

Article

Investigation of Microstructure and Mechanical Properties of Layered Material Produced by Adding Al₂O₃ to 316L Stainless Steel

Osama Albahl Alstewe Albahlol ¹, Rajab Elkilani ¹, Harun Çuğ ¹, Mehmet Akif Erden ^{2,*},
Ramazan Özmen ³ and Ismail Esen ¹

¹ Department of Mechanical Engineering, Karabuk University, Karabuk 78050, Türkiye; osama.bella46@gmail.com (O.A.A.A.); rajabelkilani@gmail.com (R.E.); hcug@karabuk.edu.tr (H.Ç.); iesen@karabuk.edu.tr (I.E.)

² Department of Biomedical Engineering, Karabuk University, Karabuk 78050, Türkiye

³ Department of Mechatronics Engineering, Karabuk University, Karabuk 78050, Türkiye; ramazanozmen@karabuk.edu.tr

* Correspondence: makiferden@karabuk.edu.tr; Tel.: +90-370-418-7141

Abstract: This study developed new advanced composite materials consisting of functional grading of 316L and Al₂O₃ specially designed for potential biomedical applications. Mechanical properties were characterized by tensile testing, and microstructural properties by optical microscope, scanning electron microscope (SEM), and Energy Dispersive X-Ray (EDX) analyses. The uniform mixture in the material, up to 40% by weight of Al₂O₃, is uniformly distributed in the 316L matrix that shows disintegration. Then, samples with 2, 3, 4, and 5 layers were produced in functionally graded 6, 7, 8, and 9 material types, respectively. The layer thicknesses were formed with an average of 900 µm. The results show that new composite materials can be produced functionally using 316L and Al₂O₃ in a layered manner. As a result of the mechanical experiments, it has been observed that the tensile strength of the layered composite structures remains within the range of 91–191 MPa, depending on the layer type. It has been observed that the elongation varies between 3.16 and 12.46%. According to these results, the materials obtained are considered suitable for use as an alternative prosthetic material in biomedical applications. The tensile strength, % elongation of the Composition 7, and yield strength of functionally graded (316 + (316L-10 Al₂O₃) + (316L-20 Al₂O₃) + (316L-30 Al₂O₃)) material are 123 megapascals (MPa), 7.3%, and 111MPa, respectively, and according to the literature, the mechanical strength of human bone is very close to this composition properties.

Keywords: powder metallurgy; SS316L alloy; Al₂O₃; additive manufacturing; microstructure; mechanical property relationship



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1. Introduction

Powder metallurgy (PM) is a self-contained production method that is economical for mass production, produces no loss or a maximum of about 3% waste material during production, and generally does not require a secondary process. Thanks to these superior features, its preferability is increasing day by day, and it is an alternative to other known traditional methods. In addition, the parts produced by the PM method have a smooth, clean surface close to the final shape compared to other methods. Stainless steels, on the other hand, are known as a frequently preferred material group in many sectors, such as the biomedical industry, due to their excellent mechanical properties, their ability to maintain their mechanical properties at high and low temperatures, as well as their excellent wear, and corrosion resistance [1–5].

Austenitic stainless steels are the materials of choice in many industrial applications. High corrosion resistance, toughness, and good weldability are the properties that make austenitic stainless steel attractive for the industry [6–8].

Due to these properties, austenitic stainless steels are preferred in petrochemistry, implants, kitchen equipment, and automotive industries. As a result, many studies have been conducted to increase the strength, hardness, and toughness of austenitic stainless steel. In particular, researchers have tried to improve this material's mechanical properties without sacrificing its toughness [4,9].

Implants have been used for a long time in human history and have been developed as a replacement material for any damaged bone fragment in the body. In order for the implants to be in complete harmony with the body, the material used as the implant material should be developed from alloying elements that will not harm the body's chemistry. In cases where it will be used as a substitute for bone, Young's modulus should be close to the bone, be compatible with the body in a short time, and should not cause infection. AISI 316L material, known as a biomaterial, is also used as an implant material for high corrosion resistance, non-toxicity, and machinability [10–12].

Aluminum oxide (Al_2O_3), also called alumina, is also known as technical ceramic and is used in manufacturing advanced ceramics. Furthermore, alumina is used in construction, fuel cells, abrasive or chemical waste cleaners, microelectronics, etc. In addition to its excessive hardness, electrical resistance, corrosion resistance, and refractoriness, alumina is an inert material with the highest biocompatibility currently used in the clinical field [13,14].

It is a biomaterial used in sterilization devices, drug delivery systems, and ventilation tubes. Single-crystal alumina is used as a dental implant; if alumina is produced from particles smaller than $4\text{ }\mu\text{m}$, the modulus of elasticity rises to 30 Gigapascal (GPa) [15]. Therefore, its use as a biomaterial causes other problems. Reducing the mechanical properties by increasing the particle size is vital in its use as a prosthesis [15].

Canpolat et al. [16] reported successfully fabricating SS316L/ Al_2O_3 functionally graded material (FGM) for biomedical applications utilizing powder metallurgy, where the microstructure, corrosion resistance, and mechanical and bioactivity properties were examined. The FGM layers were made of three distinct composites with 5, 10, and 15 wt% Al_2O_3 and were made of 316L. The hardness of the layers rose with the alumina level, according to experimental results, and the powder metallurgy approach successfully produced FGM without cracks. According to the electrochemical test results, samples examined in Ringer's solution were more prone to pitting corrosion than samples tested in Hank's solution. After 7, 14, and 21 days of in vitro bioactivity experiments, the development of apatite layers was seen in each sample. Biocompatibility is considered to be increased by the development of hydroxyapatite (HA) [16].

Kuforiji and Nganbe [17] successfully created 50 wt% SS316L and 50 wt% Al_2O_3 composite samples using powder metallurgy. They claimed that the samples had the best microstructure, the highest density, hardness, and toughness, and as a result, the maximum wear resistance. Hence, compared to commercial SS316L, the inclusion of 50 wt% alumina particles resulted in a roughly 86% reduction in wear rate and a reduction in volume loss of up to 7.2 times [17].

Using the FGM technique, Radwan et al. [18] created a highly dense, crack-free stainless steel type 316L and alumina (SS316L/ Al_2O_3) from powders and stated that the hardness values progressively rose as the Al_2O_3 content increased [18].

Using powder metallurgy, Shamsuddin et al. [19] have created composite Fe-Cr- Al_2O_3 powders. They looked at how different alumina particle wt% affected the final physical characteristics of the composites, including density, shrinkage, porosity, and hardness. According to experimental data, the best wt% of reinforcement in the matrix is 20 wt%. Higher reinforcement wt% caused the reinforcement to cluster in the matrix, which increased porosity, and decreased the density of the composites, lowering their hardness [19].

Al-Moameri et al. [13] investigated the biological uses of alumina and found that it is quite inactive and corrosion-resistant. Alumina applies smoothly for several years and causes little tissue reaction. While many of the implants are polycrystalline, some are single crystals. It is frequently employed in load-bearing applications due to its exceptional

resistance to corrosion, superior tear resistance, biocompatibility, and high compressive strength. Alumina also possesses the best tribological characteristics for articulating surfaces in orthopedic implants [13].

Tsukamoto [20] has created continuous-gradient zirconia (ZrO_2)/304 stainless steel (SUS304) FGMs using centrifugal slurry techniques and spark plasma sintering (SPS). He looked at several continuous gradient patterns made possible by adjusting the concentration of a dispersant like ammonium poly-carboxylic acid (PCA) in the slurry. According to him, the gradient patterns in the FGMs switched from being rich in metal (SUS304) to being rich in ceramic (ZrO_2) as the amount of PCA increased. Simulations of Stokes sedimentation velocity show that SUS304 particles have a higher sedimentation velocity than ZrO_2 particles. The speed of the particles' sedimentation reduces as PCA is applied with higher amounts. Results from cyclic thermal shock tests showed that FGMs, 5-layered materials, and ZrO_2 single materials exhibited the strongest resistance among samples of FGMs with SUS304-rich continuous gradient patterns [20].

