papers were also included.

- At the end of the introduction, enter what is the main contribution of the work and how does this work differ from similar works in this field? What is the reason, i.e. why should this paper be published?

AUTHORS: The Reviewer is correct. A new sentence was included. The authors are also grateful with this comment/suggestion.

- Based on which recommendations did you select compaction pressures (look at the paper <https://doi.org/10.18485/aeletters.2022.7.1.3>)

AUTHORS: The recommended reference was analyzed, and new sentence included. Also, the mentioned Reference was also included.

- State how the experiment plan was formed, as well as any limitations the researchers encountered.

AUTHORS: The Reviewer is correct. New sentences were included.

- Show photos of the equipment (microscopes, etc.) that were used during the examination.

AUTHORS: The suggestion was possibly adopted. It is remarked that Reviewer #1 has indicated that "The paper must be shortened.". Based on this, the recommendation was possibly adopted.

- Increase the number of references in the work based on the given remarks.

AUTHORS: The Reviewer is correct. The suggestion was adopted.

- Expand the discussion. Compare the obtained results with other works from this or similar fields.

AUTHORS: More references were included and discussion provided.

- Based on the extended analysis and discussion, expand the concluding considerations.

AUTHORS: The Reviewer is correct. The suggestion is adopted.

Anisotropic tensile and compressive strengths of Al-4wt.%Cu alloy powder: *Part 2 - Effect of dendritic arm spacings*

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Abstract: The investigation focuses on the effects of the compaction directions (*i.e.* transversal and longitudinal) and microstructural arrays (inside the powder utilized to constitute the specimens) on the anisotropic strengths. The initial powders are obtained from the as-cast Al-4 wt.% Cu alloys solidified in two distinct cooling rates, *i.e.* ~0.5 and 2.5 °C/s. The powder particles are compacted by using 300, 400 and 600 MPa and sintered at 540 °C for 1h. The compressive and tensile strengths are carried out and the anisotropic strengths are determined. It is found that transverse samples exhibit higher UCS (ultimate compressive strength) and UTS (ultimate tensile strength) than the longitudinal samples. It is also found that the powder compacted in the transversal direction and utilizing powder with finer dendritic arm spacing provides better UCS and UTS results. The novelty in the study concerns to the fact that is evidenced the role of the dendrite spacings concatenated with the compaction pressure and direction upon the mechanical behavior. It is concluded that depending on the compaction level intended or demanded mechanical behavior, a planning in the compaction direction is preprogrammed. Since recycled powder particles from conventional machining, drilling and turning can potentially be utilized to constitute part and components, the environmentally friendly aspects are associated; and hazardous stages in a manufacturing process are substantially reduced or eliminated.

Keywords: aluminum composite; Al-Cu alloys; solidification; dendritic spacings; mechanical properties, environmentally friendly aspects

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1. Introduction

Aluminum and aluminum alloys are increasingly used in various fields of technology, means of transport and various branches of industry. They are applied in the manufacturing, aircraft, space, military, automotive and electronic industries. A great number of Al-based composites with distinct reinforcers and additives are used. Aluminum and its alloys are one of the most widely recycled non-ferrous metal [1–5]. Bulei and colleagues [1] have demonstrated that aluminum scrap can be originated from distinctive resources and recycled infinitely without losing its properties and quality. They have stated [1] that Al-based composites can be stating from various aluminum wastes, derived from different aluminum products. There are various Al-based alloys, which can be selected, *e.g.* 2xxx, 6xxx and 7xxx series [1] as matrices for aluminum matrix composite or to consider recycling. In this present investigation, the as-cast Al-4 wt.%

Cu alloy is selected to investigation. This is similar to 2xxx series alloys, which are widely used into distinctive automotive and aerospace applications [6-11]. Also, it is recognized that these alloy are heat treatable and properties substantially modified. When directly used from casting procedures, the applied cooling rate affect its properties.

It is well recognized the effects of dendritic arm spacings upon the resulting properties in distinctive materials and alloys. It is known that an as-cast material commonly is constituted by crystallographic grains and inside a cellular or dendritic networking [12-13]. The microstructural formation is highly dependent of the operational conditions imposed (e.g. growth rate, thermal gradient, chemical composition, etc.). Particularly, the resulting microstructural arrays of Al-based alloys are significantly affected by operational parameters (e.g. cooling rate), and consequently the mechanical and corrosion properties can be planned and improved [14-17].

In the powder metallurgy, the dendrite spacings are not focused on investigation in order to prescribe the mechanical behavior. This due to in a green specimen, the compaction stage is more important to predict the resulting density distributions. Additionally, the size and distribution; the ductile or fragile characteristic; and the morphology of powder particles are parameters that impact the final mechanical features of a preform or final component [18-20]. It is also reported that the geometry and the surface of the die tools associated with the load control in the compaction stage have also important roles on the final soundness and properties of the compacted specimens [19-23].

Depending on the compaction load and its direction applied, the strength anisotropic can predict differently in each distinct condition. Particularly in powder metallurgy, the strength anisotropy has been focused on investigation of sintered, hot pressed powders and/or pressed and heat treat specimens [17-23]. Galen and Zavaliangos [18] have reported an excellent paper retracting a great number of studies concern to strength anisotropy of several different materials. It is found that the tensile strength at perpendicular direction is higher than at same line of compaction direction. They have reported that the strength anisotropy is strongly affected by density reached. The great area of the matter entitled strength anisotropy has been widely investigated since 90th. When utilizing the PRISMA concept (preferred reporting items for systematic reviews and meta-analyses), and searching in Web of Science with strings "Al-Cu based alloys" and "strength anisotropic"; more than 20,000 papers are obtained. In order to catalogue and organize these articles a "hard task" is established. Evidently, it is recognized that is limited this kind of searching. However, it is perceived that there is a possible contribution when the dendrite arm spacings are focused on its effects on the mechanical anisotropic of Al-Cu powder particles. Mainly, when these powder particles are obtained from the as-cast Al-Cu and in the powder metallurgy stage; and no melting is used. This means that the drilled powders are compacted and sintered to constitute preforms or possibly final components. These pieces depict distinctive mechanical behavior depending of the compaction direction and loading level (pressure).

Recently, it has been investigated [24] the Al-Cu composites samples, which were compacted in distinct directions (longitudinal and transversal) and sintered/heat treated. It is found different morphologies (i.e. spheroidal-like and flattened) depend on the compaction pressure, and the strength anisotropic is substantially affected. It is found that those samples transversally compacted have indicated very similar anisotropic ratios and slight increasing trends with the increase of the compaction pressure are verified. On the other hand, the longitudinal samples show non-linear decreasing trends with the increase in the compaction pressure.

However, a question is still remained concerning to the effects of the dendritic arm on the strength anisotropic. This is based on the fact that an as-cast Al-Cu alloy is used as initial material, and inside each powder particle obtained; there are some few dozen of crystallographic grains. Besides, inside each grain, a dendritic networking is provided [12].

It is recognized that finer dendrite arms improve the mechanical behavior [12–15], but it is not true that corrosion behavior is concomitantly improved, which depends on certain parameters and microstructural array conditions [14–15]. This evidences the importance of the microstructural arrays on the resulting properties. Also, it has been reported that dendritic arms spacings from the as-cast Al-based alloy will be remained or maintaining same order of magnitude even after compaction load, sintering and short aging time [20; 25–27].

Kuznetsov et al. [28] have recently reported that distinct technologies for the production of metal powders are developed, e.g. gas, water spraying, centrifugal spraying, plasma spraying, mechanical grinding and doping, solid phase recovery, electrolytic and various chemical processes. From these, distinctive morphologies, shapes and sizes are attained. It is worth noting that, in this present investigation, an alloy casting is used to produce (drilling) powder particles with characteristic remained from two distinct cooling rate applied in solidification. This also corroborates with novelty aspect.

Differently from those previously investigations concerning to compaction pressure and other operational aspects and parameter, in this present investigation the novelty and scientific/technological contributions are focused on the evaluation of the strength (tensile and compressive) anisotropic of Al-4 wt.% Cu (Al-4Cu) samples (transversally and longitudinally compacted). For this purpose, two distinctive powder microstructural arrays are considered. These are constituted by finer and coarser dendrite arms spacing originated from cooling rates of 0.5 and 2.5 °C/s, respectively. It is remarked that neither atomization or ball milling are utilized. These particles can be potentially be used from recycling of conventional machining, drilling and/or turning. This induces to reasonable decreasing into final production costs and environmentally friendly aspects associated with new ESG (environmental-social-governance) [29] practices/philosophy are also involved.

2. Materials and Methods

The process of working out the stages was carried out on a developed experimental complex, which includes: to produce powders from the as-cast Al-4 wt.% Cu alloy, drilling the ingots; to compact the powers; to sinter the preform samples; to carry out the mechanical tests; to characterize resulting microstructures. The stages are described in each subsection followed.

2.1. Powder, Compaction and Sintering

Initial powder particles are originated from the ingots of as-cast Al-4 wt.% Cu alloys produced by using two distinct cooling rates: 0.5 and 2.5 °C/s. The ingots are drilled by using a tool, which produces flakes particles, as previously described [24]. A unique range of powder size distribution is obtained due to the utilized drilling, as also previously reported [24]. The morphologies of powders are majority flaked-like or flattened. The particles have length of about 2 times higher than width (*i.e.* an average of 290 µm against ~160 µm, respectively).

