Article

Life Cycle Assessment of Tensile Specimens of Stainless Steel Obtained by Additive Manufacturing versus Conventional Manufacturing

Germán Omar Barrionuevo [1,2,*], Juan Andrade-Garzón [2], Liliana Llatance-Guevara [3] and Frank E. Alarcón [4]

[1] Department of Engineering, Universidad Católica del Uruguay, Av. 8 de Octubre 2738, Montevideo 11600, Uruguay
[2] Departamento de Ciencias de la Energía y Mecánica, Universidad de las Fuerzas Armadas ESPE, Sangolquí 171103, Ecuador; jaandrade21@espe.edu.ec (J.A.-G.)
[3] Faculty of Technical Sciences, International University of Ecuador UIDE, Quito 170411, Ecuador; lilianallatance@gmail.com (L.L.-G.)
[4] Department of Industrial and Systems Engineering, Pontificia Universidad Católica de Chile, Santiago 7820436, Chile; fealarcon@uc.cl (F.E.A.)

* Corresponding author. E-mail: gbarrionuevo@ucu.edu.uy (G.O.B.)

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ABSTRACT: Life Cycle Assessment (LCA) of additive manufacturing (AM) evaluates the environmental impacts associated with each stage of the process, from raw material extraction to end-of-life disposal. Unlike conventional manufacturing, AM offers significant advantages, such as reduced material waste, optimized designs for lightweight structures, and localized production, which can decrease transportation emissions. However, its environmental benefits are context-dependent, as energy-intensive processes like laser powder bed fusion or high reliance on specific materials can offset these gains. LCA provides a comprehensive framework to assess these trade-offs, guiding sustainable decision-making by identifying hotspots in energy use, material efficiency, and recyclability, ultimately driving innovation towards greener AM practices. This research conducted a cradle-to-gate study of a cylindrical dog-bone tensile specimen. The life-cycle inventory data were obtained from Ecoinvent for conventional manufacturing, while data from the literature review and our research were employed for laser-based powder bed fusion. The results obtained show that the additive manufacturing process is more environmentally friendly. Although the environmental impact is minor, this process consumes a large amount of energy, mainly due to the atomization process and the high laser power. Regarding the mechanical response, AM reduced the ductility but increased the yield strength and achieved the same fracture strength.

Keywords: Life cycle assessment; Additive manufacturing; Laser powder bed fusion; Stainless steel; Tensile test

1. Introduction

Stainless steel (SS) is a highly sustainable material due to its durability, 100% recyclability, and minimal maintenance requirements, which reduce waste and conserve resources [1]. While its production is energy-intensive, advancements in technology and the use of recycled materials help mitigate environmental impacts. Stainless steel's long lifespan and non-toxic nature make it ideal for various applications, further enhancing its environmental benefits.

SS is obtained through several methods, beginning with extracting raw materials like iron ore, chromium, nickel, and molybdenum, which are mined and refined. These elements are melted in electric arc or basic oxygen furnaces to produce steel with added alloying elements for corrosion resistance and strength [2]. The molten stainless steel is cast into slabs, blooms, or billets, which are further processed through rolling and forming to create sheets, bars, or other shapes.

For additive manufacturing (AM) processes like laser powder bed fusion (LPFB) or electron beam melting (EBM), SS powders are made through atomization, enabling the creation of complex and customized parts layer by layer [3–6]. Atomization is the process of breaking a molten stream of stainless steel into fine droplets, which rapidly solidify into powders. This ensures high purity, uniformity, and desirable particle morphology required in powder bed AM

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technologies [7–9]. This blend of traditional and modern methods provides versatile pathways to manufacture stainless steel for diverse industries.

There are many differences between three important parameters of AM and conventional manufacturing (CM): (1) environmental impact, (2) materials waste, and (3) energy consumption. Processes like casting and forging have a CO_2 impact and make waste pieces (similar to the desired shape) to make the final product [10]. Processes and material waste that AM processes do not require [11].

Energy expenditure in conventional SS production and atomization processes varies significantly due to differences in operational steps, the energy intensity of each method, and the final product requirements [12–14]. On the one hand, for raw material extraction and conventional processing, energy is consumed in mining iron ore, chromium, nickel, and molybdenum and converting them into usable forms using fossil fuels, electricity, and explosives in mining [2]. Then, high temperatures to melt and refine SS are required for steelmaking. In the case of electric arc furnaces (EAF), around 10–15 GJ per tonne of steel is employed, while for basic oxygen furnaces (BOF), ~13–25 GJ per tonne [15,16]. It is worth noting that additional processes are required for conventional processing, such as casting, hot rolling, cold working and forming, machining, and heat treatments, which are commonly needed. The energy employed in these steps utilizes more than 4 GJ per tonne of finished product [17].

The energy consumption for gas, water, centrifugal, and plasma atomization processes requires similar energy levels to conventional casting (10–15 GJ per tonne) [8]. Water atomization is the process that consumes the least energy since water is easier to pressurize and does not require recirculation, whereas, for gas atomization, high-pressure gas systems consume substantial energy for compression and inert gas recirculation. Atomization by plasma is an extremely energy-intensive process due to the high power requirements of plasma torches. Still, the obtained powder is of high quality, which means regular spherical shape, low satellites, and high relative density [18,19].

Powders for AM typically have particle sizes of 15–45 μm for processes like LPBF or 45–150 μm for EBM and directed energy deposition (DED). Other methods, like binder jetting and metal injection molding require smaller powder particles, 5–30 μm [7,20]. Regardless, metal powders could impact human health by their toxicity (by inhalation of ultrafine particles) for operators exposed to these processes, and the production material for AM is, in some cases, more expensive than the feedstock to CM [21].