The structural, physical, and compressive mechanical characteristics of the (SS-316L)/HA, SS-316L/calcium silicate (CS) biocomposites, and FGMs on load-bearing applications were examined by Oshkour et al. [21]. They showed that mechanical characteristics of the FGM SS316L/HA declined as temperature increased. In contrast, the mechanical properties of the FGM SS316L/CS improved as temperature grew after sintering FGM samples at three different temperatures: 1000 °C, 1100 °C, and 1200 °C. Hybrid FGM comprising micro, and nano-sized hydroxyapatite (HA), stainless steel 316L (SS316L), and carbon nanotubes (CNT) were produced by Hussain et al. [22] for use in biomedical implants. The inclusion of CNT and nanocrystalline HA enhances the densification of the FGM. In addition, both FGM reinforced with CNT increased hardness and fracture toughness. However, the increase in hardness and fracture toughness is more pronounced in FGM with micro and nanocrystalline H.A. ZrO_2 /AISI316L functionally graded materials created using spark plasma sintering for a joint prosthesis by Mishina et al. [23]. They also investigated their mechanical and tribological properties. They claimed that the fracture toughness and wear resistance rose as the FGM's layer thickness grew (more than 2 mm). The impact of micro and nano-sized hydroxyapatite (HA) reinforcement on SS316L matrix functional grade materials was investigated by Akmal et al. [24]. A pressureless sintering process for bioimplants was used to create the FGMs. Unlike micro-sized HA FGMs, nano-sized HA FGMs demonstrated superior densification, hardness, and corrosion resistance.

A survey of the literature revealed that some research had been conducted on the fabrication of (FGM) made from SS316L/0–5–10–15 wt% of Al_2O_3 for biomedical applications. Research has also demonstrated that the production of SS316L/ Al_2O_3 involves using powder metal metallurgy to incorporate Al_2O_3 as a reinforcement component.

This study aimed to enhance the 316L stainless steel's mechanical characteristics because it is employed in two different ways as a biomaterial using powder metallurgical procedures. First, the samples were made by adding reinforcement compositions of 0%, 10%, 20%, 30%, and 40%wt of Al_2O_3 . Producing samples of functionally graded SS316L/ Al_2O_3 with 10%, 20%, 30%, and 40%wt of Al_2O_3 is the alternative. According to the literature, the prosthesis and implant made using FGM will be able to adapt to the body more quickly due to the increased amount of Al_2O_3 in the 316L matrix material. Al_2O_3 was added up to 15% by weight, and it was found that doing so caused more HA to form, which led to the conclusion that the biocompatibility had improved.

The Novelty of This Study

In this study, four new FGM and five single-layered materials with SS316L matrix with up to 40% Al_2O_3 reinforcements, which have never been studied before in the literature, were formed. In terms of the chemical composition, the number of layers, and the characterization of the material, such as the determination of mechanical properties by tensile test, single and layered production of 316L/ Al_2O_3 differs from previous studies in the literature. In the literature, for example, the quantity of Al_2O_3 reinforcement available via layered powder metallurgical process is up to 15%. Up to 40% was added in this

investigation. In the literature, cylindrical samples were typically made, and hardness tests were performed. Mechanical characteristics were measured using a tensile test in this investigation. Compositions 7 and 8 in this study have mechanical properties that are remarkably similar to human femoral cortical bone. These differences highlight the study's initial importance. The purpose of this research is to determine how different Al_2O_3 reinforcements, both single and multilayer, affect the microstructural, mechanical properties of 316L stainless steel produced by powder metallurgy. Materials with near-bone qualities were created when the results obtained were investigated in terms of mechanical properties [5–7,16]. Material development investigations for prosthetic applications have been more serious recently. As a result, the relevance of bone-like materials in the human body has increased. These materials are lightweight and resistant to fatigue, wear, and corrosion. [1–7]. In this study, nine different alternative composite materials were developed and characterized. Of these materials, the mechanical properties of Composition 7 (316L + (316L-10 Al_2O_3) + (316L-20 Al_2O_3)) and Composition 8 (316L + (316L-10 Al_2O_3) + (316L-20 Al_2O_3) + (316L-30 Al_2O_3)) are very close to the mechanical properties of human femoral cortical bone, where the tensile yield stress, ultimate tensile stress, and elongation are 71.56 MPa, 92.95 MPa, and 0.67%, respectively.

2. Materials and Methods

In this study, SS316L/ Al_2O_3 samples were produced by PM. Table 1 gives the purity, the size of SS316L, and Al_2O_3 powder. The effect of single addition (non-layered) alumina and functionally graded (layered) production of microstructure and mechanical properties were investigated. The steps used in producing the samples are shown in Figure 1.

Table 1. Powders and Properties.

	Elemental Powders	Powder Size (μm)	% Purity	Supplied Company
1	316L	<149	99.9	Höganäs [25]
2	Al_2O_3	28–70	99.5	Nanografi [26]

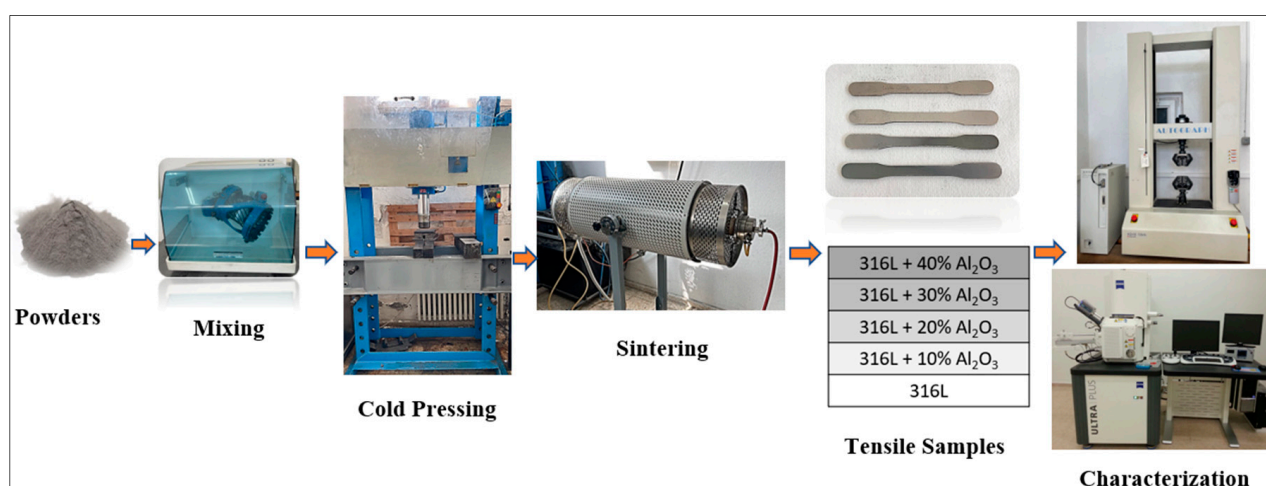


Figure 1. A schematic depiction of the fabrication stage.

In accordance with ASTM 8M requirements, mixed powders are pressed in a single direction at a pressure of 700 MPa [27]. The pressed samples were sintered for two hours at 1250 °C with a heating rate of 5 °C/min in an argon environment. Figure 2 displays the manufactured samples after sintering. The chemical makeup of the samples has been listed in Table 2.