Two tempered dies (VC131 and AISI D6, hardness ~60 HRC) are utilized. A first produces prismatic (5 x 2 x 32 mm) specimens and another provides cylindrical specimens (diameter 8 mm x 25 mm), as previously detailed [24]. All specimens are transversally and longitudinally performed with respect to along specimen axis. It is remarked that when the cylindrical samples are transversally performed, the diametrical compression is carried out, as forwardly will be discussed. The samples are designated as “transverse” when the compaction load is applied transversally to the tensile loading direction. The samples called as “longitudinal” are the cylindrical specimens due to the powders are compacted along the specimen axis, as also previously detailed [24]. This is coplanar to tensile or compressive directions loading direction. All specimens are com-

pacted by using three distinctive compacting pressures, i.e. 300, 400 and 600 MPa. A single acting hydraulic press is used and uniaxial compacting direction is provided. Due to the shape (cylindrical) of the longitudinal specimens, a bidirectional compacting is applied. In all mentioned stages, in order to guarantee the reproducibility, triplicate is adopted.

Two groups of the compacted Al-4Cu samples are constituted. A first group is sintered at 540 °C for 1h, and a heating rate ~ 10 °C/min is adopted. Subsequently, air-cooling is adopted (similar to annealing). The second group, after the sintering stage, the environmental water quenching (27 ± 2 °C) followed by natural aging during 30 days is adopted. Triplicate or duplicate are considered. Remembering that these two groups have samples produced using a higher and another lower cooling rates, which produce a finer (average 30 μm) and coarser (average of 150 μm) dendrite spacings, respectively.

2.2. Mechanical, Microstructural and Phase Characterizations

The tensile and compressive tests according with the ASTM standard E8M/04 are carried out. A speed cross head of 0.25 mm/min and a strain rate $\sim 2 \cdot 10^{-4} \text{ s}^{-1}$ at $24 (\pm 2)$ °C are considered. All specimens are positioned at machine in such way that the both transversal and longitudinal directions are performed. This same group is also examined in a second direction, which is also perpendicularly or transversal to the compaction direction. When the samples are subjected to the compressive test, and this is coincident with the tensile and compressive directions, this sample is designated as the longitudinal sample. On the other hand, when both the compressive or tensile tests are transversally carried out to the compaction direction, the samples are entitled as the transverse samples.

A scanning electron microscope (SEM), TESCAN®, model VEGA3, Brno, Czech Republic combined with an energy-dispersive x-ray (EDX) detector is used. Thus, the initial powder particles and the resulting microstructural arrays are characterized. A PANalytical® XPert diffractometer (X'Pert model), Malvern, Worcestershire, U.K. is utilized to determine the crystal phases attained. A voltage of 40 kV and current of 30 mA with Cu K α radiation associated with the wavelength of 0.15406 nm are adopted and XRD (x-ray diffraction) patterns are plotted in Origin Microcal® software and analyzed.

3. Results and Discussion

3.1. Powder Size Distribution and Microstructure

Fig. 1 depicts the typical starting powder particles obtained from the as-cast Al-4 wt.% Cu alloy ingot. It is remarked that powders were obtained by using similar operational parameters, which provide similar averages of the particle lengths. Fig. 1(a) shows the obtained powders from the as-cast ingot utilizing cooling rate of $0.5 (\pm 0.15)$ °C/s and coarser dendritic arm spacings are resulted. When a cooling rate of $2.5 (\pm 0.5)$ °C/s is applied, finer dendritic spacings are obtained. Evidently, the dendritic arms are not observed in these images, which will forwardly be demonstrated.

However, it is revealed that the distributions of size particles displace to lower measured values than coarser one, as depicted in Fig. 1(c) and 1(d). It is also remarked that the majority particles exhibits a flaked-like morphology with the length of about 2x higher than the corresponding widths. It is also interestingly verified that the bimodal

distributions are characterized, as also reported in other studies with Al powders obtained in similar operational conditions [25–28].

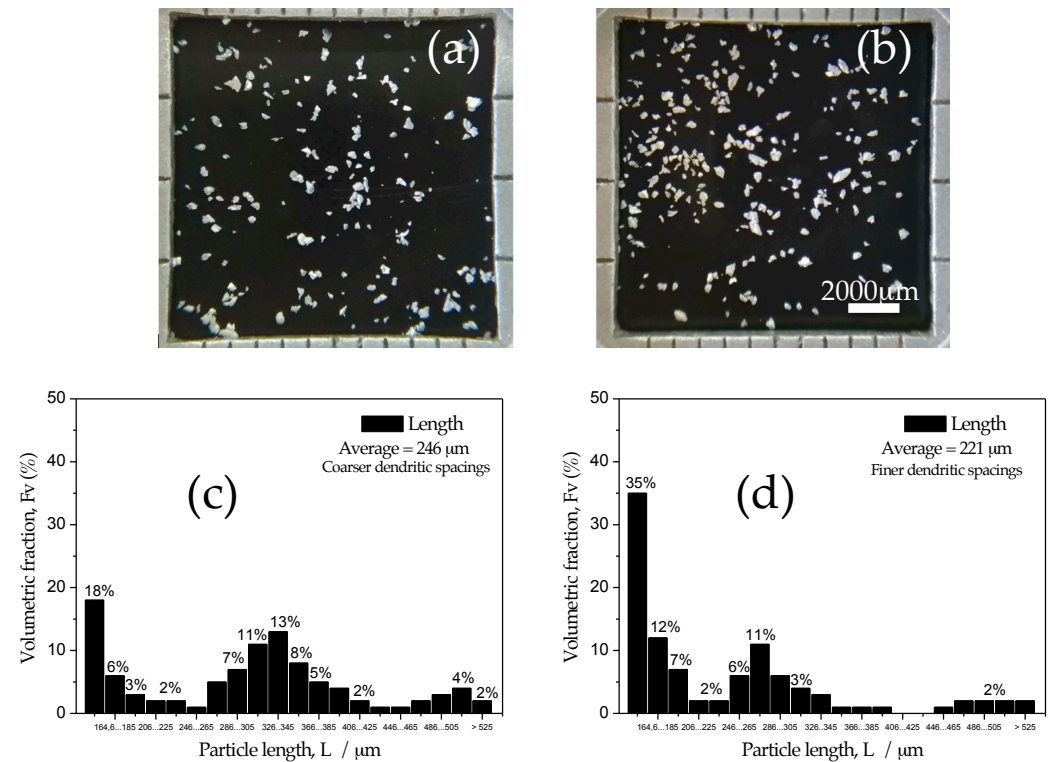


Figure 1. Typical images obtained from the as-cast Al-4Cu alloy ingot: (a) using of about ~0.5 °C/s cooling rate and (b) ~2.5 °C/s with their corresponding particle length distributions; and (c) attained coarser and (d) finer dendritic arm spacings.

It is worth noted that the powder particles are obtained by drilling, as described in the experimental procedure. Due to this stage processing, a certain “portion” of the Al-Cu alloy ingot is “withdrawn”. From the metallurgical point of view, since the powders are from as-cast condition, it is expected that inside each powder particle, a determined microstructural array is preserved. Thus, each powder particle contains some few crystallographic grains. Inside of each one of the grains, a microstructural array is constituted by dendritic spacings.

With this, intending to characterize these described microstructural parameters; a particular powder particle was examined. For this purpose, the magnifications were adopted. Fig. 2(a) depicts the starting powder particles from the drilled as-cast Al-Cu alloys. Sequentially, three magnifications are applied in order to characterize the possible grain boundaries and its internal dendrite spacing arrays, as shown in Figs. 2(b), 2(c) and 2(d). Based on the SEM typical images, it is not possible to affirm that the grain boundaries are clearly characterized. This seems to be associated with the fact that the drilling provokes the “slip” lines during the plastic deformation, as groove and rough surface depicted in Fig. 2(d).

However, it is clearly verified that the white-bright regions are characterized. These are surely corresponding with the resulting Al₂Cu intermetallic particles. It is recognized from the metallurgical point of view that, these Al₂Cu particles are allocated at interdendritic arms regions, as also shown in Fig. 2(d). It is speculated that the Al₂Cu inter-

metallic are delineated as the secondary dendritic arm spacings (λ_2) sizing of about 30 (± 6) μm , due to the examined powder particles are from the as-cast Al-Cu alloy ingot, which is more rapidly cooled.

Fig. 2(e) and 2(f) show the typical coarser and finer λ_2 prevention from the cooling rates of about 0.5 and 2.5 $^{\circ}\text{C/s}$, respectively. Similar magnitudes of λ_2 are reported in previously published articles concerning Al-Cu based alloys in the as-cast condition [12; 15; 30–34]. It is remarked that these SEM images shown in Figs. 2(e) and 2(f) are obtained and characterized when the compacted samples (under compaction pressure 600 MPa) are appropriately ground (SiC papers #1200 mesh) and examined by using a BSE (back scattered electrons) technique.