Steel production's Life Cycle Assessment (LCA) examined its environmental impacts across all stages, from raw material extraction to end-of-life recycling. Key stages include mining iron ore and coking coal, energy-intensive production in blast or electric arc furnaces, and shaping steel into products. Major environmental concerns are high energy consumption, greenhouse gas emissions (primarily CO_2), air and water pollution, and resource depletion [22]. However, steel's high recyclability mitigates some impacts, as recycling significantly reduces energy use and raw material demand. Strategies for improvement include adopting cleaner technologies, increasing recycling rates, enhancing energy efficiency, and exploring carbon capture and storage solutions [23].

Pusateri et al. [24] evaluated metallic AM's life cycle analysis (LCA), highlighting that it reduces transportation problems and packaging waste and promotes local production. However, other authors [25] and [26] suggested adverse environmental impacts due to the specific requirements of the technology. In particular, Jung et al. [24] addressed that AM leads to increased energy use and worsening environmental impacts compared to traditional production methods. Shah et al. [1] evaluated the ecological impact of an additively manufactured (AMed) beam in comparison with a conventional produced; a cradle-to-gate life cycle assessment indicated that the AMed led to 24% lower CO_2-equivalent emissions than the conventionally processed beam provided that the design has been topologically optimized. Similar results were obtained by Peng et al. [27] in the environmental impact of a hydraulic valve produced by LPBF. Jung et al. [21] examined AM and CM processes with different parameters and remark that to make AM a sustainable alternative for mass manufacturing, advances in topology optimization, computer-aided design, materials production, and use of materials are required.

LCA results should play a crucial role in shaping policies that promote the circular economy and enhance sustainability in materials processing. By identifying the environmental hotspots of a product's life cycle—such as raw material extraction, production, use, and disposal—LCA provides data-driven insights that policymakers can use to incentivize resource efficiency, waste reduction, and material recovery. Policies should prioritize eco-design strategies, extend producer responsibility programs, and adopt renewable energy sources in conventional and additive manufacturing.

Due to the boom in LPBF technology, hundreds of investigations are being carried out to evaluate its mechanical performance. This work evaluates the LCA of additively manufactured specimens for tensile testing and compares their impact to conventionally manufactured specimens according to ASTM E8.

2. Materials and Methods

2.1. Austenitic Stainless Steel

The material used in this study is an austenitic stainless steel, grade 316L. For the specimens manufactured by additive manufacturing, powders from Renishaw (New Mills, UK) were obtained through plasma atomization with a powder size distribution of 35 ± 8 µm (Figure 1a); the chemical composition is detailed in Table 1, and the energy dispersive spectroscopy (EDS) spectra are depicted in Figure 1b. The same shaft material was purchased from a local supplier for conventional processing.

Table 1. Nominal chemical composition of austenitic stainless steel 316L.

Elements (wt%)									
Fe	**Cr**	**Ni**	**Mo**	**Mn**	**Si**	**N**	**C**	**P**	**S**
Bal.	16–18	10–14	2–3	0–2	0–1	0–1	0–0.03	0–0.045	0–0.03

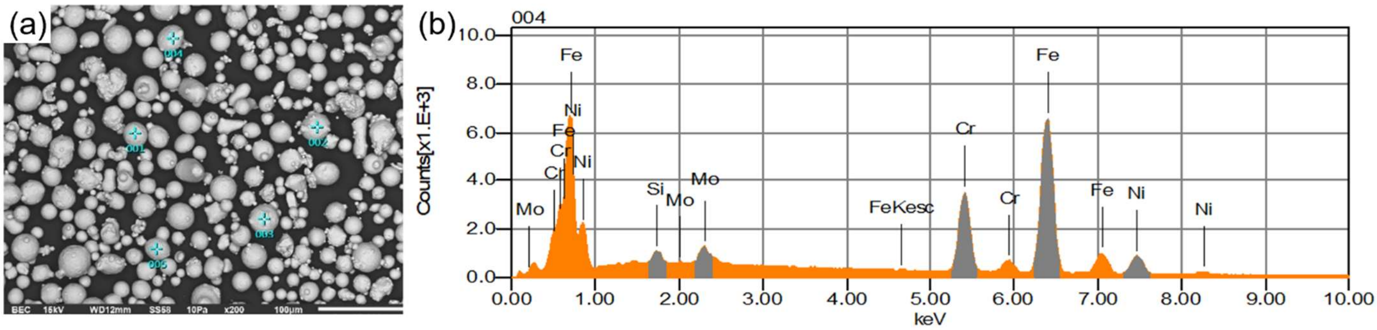


Figure 1. (**a**) Metallic powder of stainless steel 316L. (**b**) EDS analysis of the chemical composition.

2.2. Manufacturing Processes

2.2.1. Conventional Processing

The production of stainless steel begins with mining iron ore, nickel, and chromium, the primary raw materials. These are smelted in an electric arc furnace to create a molten alloy, with precise quantities of chromium and nickel added for corrosion resistance and strength. The molten steel is refined to remove impurities through argon oxygen decarburization. Once purified, the molten stainless steel is cast into slabs or billets, which are hot-rolled into sheets or rods. The final steps include cold rolling, annealing, and pickling to improve mechanical properties and surface finish, making high-quality stainless steel rods ready for industrial applications.

A 3/4-inch shaft was acquired to prepare the specimen; the chemical composition is the same as shown in Table 1. Cylindrical specimens were chosen due to the uniformity in stress distribution. The specimens were machined on a CNC lathe (TRAVIS TR1, Traviscnc, Barcelona, Spain) (Figure 2a) to achieve the dimensions indicated in the ASTM E8 standard (Figure 2c).

Tensile tests were performed using a universal tensile tester machine (Instron 3368, Instron, Norwood, MA, USA). The samples were tested in their as-built condition, and three tests were performed to ensure the veracity of the results.