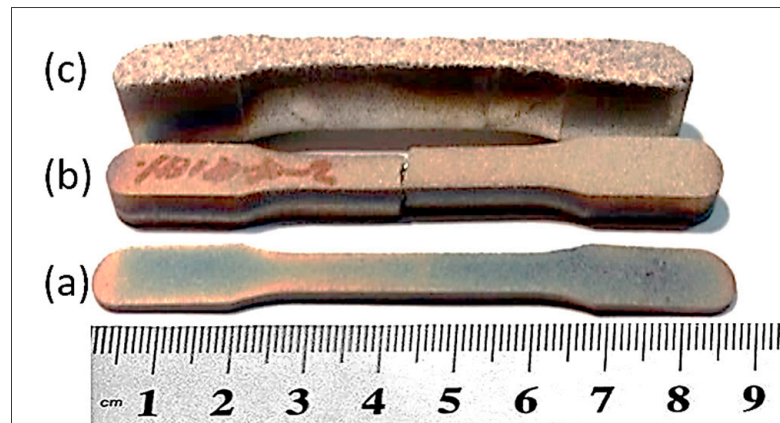


Figure 2. The produced samples after sintering. ((a)—Composition 1, (b)—Composition 7, (c)—Composition 9).

Table 2. Chemical composition of the samples produced.

Sample	Composition	Al ₂ O ₃ (%Weight)		316L (%Weight)
Composition 1	316L	-	-	100%
Composition 2	316L-10Al ₂ O ₃	10	-	90%
Composition 3	316L-20Al ₂ O ₃	20	-	80%
Composition 4	316L-30Al ₂ O ₃	30	-	70%
Composition 5	316L-40Al ₂ O ₃	40	-	60%
Composition 6	316L-(316L-10Al ₂ O ₃)	1. Layer	-	100%
		2. Layer	10	90%
Composition 7	316L-(316L-10Al ₂ O ₃)-(316L-20Al ₂ O ₃)	1. Layer	-	100%
		2. Layer	10	90%
		3. Layer	20	80%
Composition 8	316L-(316L-10Al ₂ O ₃)-(316L-20Al ₂ O ₃)-(316L-30Al ₂ O ₃)	1. Layer	-	100%
		2. Layer	10	90%
		3. Layer	20	80%
		4. Layer	30	70%
Composition 9	316L-(316L-10Al ₂ O ₃)-(316L-20Al ₂ O ₃)-(316L-30Al ₂ O ₃)-(316L-40Al ₂ O ₃)	1. Layer	-	100%
		2. Layer	10	90%
		3. Layer	20	80%
		4. Layer	30	70%
		5. Layer	40	60%

Employing a SHIMADZU tensile test instrument with a 50 kN capacity (Shimadzu, Tokyo, Japan) to apply the tensile test of sintered samples at 1 mm/min speed, ultimate tensile strengths, elongation% values, and yield strengths were calculated. Based on ASTM B 328-96, the density kit for the Radwag brand sensitive scale by Bruker Alpha, Bursa, Turkey, computed density using the Archimedes principle [28].

The surfaces of sintered samples were polished using a variety of mesh sizes of abrasive sheets (400, 600, 800, 1000, 1500, 2000, 2500, 3000, 4000, 5000, and 7000 meshes, from coarse to fine) prior to the use of an optical microscope. After that, 0.3 µm of Al₂O₃ suspension was polished. After being cleaned with distilled water, and ethyl alcohol, all samples were dried with hot air. Composition 1 sample was submitted to an electrolytic distribution with a 2-amp current intensity and 12 volts after being etched with 10 g of oxalic acid in 90 mL of clean water solution. Following the metallographic sample's fabrication, the sample's microstructure was examined by obtaining images under an optical microscope (Nikon

Epiphot 200) and a scanning electron microscope (Carl Zeiss Ultra Plus Gemini FESEM) with an enlargement capacity of $\times 50$ – $\times 1000$. The fracture surfaces of the tensile samples were also examined.

3. Results

Microstructure and tensile testing were performed on stainless steel materials made from 316L/ Al_2O_3 using the powder metallurgy process. Tensile curves for SS316L/ Al_2O_3 samples are presented in Figure 3. The results for density, porosity, and tensile strength are given in Table 3.

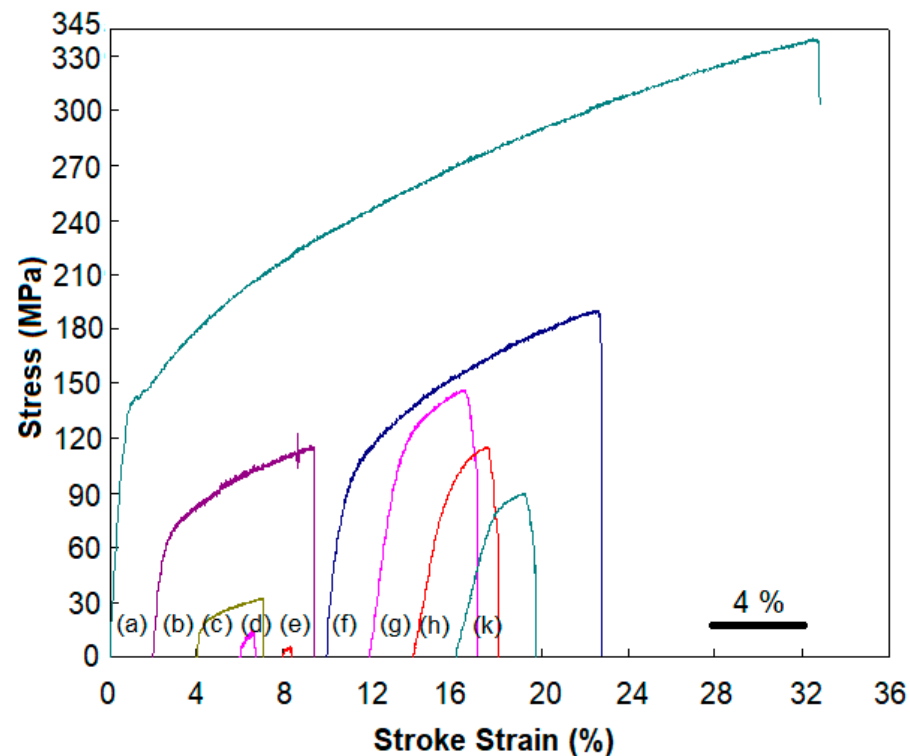


Figure 3. Tensile curves of 316L steel samples added in different amounts of weight (respectively) (Composition 1 (a), 2 (b), 3 (c), 4 (d), 5 (e), 6 (f), 7 (g), 8 (h), and 9 (k)).

Table 3. Tensile, density, and porosity results.