Figs. 3(a) and 3(b) show the obtained SEM micrographs of the coarse and fine λ_2 at magnifications of 100x and 400x. This evidences that a coarser λ_2 is of about 150 μm , while a fine λ_2 characterizes its arm spacings approximately 4 or 5 times (~ 30 μm) lower than the coarse sample. This is intimately associated with the two distinct cooling rates applied when the multi directional unsteady-state solidification is conducted. It is important to remark that the applied cooling rate has very important role on the resulting properties. For instance, a high cooling rate (higher than 5 $^{\circ}\text{C/s}$) is commonly reached when the water-cooled permanent-steel mold is involved.

Fig. 3 (c) depicts the resulting Al- and Cu-K α and the conjugated SEM images constituting the elemental maps are also shown. These indicate the Al-rich and Cu-rich (Al_2Cu intermetallics) regions. It is remembered that the solubility limit of Cu into Al matrix is $\sim 5.6\%$ [14–15], which justifies some few “red” points distributed throughout the Al matrix. The Al_2Cu intermetallics are majority located at the interdendritic regions. However, it is possible that other Al_2Cu phases (e.g. θ , θ' and θ'') be also located inside or diluted into the Al matrix, as previously reported [36–38]. These other morphologies, cubic particles, needle-like and nano-scaled needle-shaped particles (lower than 5 μm) correspond to θ , θ' and θ'' , respectively [38]. These Al_2Cu are commonly characterized using TEM techniques. The θ - Al_2Cu phase interfacing with the α -Al constitutes the eutectic network. With the magnifications of 100x up to 2,000x using both optical and SEM techniques, these phases are more easily characterized.

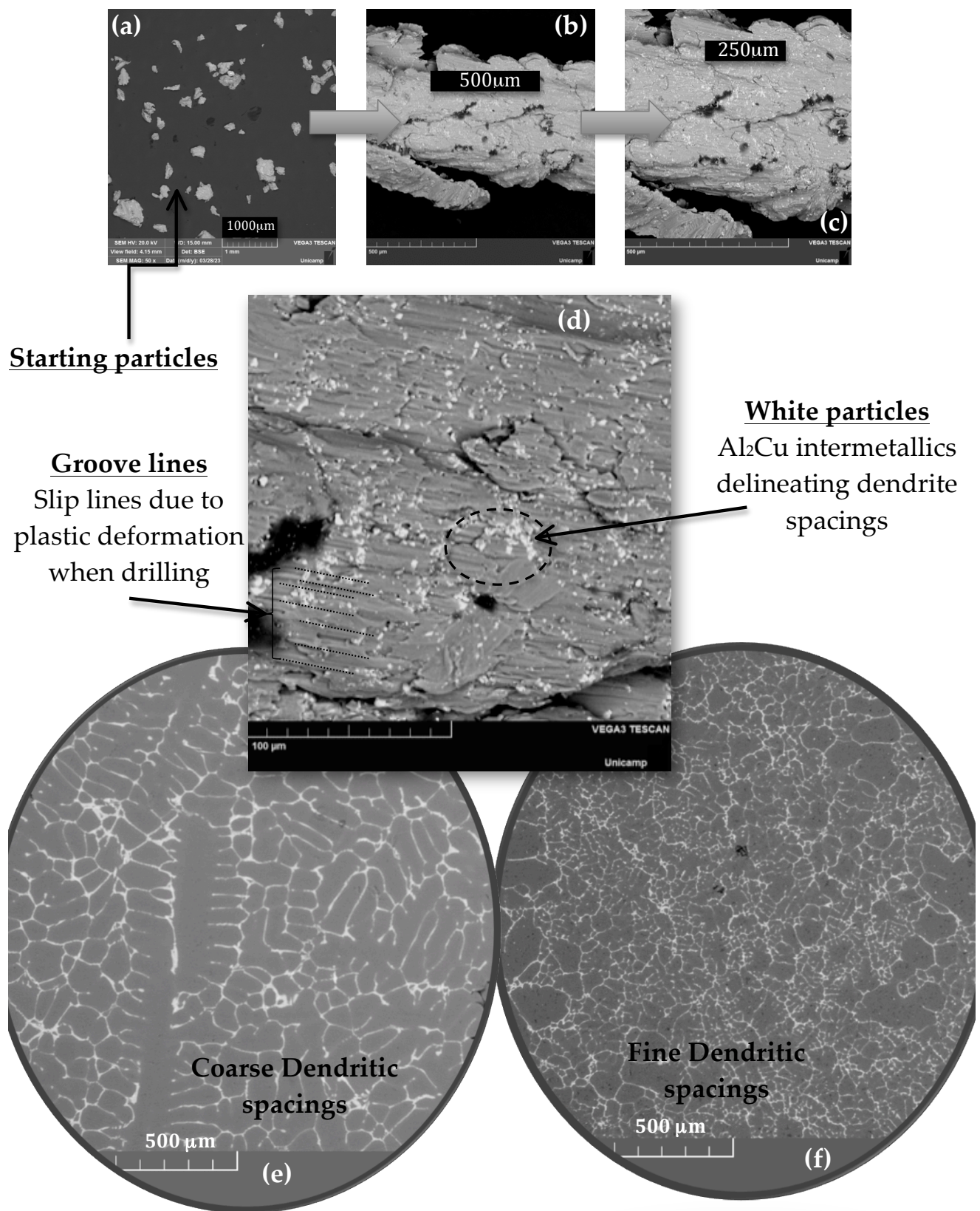
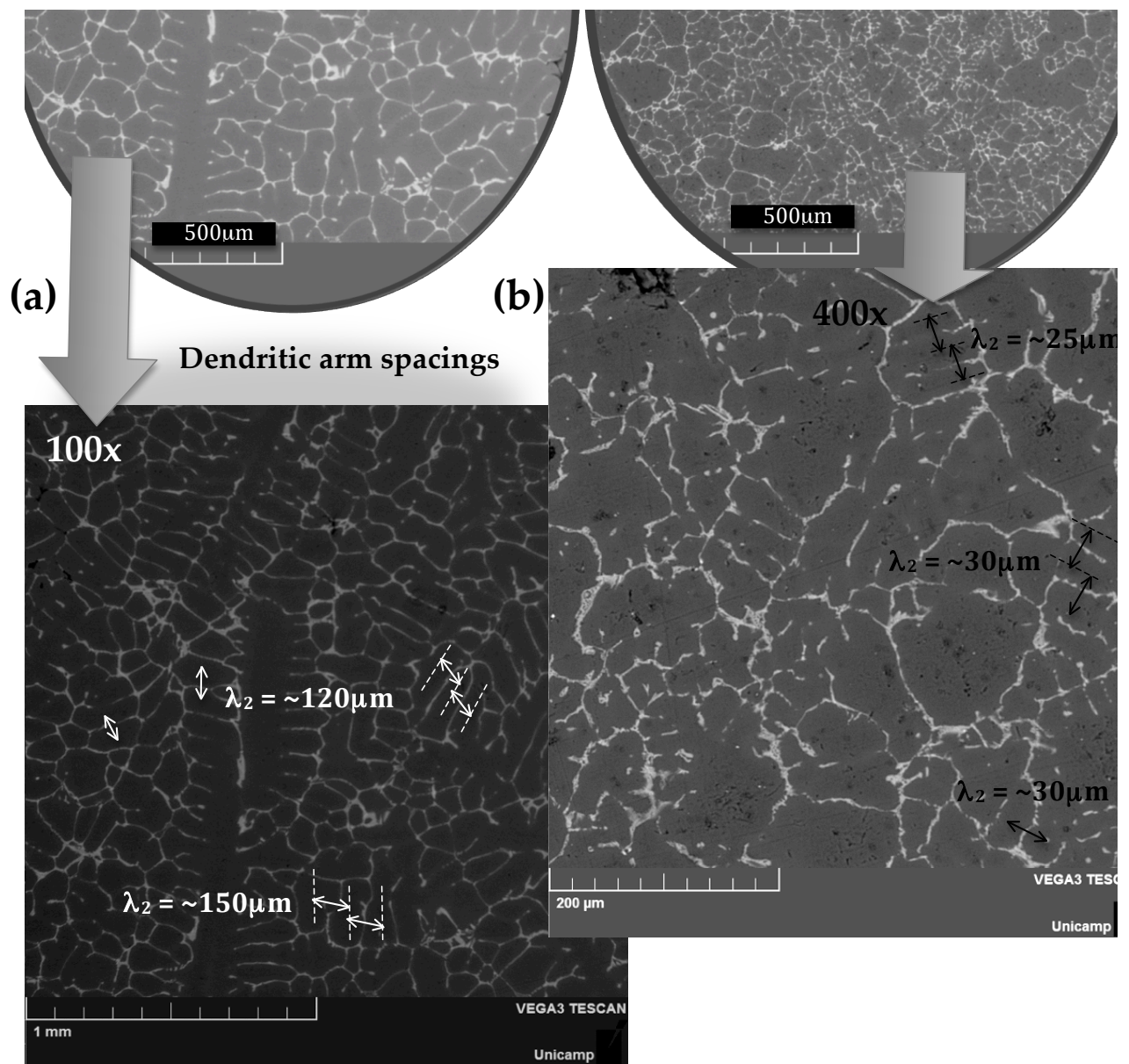


Figure 2. Typical SEM images of: **(a)** the starting drilled as-cast Al-Cu alloy powders, **(b)**, **(c)** and **(d)** distinct magnifications of powder revealing Al₂Cu intermetallics (white/bright regions), the slip lines (plastic deformation) and the rough surface of the powder, and **(e)** showing the coarse and **(f)** the fine dendritic spacings characterized in the compacted samples (600MPa).