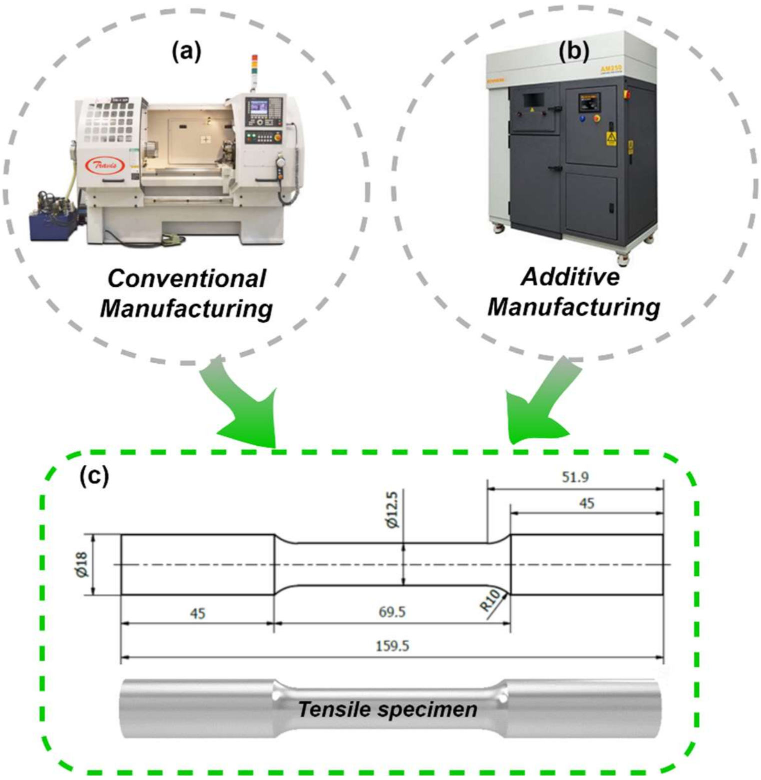


Figure 2. (**a**) CNC lathe for machining the tensile specimen. (**b**) Laser powder bed fusion additive manufacturing setup. (**c**) Cylindrical dog-bone tensile specimen.

2.2.2. Additive Manufacturing

Stainless steel powders are produced by plasma atomization, processed from molten SS sprayed into fine droplets by high-pressure inert gas or plasma, and rapidly cooled, forming spherical powder particles of uniform size and high purity. The powders are deposited on the bed of the 3D printer (Renishaw AM250, Renishaw, New Mills, UK) (Figure 2b) and fused with a 200W fiber laser at an average speed of 800 mm/s. To avoid powder oxidation, high-purity Argon was injected during the printing process (0.7 L/min).

The final dimensions of the specimens are shown in Figure 2c. The mass of the specimen corresponds to 256 g. It is worth noting that the sample used in the conventional process weighed 365 g. Since the initial diameter of the shaft is 19.05 mm, it requires a length of more than 200 mm to be clamped in the lathe jaws. Therefore, a material utilization factor of 0.70 is considered for the LCA. For additive manufacturing, 95% of the powders are transformed in the dog-bone tensile specimen, obtaining a utilization factor superior to 0.9.

2.3. Life Cycle Assessment

The life cycle assessment (LCA) was conducted following the ISO 14040-2006 standard [28]; it includes four steps: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) life cycle interpretation. Each step is described below. The product system's boundary (Figure 3) is cradle to gate, and the functional unit is the tensile specimen (Figure 2c).

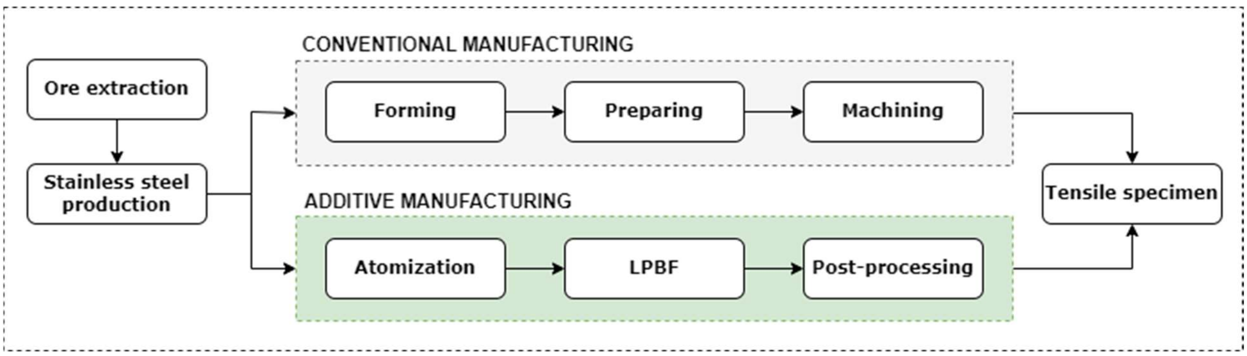


Figure 3. Product systems boundaries for tensile specimen fabrication.

2.3.1. Goal and Scope Definition

- Foundation of the Study: Compare and evaluate the environmental impacts of additively versus conventional manufacturing of a tensile specimen for mechanical characterization.
- Scope Articulation: The product system evaluated is the tensile specimen (256 g). The product system is depicted in Figure 3. The system boundaries include processes from material production (ore extraction and stainless steel production). Two product systems were considered: (1) Conventional manufacturing (CM) and (2) Additive manufacturing (AM). The unit process for CM considers forming, preparing, and machining, described in more detail in Section 2.3.2. Meanwhile, the AM process involves powder atomization, laser powder bed fusion processing (LPBF), and post-processing. Collection and transportation of steel scrap and post-manufacturing steps such as transportation of products from the mill to the end user and maintenance and end-of-life management of test specimens were not part of the analysis.