Composition	Yield Strength	UTS	Elongation (%)	Theoretical D. (gr/cm^3)	Experimental D. (gr/cm^3)	Density %	Porosity (%)
316L	145	340	32.54	7.95	7.11	89.43	10.57
316L-10 Al_2O_3	67	123	6.70	7.457	6.5143	87.36	12.64
316L-20 Al_2O_3	15	33	3.01	7.064	5.9159	83.75	16.25
316L-30 Al_2O_3	8	15	0.60	6.671	5.4632	81.90	18.10
316L-40 Al_2O_3	3	7	0.36	6.278	5.1117	81.42	18.58
316-(316L-10 Al_2O_3)	97	191	12.46	7.6535	6.7207	87.81	12.19
316-(316L-10 Al_2O_3)-(316L-20 Al_2O_3)	111	123	6.70	7.457	6.4926	87.06	12.94
316-(316L-10 Al_2O_3)-(316L-20 Al_2O_3)-(316L-30 Al_2O_3)	88	116	3.40	7.2608	6.3088	86.88	13.12
316-(316L-10 Al_2O_3)-(316L-20 Al_2O_3)-(316L-30 Al_2O_3)-(316L-40 Al_2O_3)	75	91	3.16	7.0626	5.8447	82.76	17.24

As expected, increased porosity was observed with the increase of Al_2O_3 in the form of a single layer (Composition 1, 2, 3, 4, and 5). An increase in pores showed a significant decrease in yield strength, tensile strength, and elongation%. This is also an expected situation. There are many studies on the negative effects of porosity on mechanical properties [29,30]. In addition, when the porosity values of the layered produced samples (composition 6, 7, 8, and 9) are examined, it shows that an increase in the number of layers also increases pores. However, when the compositions with single Al_2O_3 are compared, it is observed

that their mechanical properties are better; similar results have been reported in other studies [16,18,31]. Canpolat et al. determined that porosity increased with the increase in Al_2O_3 quantities in samples containing 0–5–10–15 wt% of Al_2O_3 [16,29]. When comparing Composition 7 with Composition 3, both compositions contain 20% Al_2O_3 by weight. However, while the tensile strength, % elongation, and yield strength values of Composition 3 are 33 MPa, 3.01%, and 15 MPa, respectively, the tensile strength, % elongation, and yield strength values of Composition 7 (4-layer composition) are 123 MPa, 6.70%, and 111 MPa, respectively. It has been observed that the layered sample (Composition 7) containing 20% Al_2O_3 by weight is seven times better in terms of yield strength and approximately three times better in terms of tensile strength compared to the sample (Composition 3) produced without a layer containing the same amount of Al_2O_3 . In addition, the percent elongation of Composition 7 was two times better than Composition 3, as shown in Figure 4. The reasons behind the better mechanical properties of the layered samples are the lesser porosity and the heterogeneity of the Al_2O_3 distribution in layered form. As a result, although the porosity values were close, the mechanical properties of the layered compositions were better than the unlayered compositions [16,18,31].

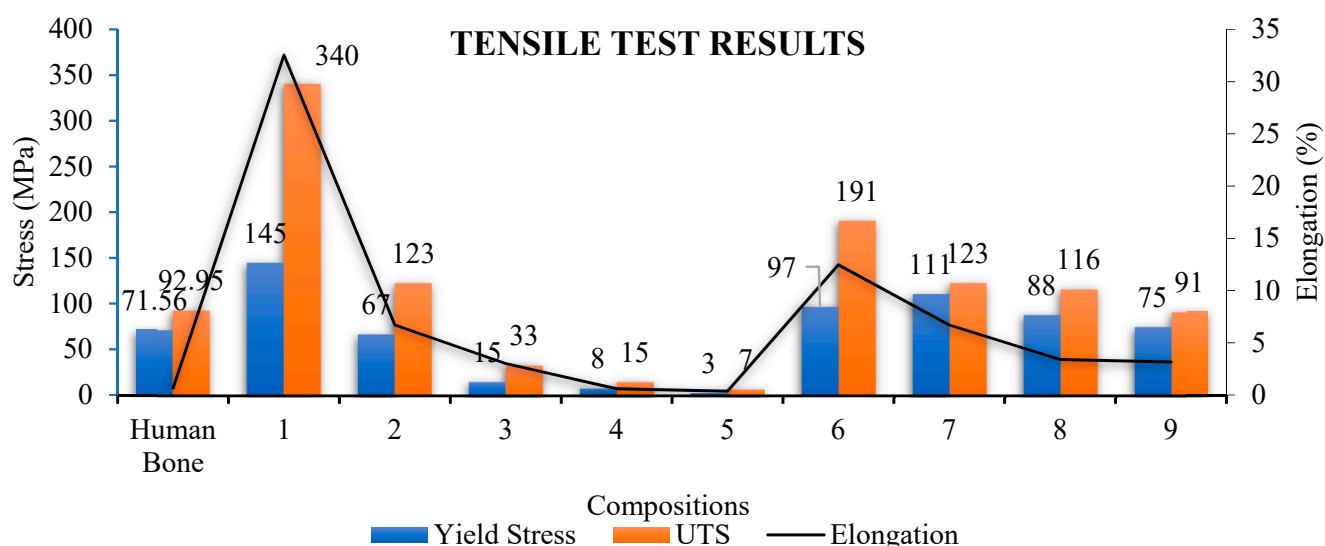


Figure 4. Yield stress, UTS, and elongation of 316L/ Al_2O_3 samples.

When the microstructure images in Figure 5 are examined, the gaps can be seen because the materials with different quantities of alumina and layer 316L materials are produced by powder metallurgy by making one-way cold pressing. This is due to small gaps in production made with powder metallurgy [32].

Figure 5a,b is examined in the pictures taken from the optical microscope. The Al_2O_3 composition and the Scanning Electron Microscope (SEM) microstructure in Figure 5c is examined in the material, and Energy-dispersive X-ray spectroscopy (EDS) analysis of the material added in the material as well as Al_2O_3 (spectrum 5), SiCrMoC (Spectrum 6), MoC(N), CrC(N), MoCrC(N), and CrMnMoC(N) in one, two, and multiple particles. In the literature, studies are conducted using SEM, X-ray diffraction analysis (XRD), and Transmission electron microscopy (TEM) to form single, binary, and multiple precipitates [33–53]. The interface properties of 316L/ Al_2O_3 are evaluated by giving optical microscope images in Figure 6. It is seen that the increase in the amount of Al_2O_3 significantly increases the porosity between the matrix and the Al_2O_3 reinforcing element and in the general microstructure. This adversely affects the mechanical properties [29,30].

These particles increase the strength of the material with strength-enhancing mechanisms such as grain size reduction, dispersion hardening, precipitation hardening, and clustering hardening [33,34,45,47,48]. Another study investigated the effect of Nb and

Al addition to micro-alloy steels produced with powder metallurgy on microstructure and mechanical properties and observed that the mechanical properties improved with Nb and Al addition. In the study, SEM, EDS, and XRD analyses were applied, and NbC was associated with precipitates, which occur with precisions, increased strength as well as grain size [35–43,49–54]. When Figures 7 and 8 are examined, it is observed that the production of single and layered composites up to 40% Al_2O_3 with 316L stainless steel matrix is carried out successfully. As the amount of reinforcement increases, it is observed that porosity increases. Similar results are shown in the literature [41–44]. Figure 9 shows SEM microstructure line EDS analysis taken from samples with different layers. When the line cuts the Al_2O_3 composition, it is observed that the Fe element rises. Figure 10 shows SEM Mapping analyses taken from the sample produced with layers. When Figure 10 is examined, it is observed that the amount of reinforcement of the Al_2O_3 composition increases in a layered manner.