(c) Elemental maps

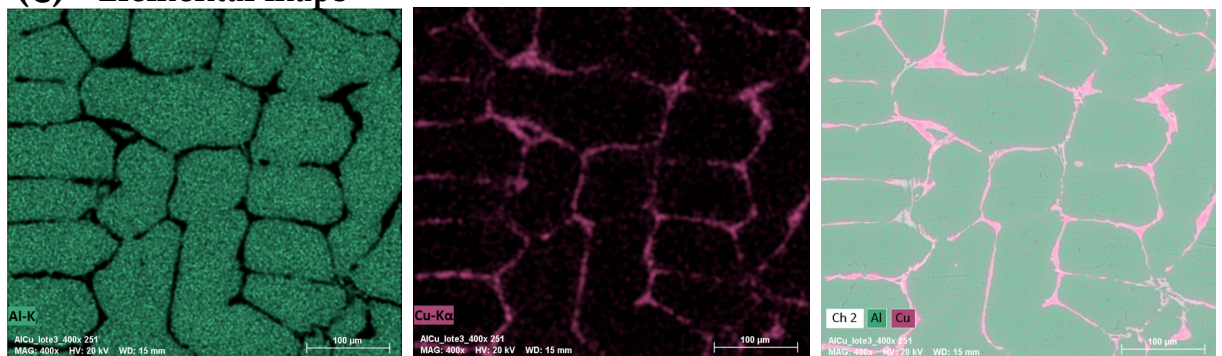


Figure 3. (a) Typical SEM/BSE images characterizing both the feature of (a) the coarse and (b) the fine dendritic arm spacings (λ_2) sizing of about 150 μm and ~30 μm, respectively; and (c) the elemental maps showing the Al-matrix and Cu-rich regions (including Al₂Cu phase).

Figs. 4(a) and 4(b) characterize the typical SEM/BSE images corresponding with the two different magnifications (50x and 100x) of the samples transversally compacted (T4 treated), which are entitled as the transverse samples, as previously mentioned. Figs. 4(c) and 4(d) demonstrate also the two distinct magnifications (50 and 100x) for the longitudinally compacted samples (designated as longitudinal samples).

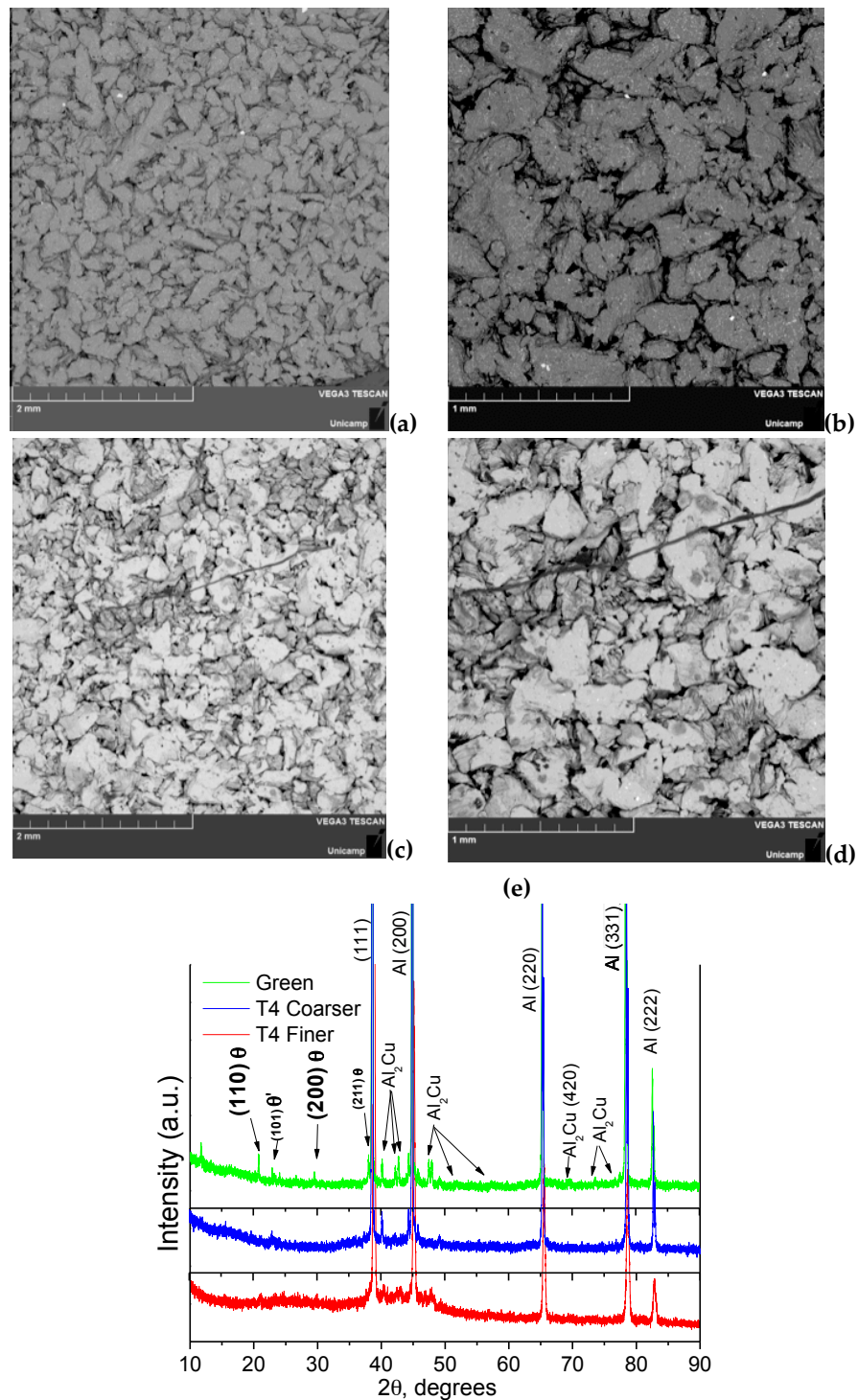


Figure 4. (a) Typical SEM/BSE images depicting morphologies of: (a) and (b) the sample transversally compacted, (c) and (d) the sample longitudinally compacted at 600 MPa; and (e) the resulting XRD patterns corresponding with the green sample, T4-treated with the coarse and the fine dendritic spacings with its corresponding detected Al₂Cu phases (JCPDS # 01-1180).

When the SEM images shown in Fig. 4 are compared, it is observed that a slight tendency to more flattened morphology favors the transverse sample; and a morphology more spheroidal characterizing the longitudinal sample is constituted. It is worth noted that the initial powder particles (flaked-like morphology, shown in Fig. 1) are identical for both the transverse and longitudinal samples. This induces that the distinctive compaction directions provide slight differences in the compacted particles morphologies. It was previously reported that both the transverse and longitudinal samples have also very similar compressibility capacities [24]. This suggests that the deformation capacity is identical under same compaction pressure. This is attributed to the nature of initial powder utilized (i.e. magnitudes of the particle sizes, chemical composition and morphology).

After compared these compacted morphologies, the resulting XRD patterns are also analyzed, as shown in Fig. 4(e). The two T4 treated samples are compared with a typical green sample (no sintered or treated), which was only compacted. Based on this comparison, it is evidenced that both the T4-treated coarse and fine samples have decreased those intensity peaks correlated with the θ -Al₂Cu, mainly those corresponding with crystallography planes (110) and (200) at ~21 and 29 degrees, respectively. Other peaks corresponding with the θ -Al₂Cu phase are also decreased, but few substantial as occurred with (110) and (200) planes. This suggests that the main θ Al₂Cu phases have partially dissolved into the Al matrix, which seems to be constituted a supersaturated solution. Forwardly, this observation will be help to explain the reason that the mechanical results are improved. Zhang et al [37] have also previously reported similar results.

Since compared the induced-Al₂Cu phases after the T4 treatment and the resulting morphologies attained, it is remained to verify the resulting mechanical behavior reached in each one of the different dendritic spacings and to analyze their correlation with the mechanical responses. In this sense, in the next section both the tensile and compressive strengths are discussed.