2.3.2. Life Cycle Inventory Analysis

The analysis was conducted using OpenLCA version 2.3.1 software (GreenDelta GmbH, Berlin, Germany) [29]. Ecoinvent database v3.5 [30] and CES Edupack 2019 data [31] were utilized to model the product system.

- Data Collection: The ore extraction and stainless steel production are the same in both processes. Where data on ore extraction and stainless steel production were obtained from the Ecoinvent 3.5 database. The difference lies in the manufacturing process. In the case of conventional manufacturing, hot rolling is used to produce long rods that must go through a cold drawing process to give the required dimensions. The preparation process involves cutting, heat treatment, and cleaning. Finally, the material is removed in the machining process to give the shape and dimensions specified by the ASTM E8 standard. The life-cycle inventories of machining were obtained from Ecoinvent 3.5. On the other hand, the additive manufacturing process contemplates obtaining powders by atomization, whose data were obtained from [10]. The LPBF process considers the energy and laser power used to print the tensile specimen. Due to the limitations of the LPBF technology, it is common to apply post-processing, starting from separating the platform where the specimen was built by wire-electrical discharge machining to machining. No subsequent heat treatments were used.

2.3.3. Life Cycle Impact Assessment

- Impact Assessment: Life cycle impact assessment (LCIA) translates emissions and resource extractions into restricted environmental impact scores through characterization factors. ReCiPe 2016 [32] method at the *Midpoint* level was used for LCIA. In this study, eighteen midpoint impact categories are informed (Table 2). In addition, *Endpoint* (H) indicators were used to reflect the issues of societal concern, which have three higher aggregation levels: ecosystem quality, human health, and resource scarcity.

Table 2. ReCiPe 2016 midpoint impact results of the tensile specimen produced by CM and AM.

Impact Category	**Abbreviation**	**Unit**	**CM**	**AM**
Agricultural land occupation	ALO	m^2a	0.887	0.634
Climate change	CC	kg CO_2-Eq	10.470	8.766
Fossil depletion	FD	kg oil-Eq	2.823	2.524
Freshwater ecotoxicity	FE	kg 1,4-DCB-Eq	0.372	0.271
Freshwater eutrophication	FEU	kg P-Eq	0.005	0.004
Human toxicity	HT	kg 1,4-DCB-Eq	4.426	3.585
Ionizing radiation	IR	kBq U235-Eq	1.065	0.835
Marine ecotoxicity	ME	kg 1,4-DCB-Eq	0.357	0.259
Marine eutrophication	MEU	kg N-Eq	0.012	0.008
Metal depletion	MD	kg Fe-Eq	4.266	2.980
Natural land transformation	NLT	m^2	0.001	0.001
Ozone depletion	OD	kg CFC-11-Eq	0.000	0.000
Particulate matter formation	PMF	kg PM10-Eq	0.035	0.028
Photochemical oxidant	PO	kg NMVOC	0.031	0.025
Terrestrial acidification	TA	kg SO_2-Eq	0.049	0.043
Terrestrial ecotoxicity	TE	kg 1,4-DCB-Eq	0.001	0.001
Urban land occupation	ULO	m^2a	0.104	0.070
Water depletion	WD	m^3	0.079	0.206

2.3.4. Life Cycle Interpretation

Data Analysis: The environmental impact of CM and AM in producing the cylindrical dog-bone tensile specimen is discussed in the next section.

A sensitive analysis was performed to evaluate the results' robustness, varying the powder bed yield, energy consumption, atomization methods, and argon consumption.

3. Results and Discussion

Table 2 reports the midpoint indicators, which focus on environmental problems related to climate change, terrestrial acidification, freshwater eutrophication, and human toxicity. These indicators are situated midway in the cause-effect chain, focusing on quantifiable environmental processes rather than ultimate damages [10]. As can be seen, the CM process has a major impact on the 18 impact categories.

The results from the midpoint impact show that climate change (CC), human toxicity (HT), and metal depletion (MD) have the greatest impact, respectively. In that sense, the LPBF process reduces the effects of CC by 1.7 kg CO_2-Eq. For MD, 1.2 kg Fe-Eq is diminished. The other impact categories show a slight saving, although less than unity. Therefore, it is possible to establish that additive manufacturing has a lower impact on producing stainless steel specimens compared to the same obtained conventionally. The environmental impact of SS must be weighed against the long-term benefits, such as corrosion resistance, which reduces maintenance requirements and extends design life.

Figure 4 shows a comparative evaluation of the normalized impact categories obtained through ReCiPe Midpoint H. It can be seen that CC, HT, and MD have the greatest environmental impact. It is worth noting that in most categories, CM has a greater effect; additive manufacturing only has a greater environmental impact in FD. FD refers to reducing non-renewable fossil resources, such as oil, coal, and natural gas, due to human extraction and use. Therefore, LPBF leads to better environmental performance than CM.