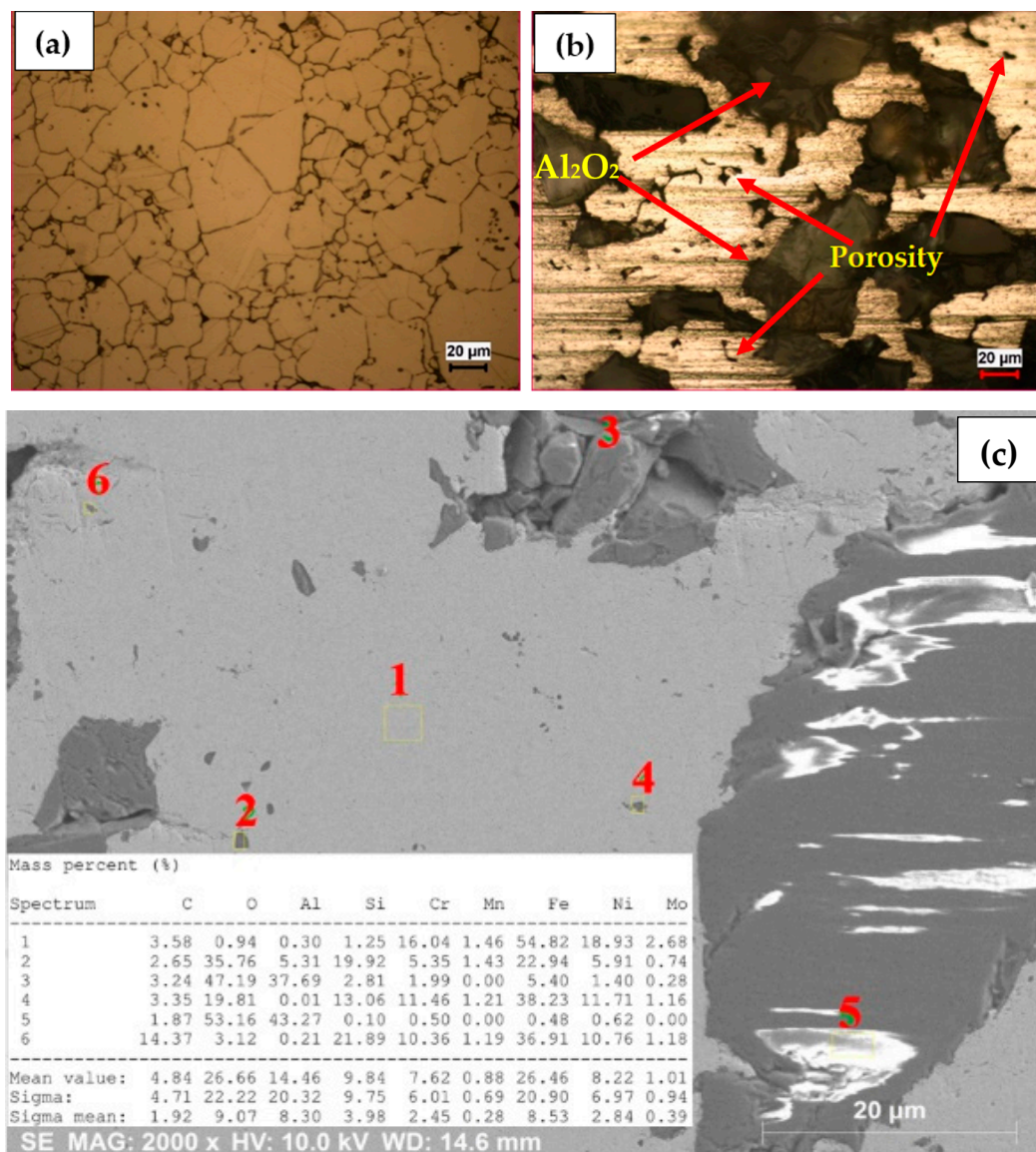


Figure 5. Optical microscope and SEM point EDS analysis of samples with different Al_2O_3 ratios. ((a)—316L (Composition 1), (b)—Composition 4, (c)—Composition 3).

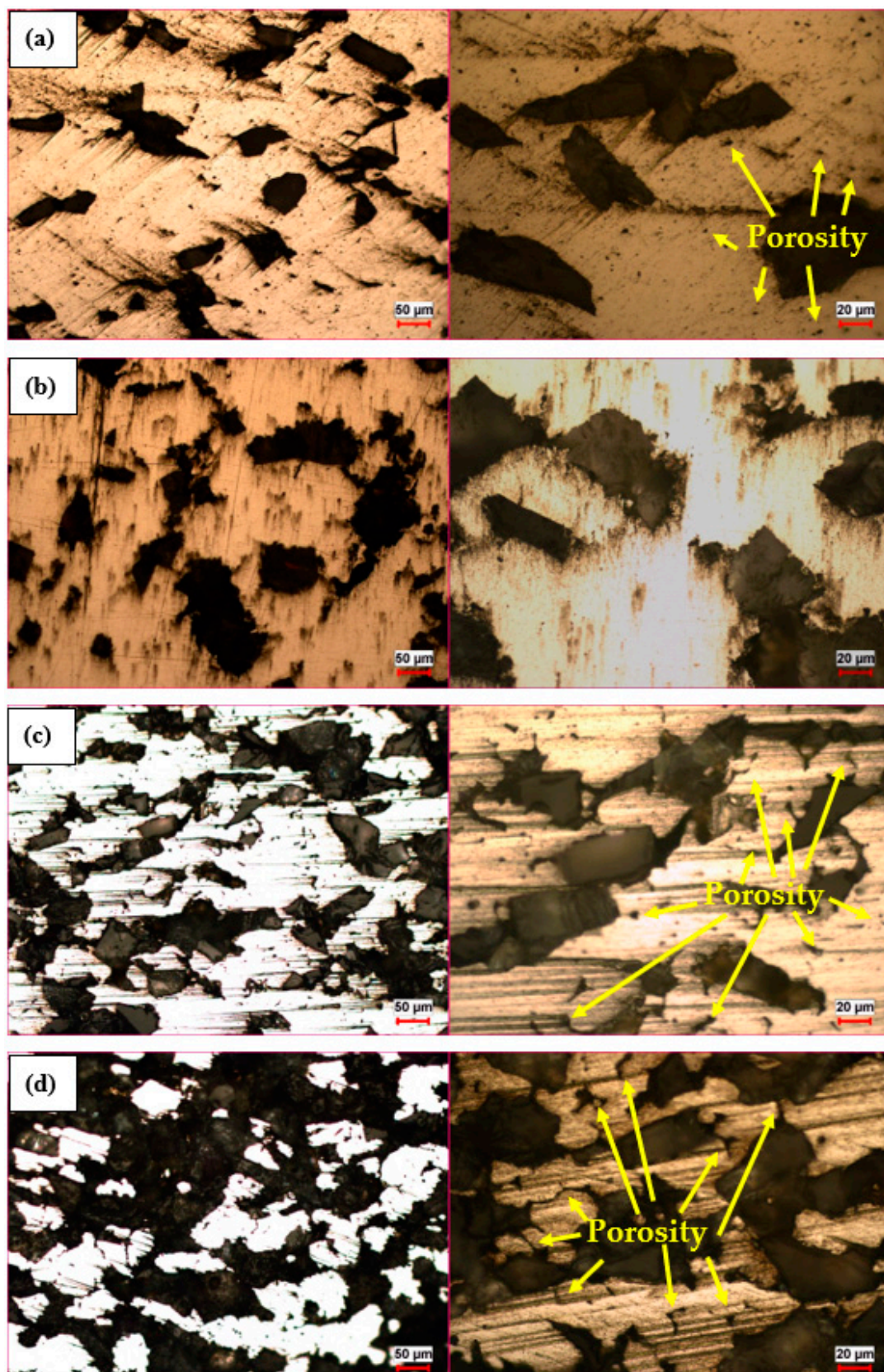


Figure 6. Optical microscope images of samples (Composition 1–3 (a–c), and Composition 4 (d)), (200 $\times$ –500 $\times$).