3.2. Anisotropic Tensile and Compressive Strengths

Fig. 5 demonstrates the experimental results of the tensile strengths of both the transverse and longitudinal samples. Duplicate results are depicted in each one of the plotted graphs. Fig. 5(a), (b) and 5(c) show the tensile strengths results of the transverse samples using the three distinct compaction pressures, i.e. 300, 400 and 600 MPa. It is clearly observed that the increase of the compaction pressure, the UTS results of both the fine and the coarse samples are also increased. These results are summarized in Table 1 in order to facilitate the comparisons among the examined samples. A comparison among all examined transverse samples are depicted in Fig. 5 (d). Since all examined longitudinal samples have demonstrated similar (or equal) tendency, a typical stress vs. strain curves utilizing the fine and coarse dendritic spacings as initial powders is shown in Fig. 5 (e). This occurrence seems to be associated with the compaction method, which provides a neutral line located approximately at the same line or fracture plane, i.e. perpendicular to the tensile direction. It is remarked that these samples are bi directionally compacted, but the neutral line is not prevented. Based on this, the tensile strengths of these longitudinal samples will be considered as those results obtained from the diametric compression, as also previously reported [24].

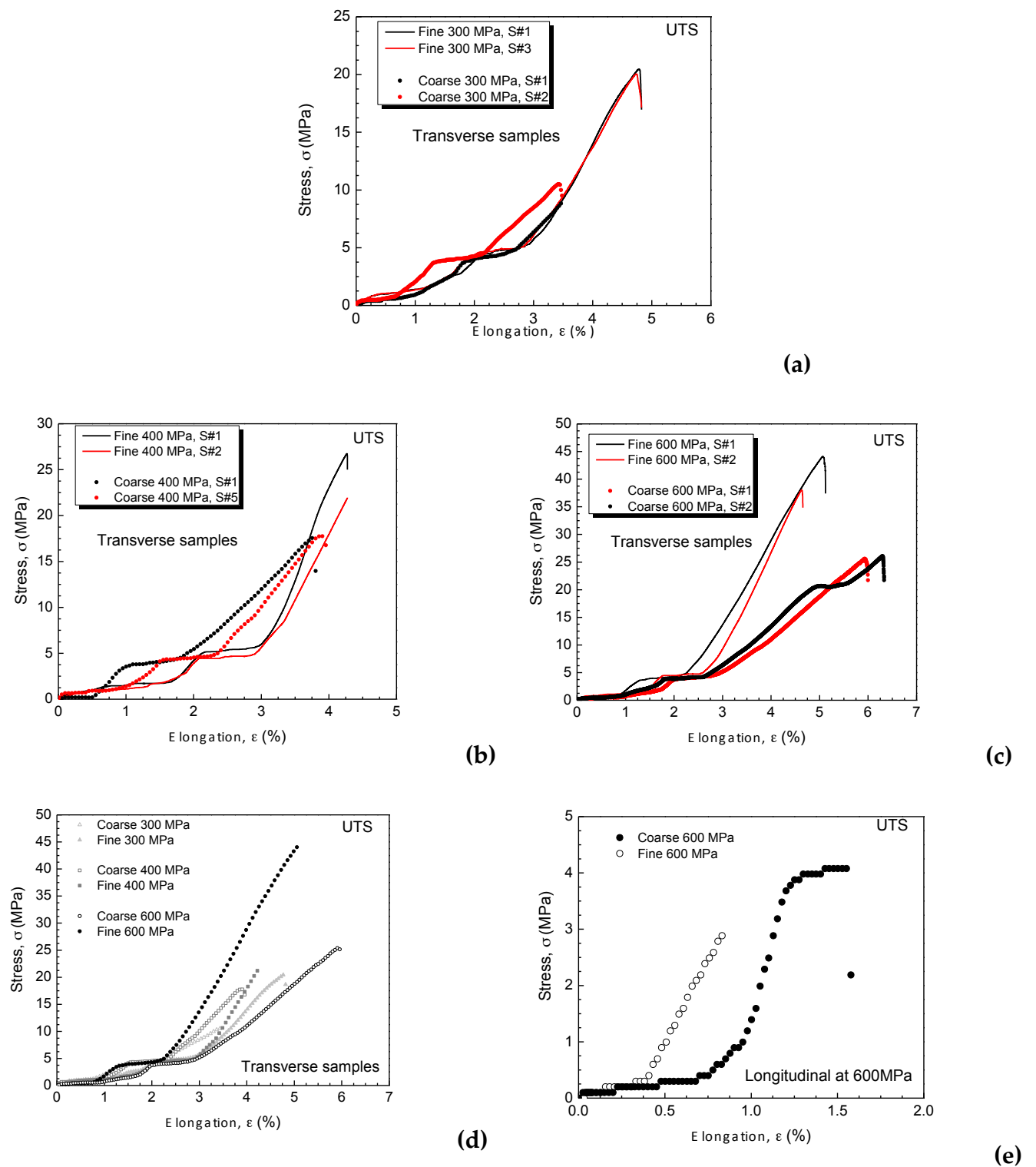


Figure 5. The experimental results of the tensile strengths (stress vs. strain) of the Al-4Cu composite samples using the coarse and fine dendritic spacings as initial powders, and the compacted at the transverse direction using: (a) 300 MPa, (b) 400 MPa and (c) 600 MPa and (d) comparison among all transverse samples. Typical stress vs. strain curves utilizing the fine and coarse dendritic spacings as initial powders, which were compacted at the longitudinal direction.

Table 1 summarizes the ultimate tensile strengths (UTS) and elongations (ϵ) of the all examined transverse and longitudinal samples. It is evidenced that when the initial powders containing finer dendritic arm spacings are observed, the UTS results are higher than those samples containing coarser spacings, i.e. $\sim 1.5\times$ utilizing compaction pressure of 300 and 400 MPa, and of about $1.7\times$ when 600 MPa is used. Comparing the UTS among the coarse spacings samples and among the fine spacings, the increase of about $1.5\times$ in the compaction pressures is reached. An increasing of about $1.5\times$ is also reached, as also observed in previous investigation [24]. As aforementioned, all longitudinal samples have reached the same order of magnitude of both the UTS and ϵ . This is intimately associated with the neutral line provoked when the longitudinal samples are compacted.

Table 1. Summarized values of the UTS (ultimate tensile strength) and elongation (ϵ) obtained from the stress vs. strain curves of the Al-Cu alloy samples utilizing two the distinct dendritic arm spacings (λ_2) inside the initial powders. The samples are compacted in both the transverse and longitudinal compaction directions.

Compaction Pressure	Dendritic Spacings	TRANSVERSAL		LONGITUDINAL	
		UTS (MPa)	ϵ (%)	UTS (MPa)	ϵ (%)
300 MPa	Fine	20 (± 2)	5 (± 1)	2.0 (± 0.5)	0.3 (± 0.05)
	Coarse	13 (± 2)	4 (± 1)	2.5 (± 0.5)	0.5 (± 0.05)
400 MPa	Fine	25 (± 2)	4 (± 1)	2.8 (± 0.3)	0.3 (± 0.05)
	Coarse	17 (± 2)	4 (± 1)	2.2 (± 0.6)	0.4 (± 0.05)
600 MPa	Fine	43 (± 3)	5 (± 1)	3.8 (± 0.5)	1.0 (± 0.05)
	Coarse	25 (± 2)	6 (± 1)	3.2 (± 0.6)	0.8 (± 0.05)

Figs. 6(a), 6(b) and 6(c) depict the experimental results of the compressive tests in the longitudinal directions utilizing the fine and coarse dendritic arm spacings and under the three distinct compaction pressures. Fig. 6(d) and 6(e) show the results of compressive strengths corresponding with the samples utilizing both the fine and coarse spacings and adopting the three compaction pressures considering the transversally compacted samples, respectively.

As also observed to the tensile strength results, the ultimate compressive strength (UCS) increases with the increase of the compaction pressure (of about $1.3\times$). Similar results are observed when the T4 and the sintered samples are compared [24]. Besides, the samples with finer dendritic arm spacings have shown their corresponding UCS values at least $1.9\times$ higher than the coarser ones. When the longitudinal samples are compared, also those samples produced using powders with finer arm spacings provide the UCS higher ($\sim 1.6\times$) than the coarser ones. It is remarked that the stress vs. strain for all examined samples have similar shaped-curves with the three distinct regions. A first region designated as nonlinear elastic region, the quasi-linear elastic and the last region characterizing the stable crack extension, as also previously reported [38].

Table 2 shows the UTS values, elongations and diametrical compression (DC) based on Hertz's equation, as previously reported [23–24, 38–39]. The determined DC values are used in order to calculate the anisotropy ratio (AR) or the anisotropy degree. Although the DC corresponds with the indirect tensile strength and commonly is determined for composites and ceramic composites, it was previously reported [24] that the DC represents perfectly the tensile strength of the Al-Cu powders as sintered and T4 treated samples. Based on this, the DC results are used to determine anisotropy ratio

(AR). This due to the UTS results determined in the longitudinal samples have not evidenced tendencies or behavior. This occurrence is associated with the neutral line (or plane) formation when the bidirectional compaction is carried out, as previously mentioned.