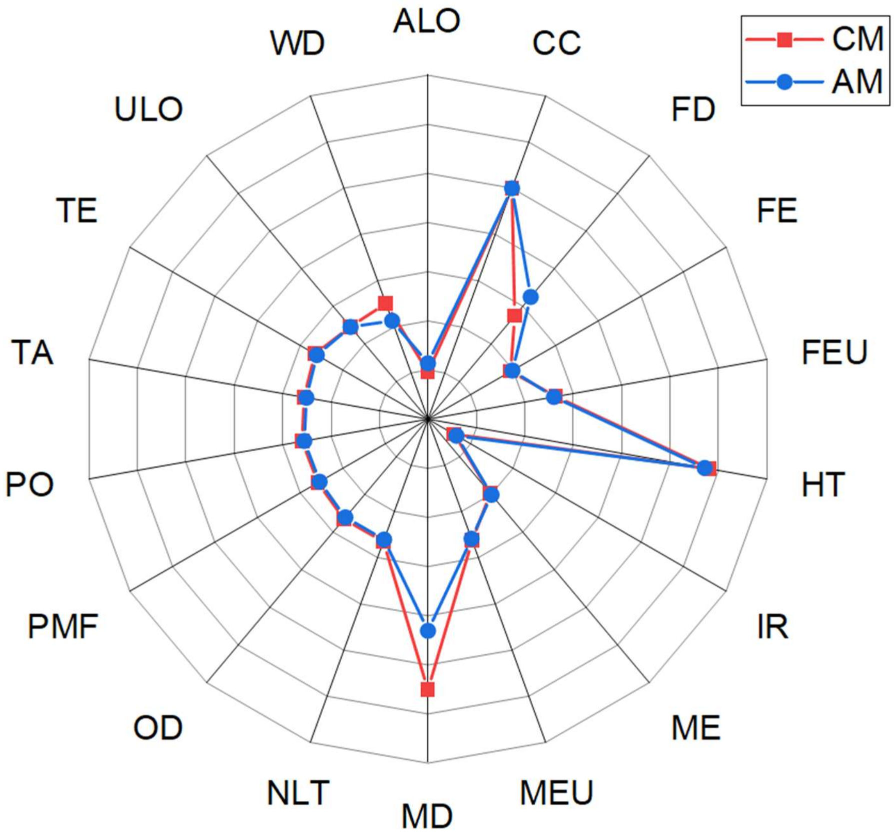


Figure 4. Normalized impact factors obtained through ReCiPe Midpoint H.

Moreover, the endpoint assessment in the ReCiPe methodology translates the midpoint indicators into broader, more aggregated categories that represent the potential impacts on protection areas: ecosystems, human health, and resource availability [32]. This higher-level approach provides a clearer understanding of the ultimate consequences of environmental pressures. However, this aggregation also introduces more uncertainty, as it relies on models to link midpoints to ultimate damages.

Figure 5 shows the impact on protection areas, highlighting that the AM has a lower impact in all categories. In particular, the effect on human health drops from 0.93 to 0.44. This is because harmful chemicals, such as cutting fluids, are used during machining [27].

LPBF can be more environmentally friendly than machining due to its material efficiency, reduced waste, and ability to produce lightweight, optimized designs that lower lifecycle emissions [12,33,34]. However, LPBF often requires high-energy input and specialized material powders, which can offset its benefits.

The energy used for conventional manufacturing of tensile specimen production involves foundry, extrusion, profiling, roughing, and machining, whose energy consumption is shown in Figure 6a. About 35 MJ/kg is required to process the specimen. It is important to note that in the data collected, different machines, suppliers, and even different methodological calculations are used; this could mean that the comparisons are not exact and, therefore, give a result that should be interpreted as an approximation. On the contrary, by including more suppliers, machines, and even calculations, even if a single line of analysis is not respected, by determining an average, we are working with a representation of all the data in general, so we have a more global and representative analysis.

For the production of the specimen by additive manufacturing, production of primary materials (PPM), powder atomization (PA), LPBF, and recycling of waste materials (RWM) were considered. PPM involves the production of primary material by extracting primary raw material from the earth and processing it into ingots, whose energy consumption is around 22 MJ/kg. In PA, a material ingot is melted, and the melted material is disintegrated into fine droplets using a high-pressure stream of gas or water; energy consumption is 47 MJ/kg. The most energy-intensive process is LPBF due to the high laser power required (200 W), the controlled atmosphere requirement, and the time needed to produce each component. Its energy consumption amounts to 105 MJ/kg. In addition, it has been reported that it is possible to reuse the powders that were not melted during the AM process [35]; in that sense, the energy consumption of their recycling has been included. RWM involves about 5 MJ/kg. Therefore, the AM process requires 180 MJ/kg to produce the tensile samples.