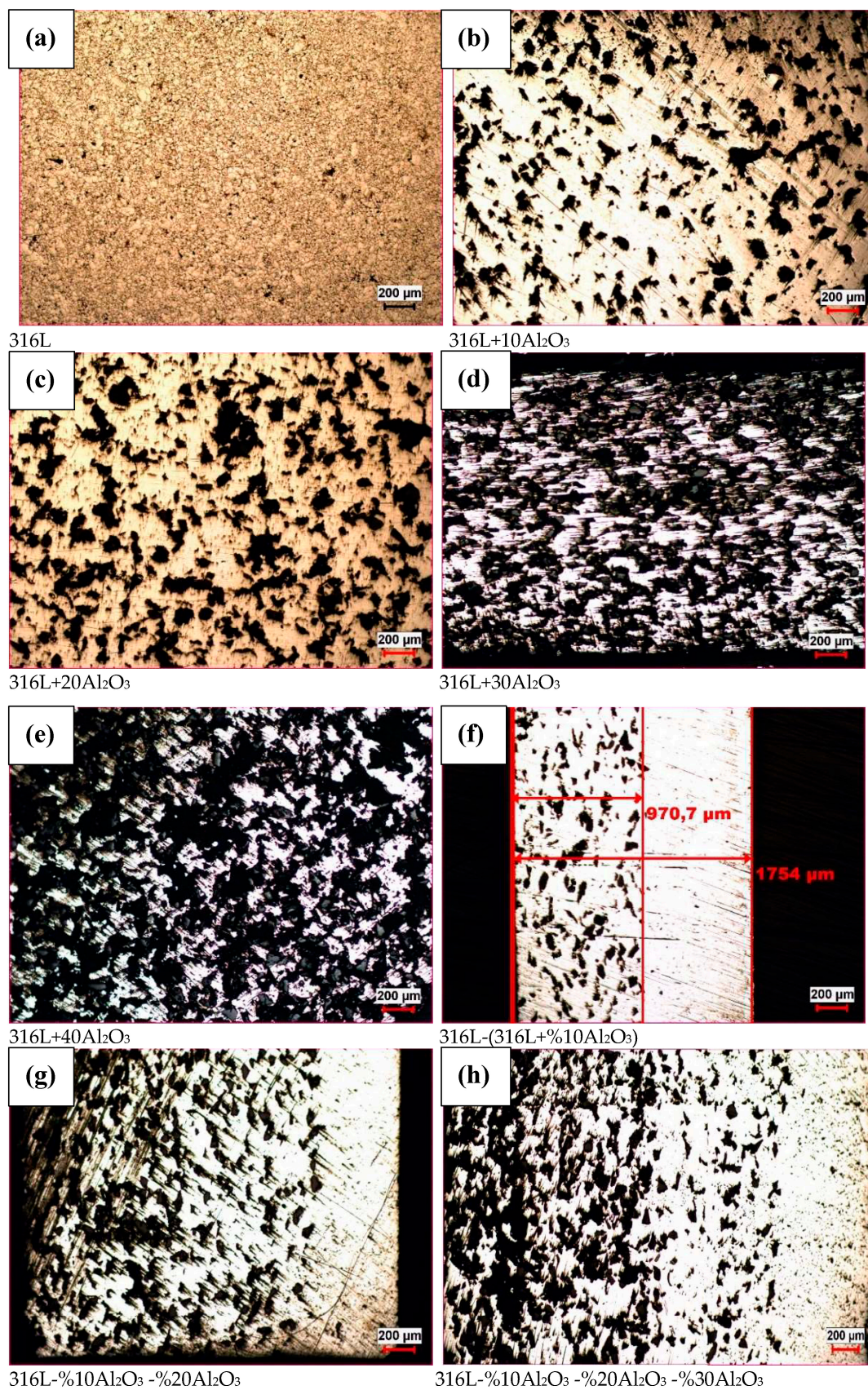


Figure 7. Cont.



316L-%10Al₂O₃-%20Al₂O₃-%30Al₂O₃-%40Al₂O₃

Figure 7. Optical microscope images of samples (Composition 1–8 (a–h), and Composition 9 (i)), (50×).

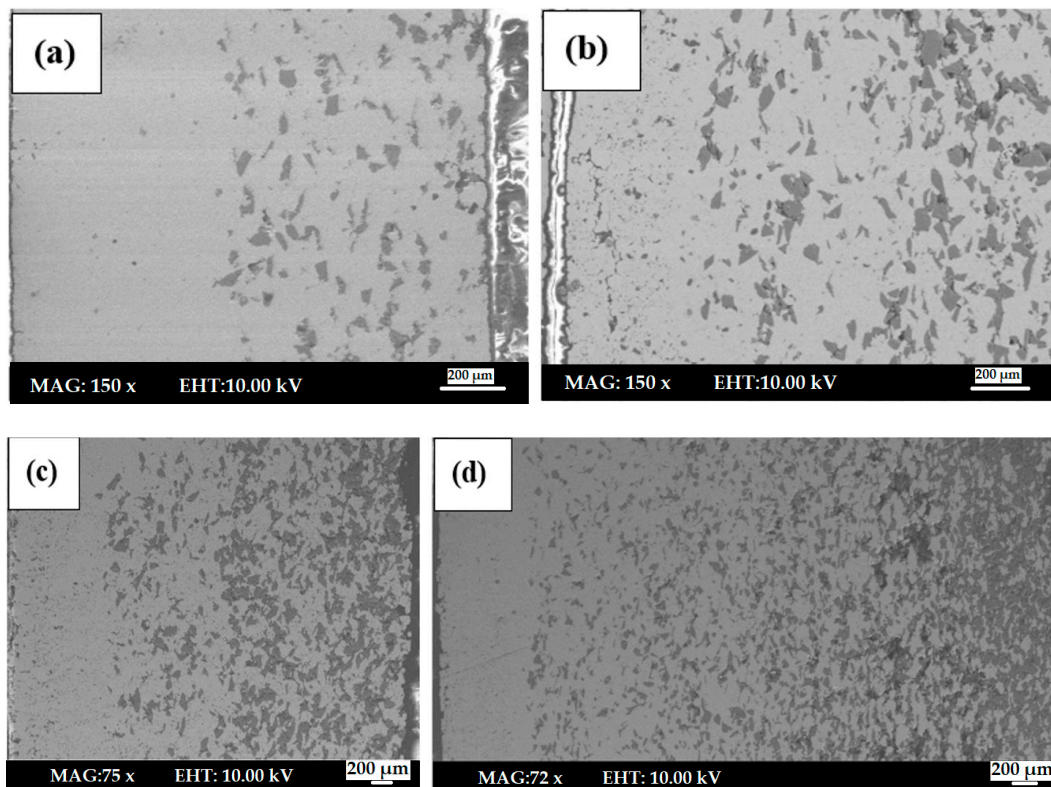


Figure 8. SEM Microstructure pictures of the layered samples (composition 6 (a), 7 (b), 8 (c), and 9 (d)).

In Figure 11, there are the fracture surface pictures taken from the samples reinforced with different ratios of Al₂O₃ into the 316L matrix after the tensile test. When the fracture surface pictures (Figure 10) are examined, it is observed that the honeycomb structure, which represents the ductility, decreases with the increase in the amount of Al₂O₃, and the separation planes, which represent the brittleness, increase. Studies in the literature show that brittleness increases with the increase in reinforcement [24,35,46–48]. For example, Özdemirler et al. investigated the effects of NbC additives on microstructure and mechanical properties. As the amount of NbC increased, it was observed that the separation planes representing the brittleness of the material increased, while the honeycomb structure representing the ductility decreased. In addition, the increase in the amount of reinforcement increased the porosity. Especially with the addition of 40% Al₂O₃ by weight, it is seen that the voids between the Al₂O₃ embedded in the matrix and the matrix are concentrated. The increase in the amount of alumina and pores in single-layer compositions caused a

decrease in the tensile strength and a decrease in the % elongation values and adversely affected the mechanical properties. In Figure 12, there are fracture surface pictures taken from the fracture surfaces of the samples reinforced with Al_2O_3 in different ratios to the 316L matrix produced as layers after the tensile test. When the cracked surface pictures are examined, it is seen that the honeycomb structure decreases with the increase in the amount of Al_2O_3 in each layer; the separation planes and the number of pores increase. Increasing the amount of Al_2O_3 increased the brittleness and porosity. Although the number of pores in the layered compositions was approximately the same compared to the single-layer compositions, the yield strength, tensile strength, and % elongation values were higher. The good mechanical properties are due to the heterogeneous distribution of pores in the matrix. During the tensile test, it is thought that the fracture crack starts from the layer containing 40% Al_2O_3 by weight with high porosity and progresses to the 316L layer that does not contain Al_2O_3 .