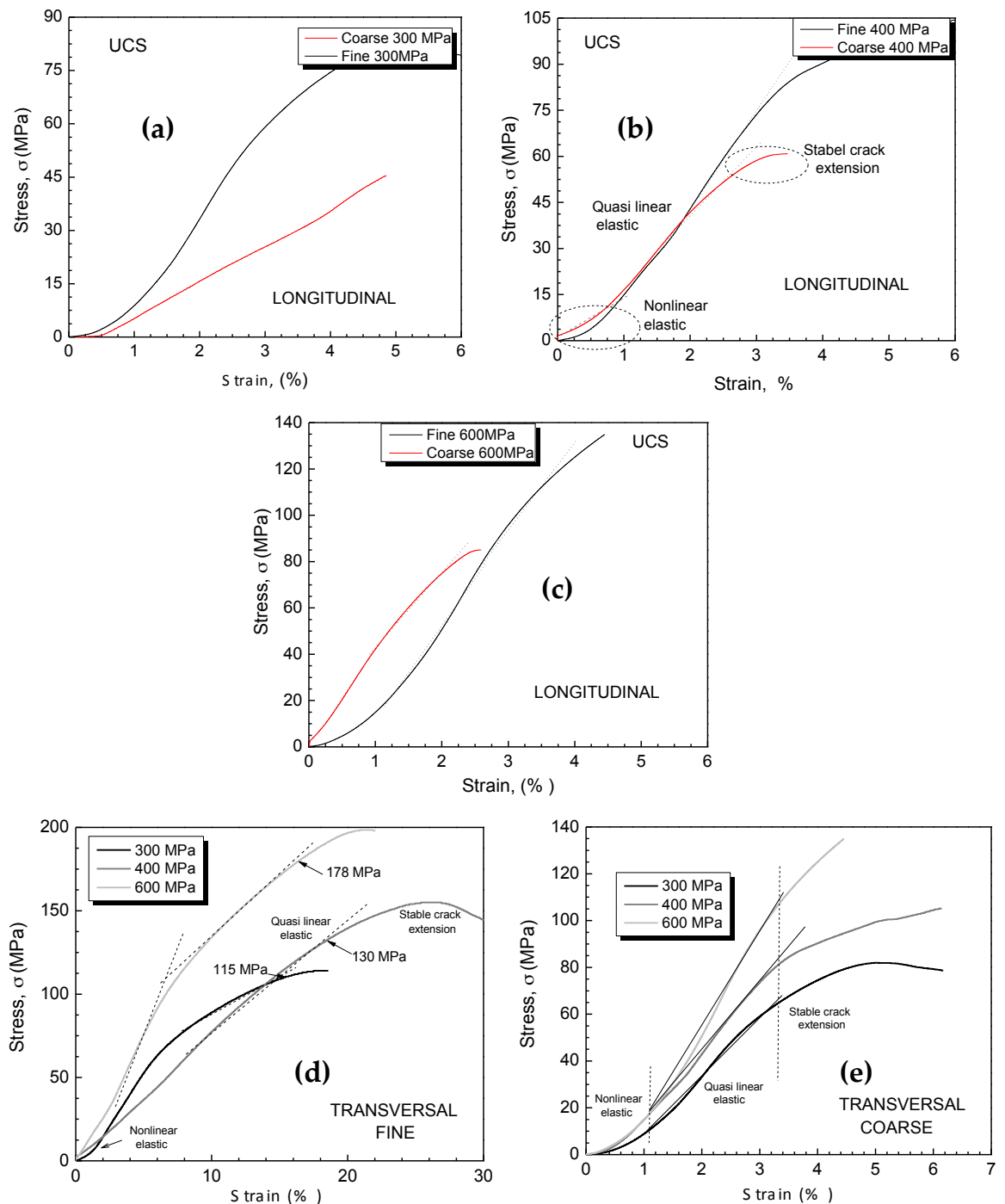


Figure 6. Experimental results of the compressive strengths (stress vs. strain) of the samples utilizing coarse and fine spacings compacted in the longitudinal direction: (a) at 300 MPa, (b) 400 MPa and (c) 600 MPa. The transverse samples under the three compactions with: (d) finer and (e) coarser arm spacings.

Table 2. Experimental UCS (ultimate compressive strength), elongation (ϵ), diametrical compression (DC) and anisotropic ratio (AR) considering both the finer and coarser dendritic arm spacings inside the initial powders utilized to produce the Al-Cu alloy composites.

Samples	Finer spacings				Coarser spacings			
TRANSVERSAL	UCS (MPa)	ε (%)	DC* (MPa)	AR **	UCS (MPa)	ε (%)	DC* (MPa)	AR **
300 MPa	120 (± 10)	2.0 (± 0.5)	--	0.183	60 (± 5)	3.5 (± 0.5)	--	0.200
400 MPa	130 (± 8)	2.2 (± 0.5)	--	0.192	80 (± 5)	3.0 (± 0.8)	--	0.213
600 MPa	180 (± 10)	1.6 (± 0.5)	--	0.250	110 (± 8)	3.0 (± 0.6)	--	0.227
LONGITUDINAL	UCS (MPa)	ε (%)	DC* (MPa)	AR **	UCS (MPa)	ε (%)	DC* (MPa)	AR **
300 MPa	75 (± 5)	3.5 (± 0.5)	10 (± 4)	0.133	45 (± 5)	3.5 (± 0.5)	9 (± 3)	0.191
400 MPa	90 (± 5)	3.0 (± 0.5)	13.5 (± 0.5)	0.150	60 (± 8)	2.5 (± 0.5)	11.5 (± 3)	0.200
600 MPa	135 (± 8)	3.0 (± 0.5)	27 (± 3)	0.200	80 (± 10)	2.0 (± 0.5)	23 (± 0.8)	0.288

* DC = $2 \times F / \pi \times L \times D$, where F is the load at failure, L and D are the initial length and diameter of the sample [12-13; 26-27].

** AR = UTS/UCS (Anisotropy Ratio)

Figs. 7(a) and 7(d) show the specimens of the Al-Cu composites designated as the transverse and longitudinal samples. Fig. 7(c) depicts the longitudinal (cylindrical) sample after the tensile test, which has induced to a tension in the same direction of the compaction direction. Fig. 7(d) shows a transverse sample (flat specimen) after the tensile test, which was carried out in a perpendicular direction with relation to the compaction direction. The fracture plane in the cylindrical specimen (longitudinal sample) is perpendicular to both the compaction and tensile testing directions. On the other hand, the flat specimen (transverse sample) has their fracture plane perpendicular to the tensile test, but at parallel to the compaction direction. Figs. 7(e), 7(f) and 7(g) depict the three flat specimens subjected to the compression tests, which are perpendicular to the compaction direction. It is clearly observed that the distinct cracks are produced. Fig. 7(e) is a post-mortem transversal compression (using powder with finer arm spacings) carried out in a transverse sample compacted using a pressure of 300 MPa. It is observed a crack displayed in the central region of the specimen and extended in the same direction of the compressive load (vertical). Figs. 7(f) and 7(g) are similar samples, which were compacted using 400 and 600 MPa, respectively. It is clearly observed that the cracks extend differently from that occurred in Fig. 7(e), which the crack damage is more pronounced. Fig. 7(g) shows smaller cracks than other examined sample and more homogeneously distributed to bulk of the specimen.

Figs. 7(h) and 7(i) show the typical fractographic images after the tensile tests of the flat and cylindrical specimens, respectively. It is reasonably perceived that the flat (transverse) sample is more consolidated in terms of the coalescence of particles and bonding than the longitudinal sample. It is recognized that the intergranular fracture, smooth surface without dimples formation characterizing cleavage facets are main features associated with the low plastic deformation indicating a brittle fracture [39-40]. Distinct fracture mechanisms considering nano, micro and macro-reinforced matrix metal, considering Al-based composites are reported [41-44].