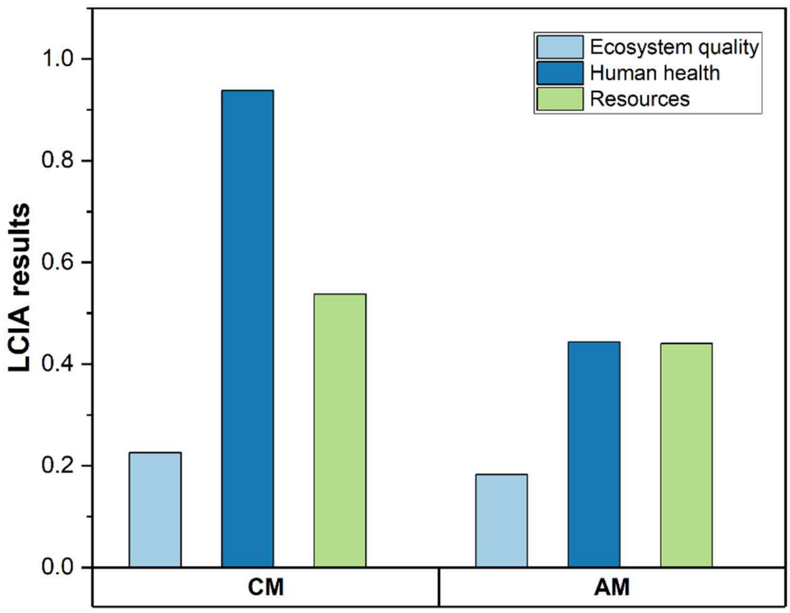


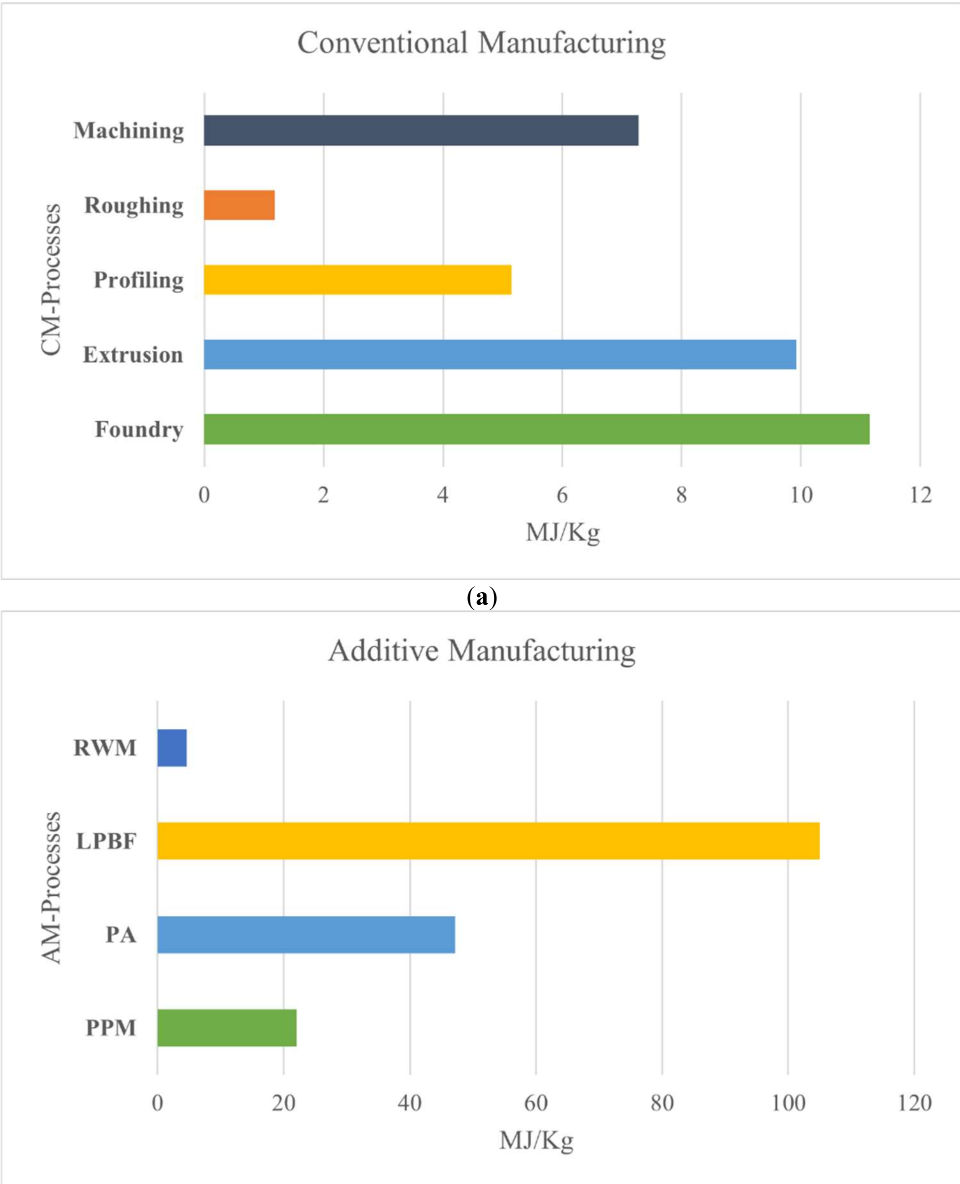
Figure 5. Contribution of conventional (CM) and additive manufacturing (AM) based on ReCiPe 2016 Endpoint (H) method.

AM often requires higher energy input compared to CM methods. However, this increased energy consumption can be offset by several key advantages that enhance overall sustainability. AM enables the production of highly durable and lightweight components with optimized geometries, which can extend product lifespan and reduce material waste [36,37]. Advanced design capabilities, such as topology optimization, allow for stronger yet lighter parts, improving energy efficiency in aerospace and automotive applications. Additionally, AM reduces the need for extensive supply chains by enabling localized, on-demand production, which cuts transportation emissions and logistical costs [38].

It is important to note the lack of standardized data (treated and in adequate format) available to computationally work on the environmental impacts of different additive manufacturing processes [24]. This leads to a more theoretical analysis based on the available literature, which is less exact. It is, therefore, essential to establish a standard in the publication of results on the environmental impact of additive manufacturing processes.

Indirect data was utilized to perform calculations, specifically through conversions and applying the rule of three to normalize mass. A significant variability in results was observed for a particular process, potentially indicating human error, such as incorrect assumptions during calculations or substantial differences in methodologies or equipment. If no human error occurred, this variability might suggest that the machine and methodology with the least energy consumption in the market were employed—an insight valuable to the industry.

To be able to extrapolate reliable results to serve as a basis for decision-making, it is recommended that LCAs be developed following the guidelines of ISO 14040 and ISO 14044, as well as ISO/ASTM 52900 and ISO/ASTM 52915 for additive manufacturing processes.



(**b**)

Figure 6. Energy consumption in (**a**) conventional and (**b**) additive manufacturing.

It is worth noting that post-processing and end-of-life recycling significantly influence the environmental impact of AM and CM, particularly in the context of the circular economy. In AM, post-processing steps—such as heat treatment, surface finishing, and support removal—can add energy and material demands, potentially offsetting some sustainability gains from the additive process. However, AM often generates less scrap material than conventional subtractive manufacturing, where machining waste is substantial [23].

End-of-life recycling plays a crucial role in both methods. AM enables the use of recycled metal powders, reducing the need for virgin materials and lowering overall environmental impact. While often more mature in recycling practices (e.g., remelting metal chips), CM struggles with high material losses during production. Effective recycling systems, closed-loop material flows, and advancements in metal powder reusability can enhance the circular economy potential of AM [35]. By integrating sustainable post-processing methods and improving recyclability, AM and CM can further reduce waste, energy consumption, and reliance on raw materials, making production more resource-efficient and environmentally friendly.