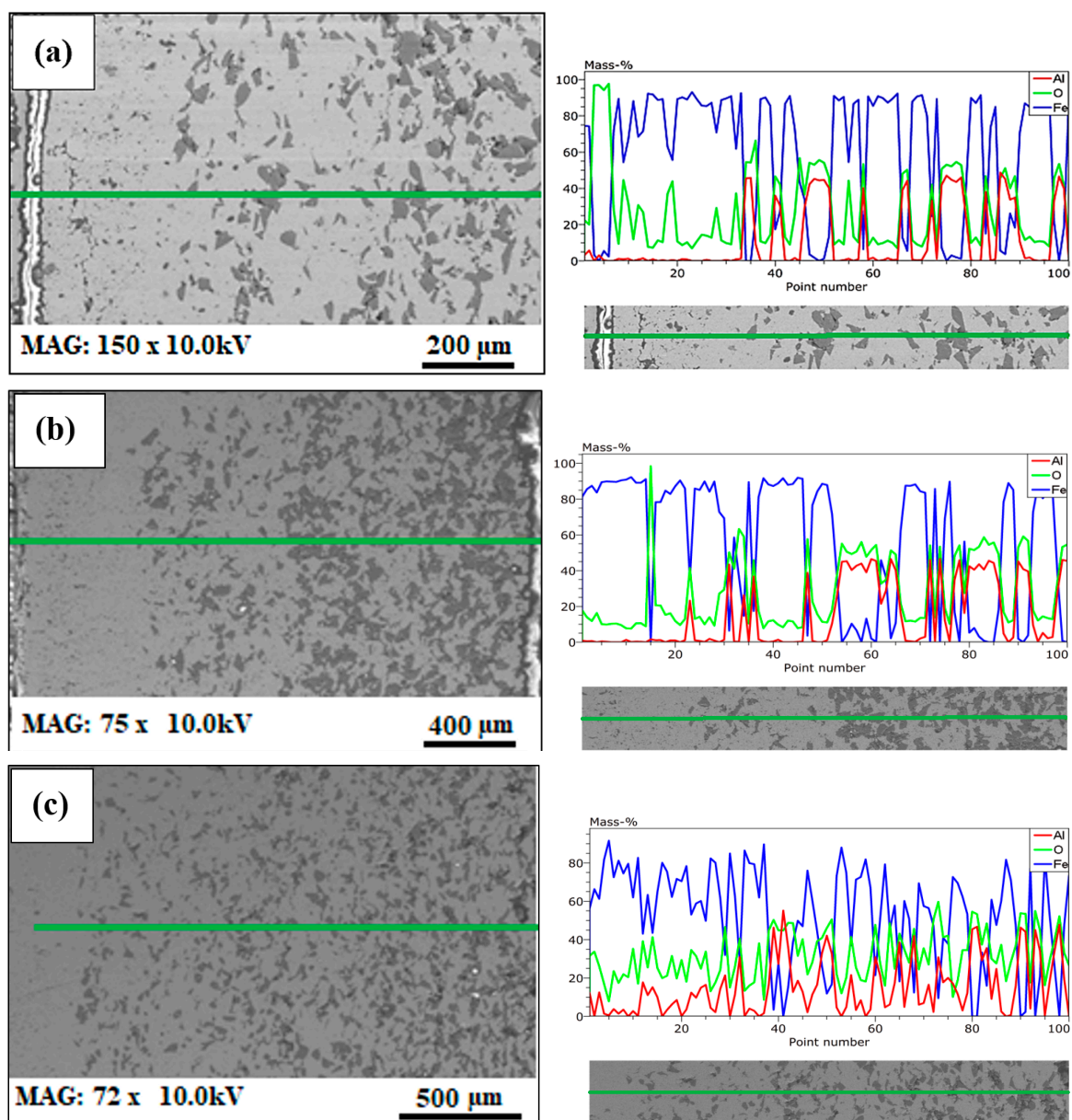


Figure 9. SEM. Line E.D.S. images of Composition 7 (a), 8 (b), and Composition 9 (c).

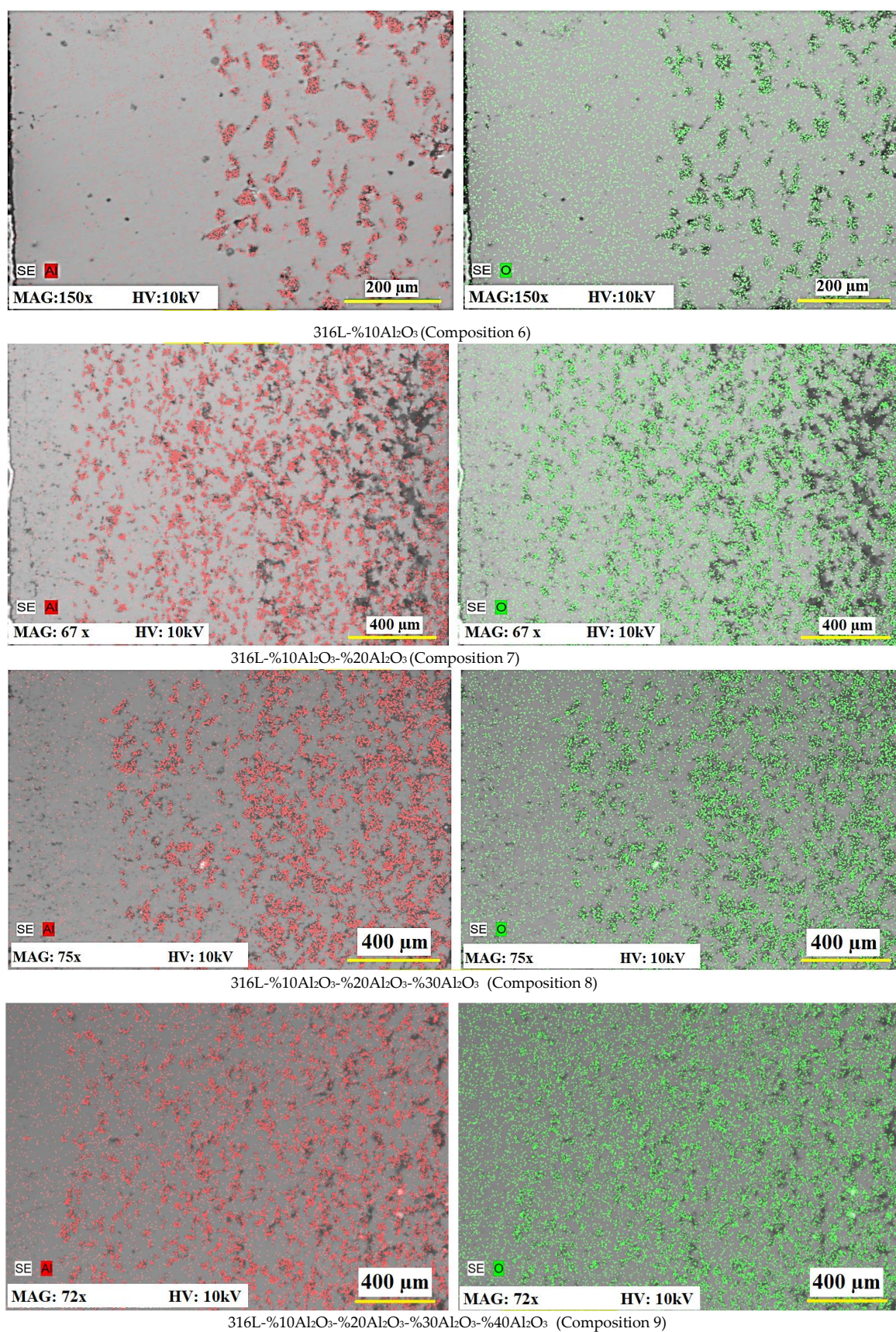


Figure 10. SEM mapping images of samples.