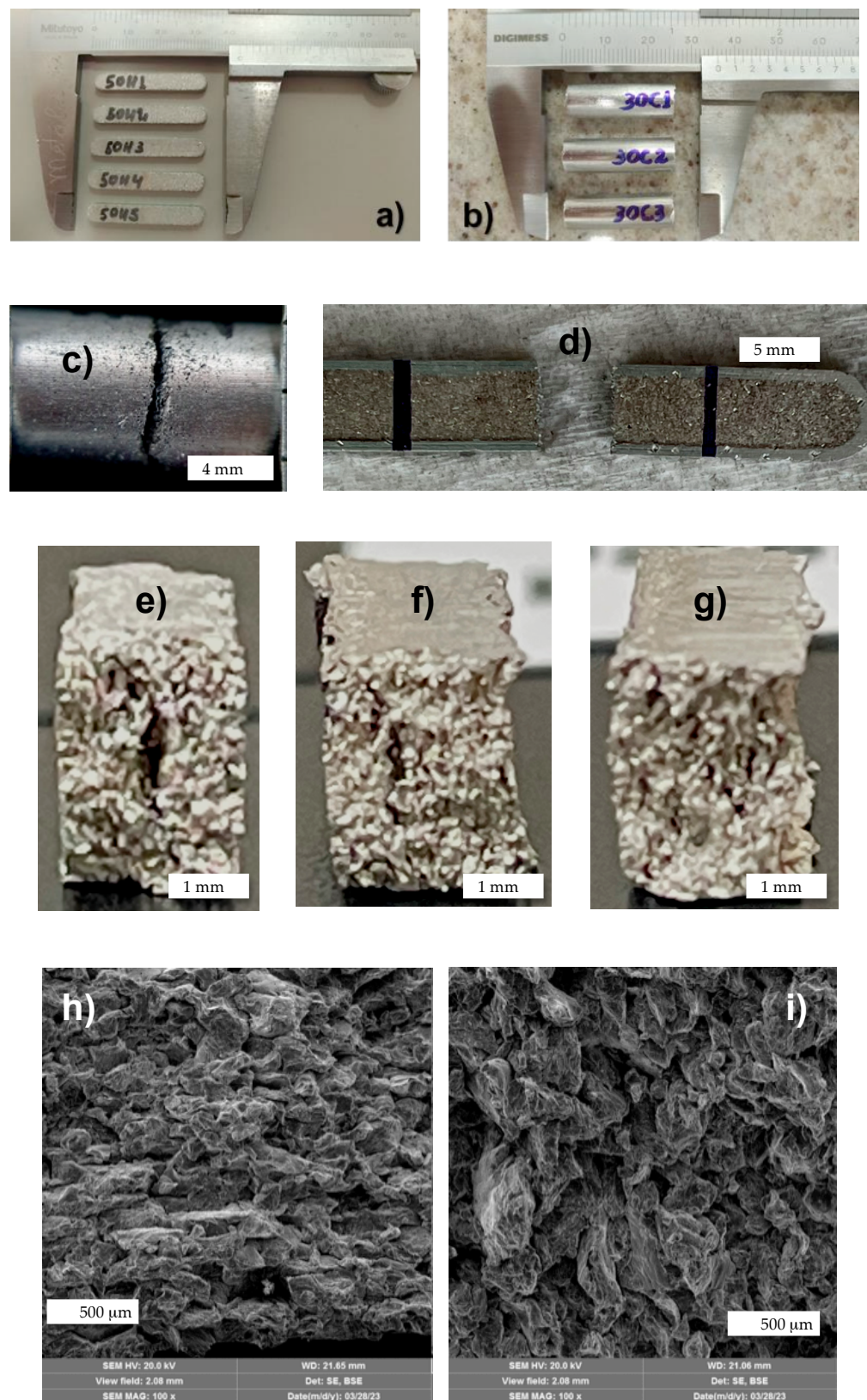


Figure 7. The compacted and sintered samples: (a) flat (transverse) and (b) the cylindrical (longitudinal) samples, (c) typical fracture in the cylindrical sample, (d) typical fracture in the transverse sample; the resulting crack aspects in the sample compacted at: (e) 300 MPa, (f) 400 MPa and (g) 600 MPa evidencing distinct crack distributions; and (h) and (i) are the SEM images (magnification 100x) showing the fracture surface of a flat (transverse) and the cylindrical (longitudinal) samples, respectively.

It is reported that the particle size, spatial distribution and nature (brittle or ductile) of particles (as reinforce or initial powders) have important roles for the fracture mechanism and consequently upon the resulting mechanical behavior. Yang et al [41] have recently reported that an A356 alloy containing a dendritic formation as microstructural characteristic, the sample with the fine dendrites has crack propagation occurring predominantly in a *trans-dendrite* path (~62% of the total length of cracks in fracture section). On the other hand, when a coarser microstructure arrays is examined, the fracture mechanism favors that the cracks occurring along the eutectic regions [41].

Although any correlation with the fracture aspect and/or with the fracture mechanisms (evidencing *trans-dendritic* or *transgranular* cracking propagation) is clearly confirmed, it seems that the transverse sample has a less “porous” or less rough surface than the cylindrical (longitudinal) sample. It can be said that a mixture between brittle and ductile fractures domains the resulting mechanism for all examined samples. The longitudinal sample seems to be slightly more ductile than the transverse samples, which can be confirmed with those UTS and elongation shown in Table 2. Additionally, it is presumed that the transverse sample has more bridging effect increasing the bonding energy due to the interface among the elongated/deformed particles, as also previously reported by Galen and Zavaliangos [18].

3.3 Anisotropic Ratios

Fig. 8(a) and 8(b) summarizes the UCS (ultimate compressive strength) and the UTS (ultimate tensile strength) as a function of the compaction pressures considering both the coarser and finer dendritic spacings. It is evidenced that both the compaction direction and refinement of the dendrite spacings affect significantly the resulting mechanical responses. The highest UTS and UCS are attained when the transverse and finer arm spacings are considered.

A correlation between the UCS and UTS is shown in Fig. 8 (c). As also previously reported [24], a nonlinear trend is characterized. A unique logarithmic equation (i.e. $UCS = 69 \ln(UTS) - 90$) describes the trends for both the transverse and longitudinal samples, but when the powder with finer dendritic arm spacings are utilized. Interesting this trend equation is very similar to that obtained when the transverse and longitudinal samples for the sintered Al-Cu alloy samples were investigated, i.e. $64 \ln(UTS) - 80$. On the other hand, when the sample utilizing powders with the coarse dendritic spacings, the tendency for the longitudinal sample is different of the transverse sample. The ratio between the UCS and UTS of the transverse sample is higher than the ratio of the longitudinal samples, as depicted in Fig. 8(c).

The strength anisotropy or anisotropic ratio is determined by determining the ratio between the UCS and UTS considering the transverse and longitudinal samples associated with the coarse or fine dendritic arm spacings to produce the samples. Galen and Zavaliangos [18] have stated that the anisotropy ratio for deformable materials is lower than 1 and becomes smaller with increasing the densification.

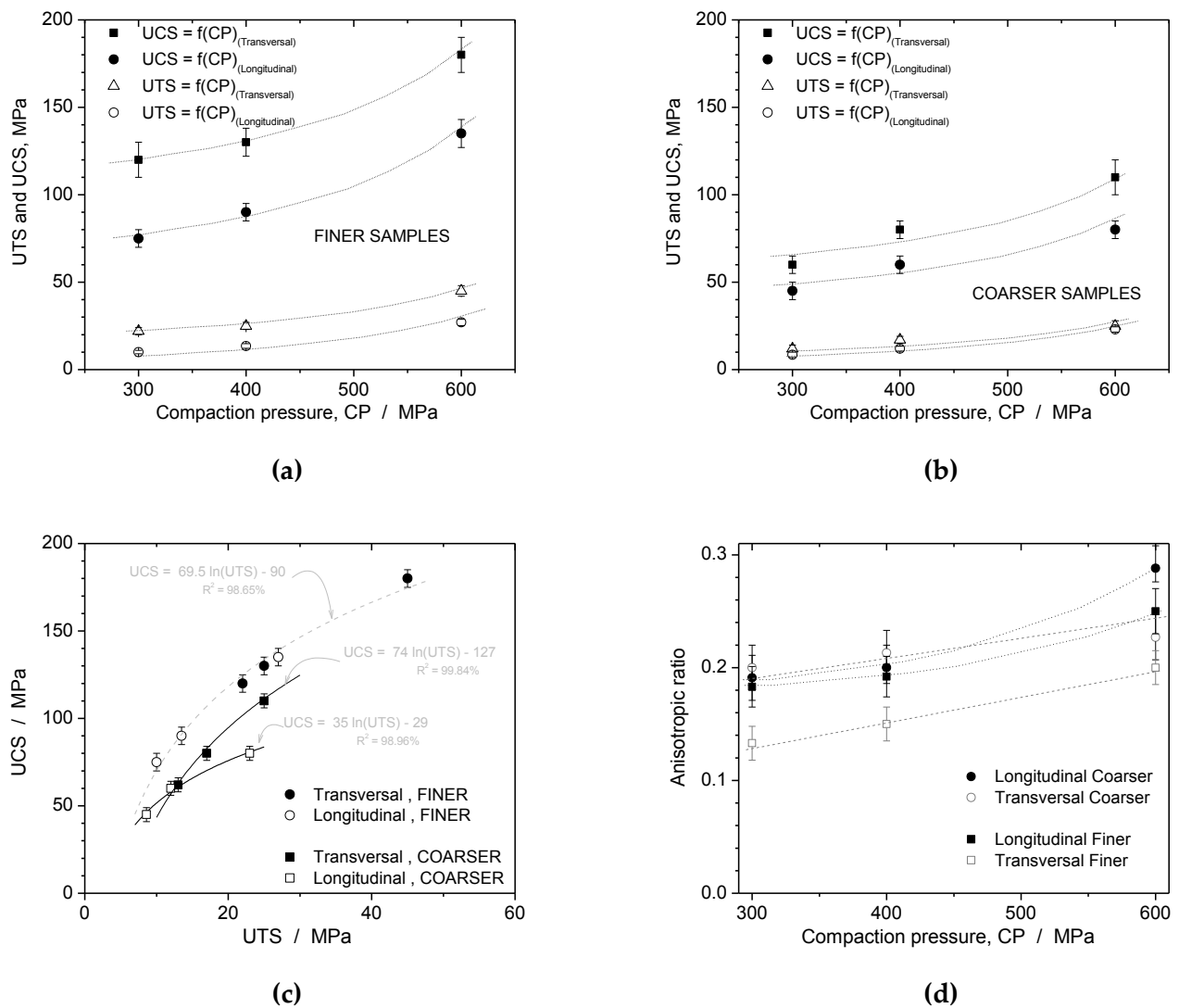


Figure 8. The experimental results of the UTS and UCS vs. the compaction pressure (CP) considering: (a) finer and (b) coarser dendritic arm spacings; (c) correlation between the UCS and UTS; and (d) the anisotropic ratio between the UCS and UTS for the longitudinal and transverse samples considering both the coarse and fine dendrite arm spacings.