Finally, the energy consumption required to use a universal testing machine and apply the tensile test according to ASTM E8 is less than 2 MJ, which is relatively low compared to processes like powder atomization or laser powder bed fusion.

Table 3 reports the sensitive analysis, using the LPBF as a reference. The yield of the powder bed, energy consumption in AM, atomization methods (gas/plasma), and argon consumption were considered. According to the results, the more sensitive factor is energy consumption, followed by powder yield, while atomization methods and argon consumption appear to be non-significative parameters. This observation involves a research niche with room for improvement concerning AM energy consumption. That is, if energy consumption can be reduced during the production of powders and laser utilization, the LPBF process would be more efficient and environmentally friendly.

Table 3. Sensitive analysis of varying the yield of the powder bed, energy consumption, atomization methods, and argon consumption.

	Default Value	Variation	Sensitivity
Yield of the powder bed	90%	±5%	0.43
Energy consumption	100 MJ	±25%	12.61
Atomization methods	Plasma	gas	0.1
Argon consumption	0.7 L/min	±15%	0.05

Figure 7 shows the tensile test response of specimens processed by AM and CM. The yield stress in the CM specimen was 325 MPa, while the additively manufactured specimen was 522 MPa. The ultimate tensile stress was around 624 MPa for both cases. Obtaining a difference in the material’s ductility while achieving the same strength.

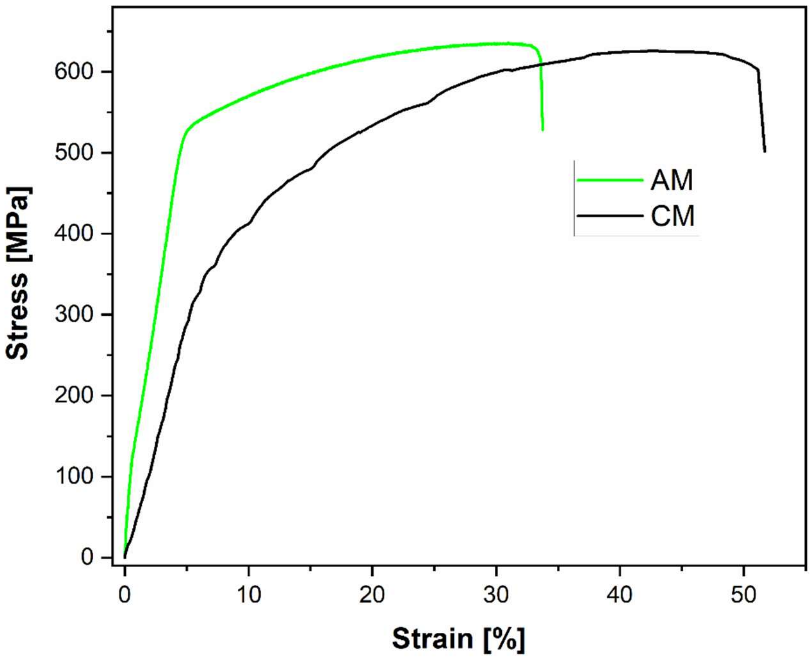


Figure 7. Representative stress-strain curve for 316L SS processed by CM and AM.

4. Conclusions

The present research explored the life cycle assessment in producing cylindrical dog-bone tensile specimens of 316L stainless steel produced by conventional and additive manufacturing (LPBF). Based on midpoint and endpoint methodologies, it is concluded that:

- Additive manufacturing (LPBF) represents a more environmentally friendly process as all midpoint impact results are lower than those of conventional processing of stainless steel specimens.
- For both manufacturing methods, there was evidence of high environmental impact, human toxicity, and metal depletion. However, it is worth noting that stainless steel production is sustainable since it reduces maintenance requirements and extends design life due to its corrosion resistance.
- The energy consumption for additive manufacturing exceeds 180 kJ/kg, while conventional processing yields only 35 kJ/kg. Despite higher energy consumption during production, LPBF for 316L stainless steel is more material-efficient than traditional methods, with near-zero waste.
- Regarding the mechanical response of the tensile test, the same value of ultimate tensile stress was reached in both cases. However, the conventionally manufactured specimen shows a higher ductility.

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Author Contributions

Conceptualization, G.O.B. and F.E.A.; Methodology, G.O.B. and J.A.-G.; Software, J.A.-G.; Validation, L.L.-G., and F.E.A.; Formal Analysis, G.O.B. and L.L.-G.; Investigation, G.O.B. and J.A.-G.; Data Curation, L.L.-G. and F.E.A.; Writing—Original Draft Preparation, G.O.B.; Writing—Review & Editing, J.A.-G. and F.E.A; Visualization, L.L.-G.; Supervision, F.E.A.