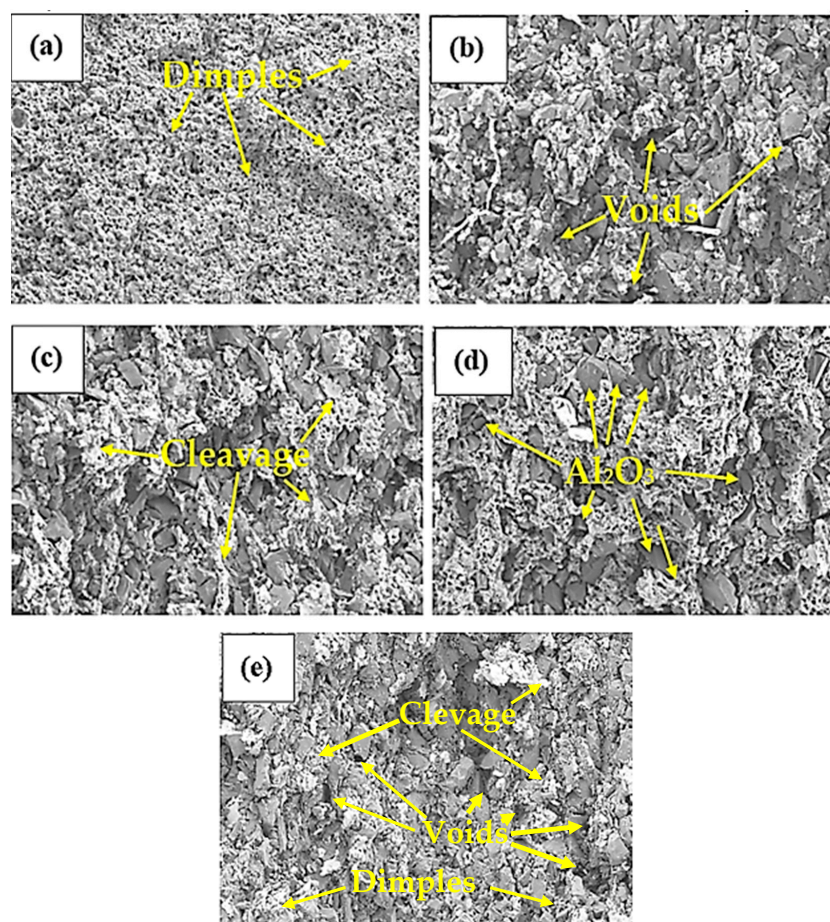


Figure 11. Fractured surface images of single-layer compositions. (Composition 1–5 (a–d), and Composition 5 (e)); (250×).

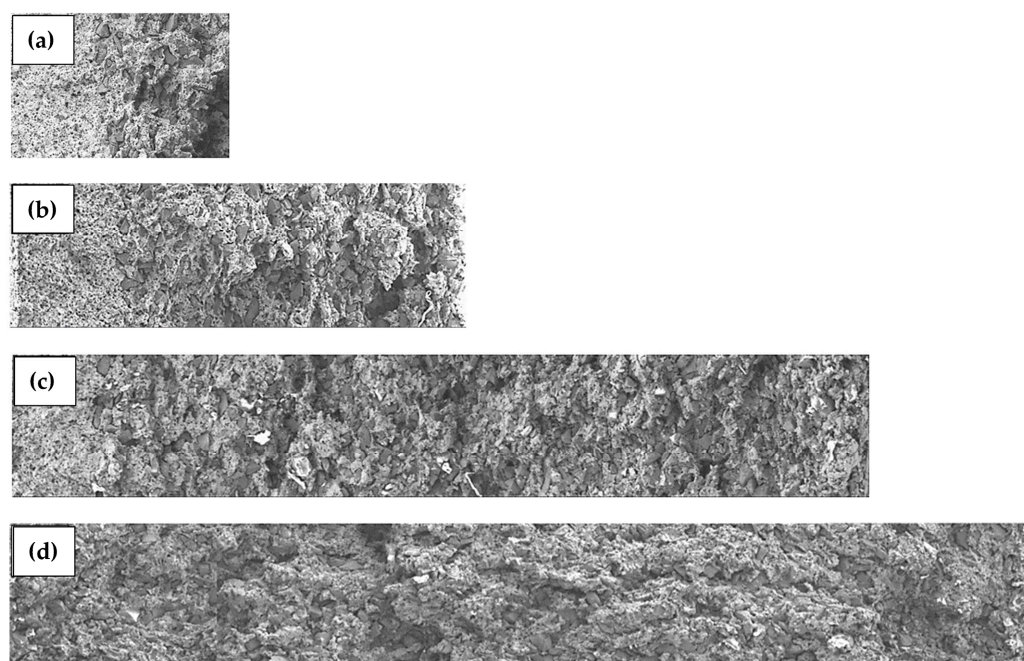


Figure 12. Fractured surface images of layered compositions. (Composition 6–8 (a–c), and Composition 9 (d)); (250×).

4. Conclusions

This work examined the impacts of layer manufacturing and the addition of Al_2O_3 composition to 316L stainless steel at various ratios (0, 10, 20, 30, and 40%) on the mechanical properties and microstructure. The following is a list of some of the significant findings from this study:

- Powder metallurgy of 316L steels added at various rates has been used successfully in single and multilayer manufacturing;
- For all samples, the porosity rises as the amount of Al_2O_3 does. The samples that were functionally graded, however, exhibited slightly less porosity;
- Functionally graded samples' yield strength, ultimate tensile strength, and elongation values declined marginally, but those of single composition samples decreased dramatically as Al_2O_3 content was increased;
- Although the porosity of layered and single composition samples was comparable for the same amount of Al_2O_3 applied, the layered composition samples had superior mechanical characteristics;
- When compared to the sample (Composition 3) generated with a single composition containing the same quantity of Al_2O_3 , Composition 7 containing 20% Al_2O_3 by weight is seven times better in terms of yield strength, about three times better in terms of tensile strength and two times better in elongation, including the additional samples while contrasting functionally graded samples with samples of a single composition with the same concentration of Al_2O_3 ;
- Images of the fracture surface demonstrate that as the amount of Al_2O_3 increases, the honeycomb structure, which represents ductility, diminishes while the separation planes, a representation of brittleness, grow.

As a result of the mechanical tests, it has been observed that the tensile strength of the laminated composite structures is in the range of 91–191 MPa, depending on the layer type. It has been observed that the elongation varies between 3.16% and 12.46% and is close to the mechanical properties of human bone.

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