Fig. 8 (d) shows the strength anisotropy ratio (AR) as a function of the compaction pressure. It is verified that all examined samples have the AR lower than 1. This suggests that these examined samples exhibit the ductile behavior, as reported by Galen and Zavaliangos [18]. However, a ductile material commonly demonstrates its degree of anisotropy decreasing with the increase of the densification, i.e. with the increase of the compaction pressure. Based on the attained AR results, all examined samples show increasing trends with the increase of the compaction pressure. This suggests that the examined samples become more isotropic with the increase of the compaction pressure.

This means that independent of the compaction direction, i.e. longitudinal or transversal, there exist a trend to become more isotropic with the increase of the compaction pressure. It is important to remark that this tendency is not permanently observed when the ductile materials are compacted, as the case of the Al-Cu alloy powders utilized in a previous investigation [24]. In this mentioned study [24], the transverse samples have demonstrated the anisotropic ratios quasi-linearly increased trends, while the longitudinal samples shown non-linear decreasing trends. This was verified independently of only a sintering treatment is applied or if the T4 is carried out. Additional-

ly, the effects of the heat treatments have also revealed that the sintered longitudinal samples are more isotropic or less anisotropic than the T4 treated longitudinal samples.

Galen and Zavaliangos [18] have reported that a same material with non-equiaxed morphology (acicular) has higher strength anisotropy than the same material with equiaxed morphology. In a previous investigation [24], it was also observed a same tendency (decreasing) when the longitudinal samples produced with the Al-Cu alloy powders are considered. It is found that the morphology, the compaction pressure and the heat treatments are important parameters affecting the anisotropic strength.

Additional to these studies, and based on the foreshown results, it is found that the microstructural arrays constituting the initial powders (i.e. distinct dendrite arm spacings) have also important roles on the anisotropic ratio. It is recognized that there is a limitation in this present investigation due to, up to the present moment and considering the analyzed results, it is not possible to determine or to state if the dendritic spacings are more influent than other parameters, or if there exists a conjugated or associated effect among them. Although a very similar tendency of the correlation between the UCS and UTS is verified when compared with previous study [24], i.e. $69.5 \ln(UTS) - 90$ and $64 \ln(UTS) - 80$, respectively, the correlation AR vs. compaction pressure demonstrates that both the AR trends of the longitudinal and transverse samples are increased. Also, transverse and longitudinal samples exhibit nonlinear and linear trends, but in this investigation, all AR trends are increased trends and previous one has opposite trends. Another interesting observation that is different from previous study is the fact that, for example, at 300 and 400 MPa, excepting the transverse sample with finer arm spacings, all examined samples have shown AR values in a same order of magnitude.

When at 600 MPa the AR is analyzed, slight differences are observed, as can be seen in Fig. 8(d). The longitudinal samples (with coarse and finer arm spacings) have the AR between ~0.24 and 0.30, while those corresponding with the transverse samples (coarser and finer) are slight lower (between 0.18 and 0.22) than the longitudinal ones. Interesting when observing the AR values at 600 MPa in previous study [24], the AR for all examined samples are similar (~0.14), excepting for the T4 samples with the AR is 0.08.

At 600 MPa the anisotropy ratios demonstrate a decreasing sequence with the highest ratio is that of the longitudinal coarser spacing sample followed by the longitudinal finer spacing sample and the transverse samples with the coarse and fine arm spacings at the last two positions; and the lowest value is that of the transverse finer spacing sample. This evidences that the transverse samples, when compacted at 600 MPa have higher differences between the UCS and UTS values and the finer dendrite arm spacings contribute to increase the mentioned difference. Although there are differences in the UTS and UCS values depending on the microstructural refinement, a same order of magnitude in the UCS is attained. For example, the longitudinal finer spacings sample has an UCS reaching of about 90 MPa and the transverse coarser spacings sample reaches of about 80 MPa. Considering the error ranges, equal ranges of values are attained. This shows that depending on the compaction level intended, a planning in the compaction direction should be preprogrammed, or vice versa. Also, when a restriction or limitation in the compaction direction and pressure (e.g. 400 MPa) is prevalent in a certain project or component, it can also be programmed or planned if a powder is obtained from the ingots or from the recycled alloys which possess a more refined microstructural arrays.

With this, it seems that the dendrite arm spacing confirms its effect on the AR of Al-Cu alloys produced using powders constituted by the distinct sizes of the dendrite spacings. Associating with this very recognized metallurgical effect to the compaction direction, the highest mechanical behavior is that of the sample produced with finer spacings and applying a compaction in the transversal direction. Considering the effects of the dendritic arm spacings on the anisotropy strength, it can be stated that the largest anisotropy ratio is that of the sample with finer dendrite arm spacing, which has its transverse strength of about 1.5 times higher than the longitudinal strength (considering

both UTS and UCS results). Similar observation is perceived when Galen and Zavaliangos [12] have investigated the anisotropy strength in the steel powders and associating with the resulting morphology powders, and not correlating with the microstructural refinement. Additionally, the finer arm spacings associated with the compaction carried out in the transversal direction, the highest anisotropy ratio is constituted.

4. Conclusions

Based on the attained results of mechanical behavior using two distinct powders containing different dendrite arm spacings (coarse and fine) of the as-cast Al-Cu alloy, the following conclusions can be drawn:

- It is found that, although distinct microstructural arrays (i.e. dendrite spacings) are obtained as a function of the cooling rates applied, very similar morphologies of the drilled powders are attained. Also, all crystallographic phases identified are very similar for all examined samples. After the compaction and sintering, the identified phases are identical to those in the as-cast condition.
- It is also found that the increase of the compaction pressures both the UCS (ultimate compressive strength) and UTS (ultimate tensile strength) are also increased. When analyzing the sample compacted at transversal and longitudinal directions, it is evidenced that the UCS and UTS values corresponding with the transverse samples are higher (~1.5x) than the longitudinal samples. When the powders utilized to produce the specimens are separated between finer (~30 µm) and coarser (~150 µm) dendritic spacings, it is revealed that the fine dendritic spacing provides a higher UCS and UTS in both the transverse and longitudinal samples. This induces that the dendritic spacings have also important roles to determine the anisotropic strengths of the samples examined.
- The anisotropic ratio (AR) is determined using the UTS/UCS ratio. Based on the attained AR results, it is found that all examined samples have shown the increasing tendencies with the increase of the compaction pressure. This induces that independent of the compaction directions, i.e. longitudinal or transversal, a tendency to become more isotropic with the increase of the compaction pressure is characterized.
- When the UCS per UTS ratios are analyzed, a unique mathematic relation describes this trend ratio (i.e. $69.5 \ln(UTS) - 90$) involving both the transverse and longitudinal samples. However, it is interestingly observed that when only the samples containing the fine dendrite arm spacings are considered. When the longitudinal and transverse samples with coarser dendritic spacings are examined, the UCS/UTS ratios characterize two distinctive equations to describe the tendencies, which are different from those determined to the samples with finer spacings.
- Considering the anisotropy ratios, independently if coarser or finer arm spacings are considered, the transverse samples have depicted linear increasing trends. On the other hand, the longitudinal samples considering both coarser and finer arm spacings, nonlinear increasing trends are clearly established. Although it is not possible to determine how much the dendritic spacing overlaps or overestimates the effects of the compaction directions (transverse or longitudinal), the compaction loading and the powder morphology, it is evidenced that they have important roles up on the anisotropic strengths. It seems that the effect is combined or conjugated with the compaction direction, which affects significantly the tensile and compressive anisotropic strengths.
- It is also found that at 300 and 400 MPa, excepting the transverse sample with finer arm spacings, all examined samples have same order of magnitude for the anisotropy degree. Interestingly, at 600 MPa, the anisotropy ratios depict a decreasing

sequence being: the highest ratio is that of the longitudinal coarser spacing sample followed by the longitudinal finer spacing sample and the transverse samples with coarser and finer arm spacings. Although there are differences in the UTS and UCS values depending on the microstructural refinement, a same order of magnitude in the UCS is prescribed. Depending on the compaction level intended, a planning in the compaction direction can be preprogrammed or vice versa. Based on the fact that the recycled powder particles from the conventional machining, drilling and turning can be considered. With this, environmentally friendly aspects are attained and hazardous stages are also substantially decreased or eliminated.

Author Contributions: R.S.B. and J.F.Q.R. have prepared alloy samples and also contribute with discussion and writing texts/discussion. R.S.B., R.F.G.B. and L.C.P. have carried mechanical behavior measurements, organized the data and also provide correlations. A.D.B. and J.F.Q.R have carried out the XRD measurements and organized and treated the data attained. A.D.B. has also helped with the general organization and with the English written manuscript. W.R.O., R.S.B, L.C.P. and A.D.B have contributed with the general organization of the experimentations and analyses and correlations. W.R.O. and A.D.B have also written and organized the proposed manuscript. All authors have read and agreed to the published version of the manuscript.

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