Ethics Statement

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Informed Consent Statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Shah IH, Hadjipantelis N, Walter L, Myers RJ, Gardner L. Environmental life cycle assessment of wire arc additively manufactured steel structural components. *J. Clean. Prod.* **2023**, *389*, 136071. doi:10.1016/j.jclepro.2023.136071.
2. Na H, Sun J, Qiu Z, He J, Yuan Y, Yan T, et al. A novel evaluation method for energy efficiency of process industry—A case study of typical iron and steel manufacturing process. *Energy* **2021**, *233*, 121081. doi:10.1016/j.energy.2021.121081.
3. Fu J, Qu S, Ding J, Song X, Fu MW. Comparison of the microstructure, mechanical properties and distortion of stainless steel 316 L fabricated by micro and conventional laser powder bed fusion. *Addit. Manuf.* **2021**, *44*, 102067. doi:10.1016/j.addma.2021.102067.
4. Yin Y, Tan Q, Bermingham M, Mo N, Zhang J, Zhang MX. Laser additive manufacturing of steels. *Int. Mater. Rev*. **2021**, *67*, 487–573. doi:10.1080/09506608.2021.1983351.
5. Bakhtari AR, Sezer HK, Canyurt OE, Eren O, Shah M, Marimuthu S. A Review on Laser Beam Shaping Application in Laser-Powder Bed Fusion. *Adv. Eng. Mater.* **2024**, *26*, 2302013. doi:10.1002/adem.202302013.
6. Ali MH, Sabyrov N, Shehab E. Powder bed fusion--laser melting (PBF--LM) process: Latest review of materials, process parameter optimization, application, and up-to-date innovative technologies. *Prog. Addit. Manuf.* **2022**, *7*, 1395–1422.
7. Mazzer EM, Kiminami CS, Gargarella P, Cava RD, Basilio LA, Bolfarini C, et al. Atomization and selective laser melting of a Cu-Al-Ni-Mn shape memory alloy. *Mater. Sci. Forum* **2014**, *802*, 343–348. doi:10.4028/www.scientific.net/MSF.802.343
8. Kassym K, Perveen A. Atomization processes of metal powders for 3D printing. *Mater. Today Proc*. **2019**, *26*, 1727–1733. doi:10.1016/j.matpr.2020.02.364.

9. Lagutkin S, Achelis L, Sheikhaliev S, Uhlenwinkel V, Srivastava V. Atomization process for metal powder. *Mater. Sci. Eng. A* **2004**, *383*, 1–6. doi:10.1016/j.msea.2004.02.059.
10. Fagerberg E, Rotter C. Life Cycle Assessment of Metal Laser Powder Bed Fusion: A Deep Dive into the Significance of System Boundary Expansion and Improvement Potential. Master's Thesis, Linköping University, Linköping, Sweden, 4 July 2023.
11. Barrionuevo GO, Toapanta M, Mullo JL, Camacho-Játiva L. Recovery of Hydro Turbines: From Welding to Additive Manufacturing. *Solid State Phenom* **2022**, *338*, 55–62. doi:10.4028/p-lx8uye.
12. Vinod Kumar S, Reddy U, Nagpal A, Kumar A, Jayronia S, Hussien RA. Towards Sustainable Additive Manufacturing: Exploring Eco-friendly Materials for Green 3D Printing. In Proceedings of the 3rd International Conference on Applied Research and Engineering (ICARAE2023), Cape Town, South Africa, 17–19 November 2023. doi:10.1051/e3sconf/202450501009.
13. Gutowski T, Jiang S, Cooper D, Corman G, Hausmann M, Manson JA, et al. Note on the Rate and Energy Efficiency Limits for Additive Manufacturing. *J. Ind. Ecol.* **2017**, *21*, S69–S79. doi:10.1111/jiec.12664.
14. DebRoy T, Mukherjee T, Wei HL, Elmer JW, Milewski JO. Metallurgy, mechanistic models and machine learning in metal printing. *Nat. Rev. Mater.* **2021**, *6*, 48–68. doi:10.1038/s41578-020-00236-1.
15. Hong TY, Chen CA, Chien CF. Towards sustainable production with resource efficiency: An empirical study of steelmaking continuous casting scheduling. *Resour. Conserv. Recycl.* **2024**, *209*, 107806. doi:10.1016/j.resconrec.2024.107806.
16. Na H, Sun J, Yuan Y, Qiu Z, Zhang L, Du T. Theoretical Energy Consumption Analysis for Sustainable Practices in Iron and Steel Industry. *Metals* **2024**, *14*, 563. doi:10.3390/met14050563.
17. Yang L, Li Z, Hu H, Zou Y, Feng Z, Chen W, et al. Evaluation of Energy Utilization Efficiency and Optimal Energy Matching Model of EAF Steelmaking Based on Association Rule Mining. *Metals* **2024**, *14*, 458. doi:10.3390/met14040458.
18. Mandal S, Sadeghianjahromi A, Wang CC. Experimental and numerical investigations on molten metal atomization techniques–A critical review. *Adv. Powder Technol.* **2022**, *33*, 103809. doi:10.1016/j.apt.2022.103809.
19. Yu S, Zhao Y, Zhao G, Liu Q, Yao B, Liu H. Review on preparation technology and properties of spherical powders. *Int. J. Adv. Manuf. Technol.* **2024**, *132*, 1053–1069. doi:10.1007/s00170-024-13442-w.
20. Nalivaiko AY, Arnautov AN, Zmanovsky SV, Gromov AA. Al–Si–Cu and Al–Si–Cu–Ni alloys for additive manufacturing: composition, morphology and physical characteristics of powders. *Mater. Res. Express* **2019**, *6*, 086536. doi:10.1088/2053-1591/ab1828.
21. Jung S, Kara LB, Nie Z, Simpson TW, Whitefoot KS. Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production? *Environ. Sci. Technol.* **2023**, *57*, 6373–6386. doi:10.1021/acs.est.2c04927.
22. Xiao H, Gao B, Yu S, Liu B, Cao S, Peng S. Life cycle assessment of metal powder production: A Bayesian stochastic Kriging model-based autonomous estimation. *Auton. Intell. Syst.* **2024**, *4*, 20. doi:10.1007/s43684-024-00079-5.
23. Ramadugu S, Ledella SRK, Gaduturi JNJ, Pinninti RR, Sriram V, Saxena KK. Environmental life cycle assessment of an automobile component fabricated by additive and conventional manufacturing. *Int. J. Interact. Des. Manuf.* **2024**, *18*, 847–858. doi:10.1007/s12008-023-01532-0.
24. Kokare S, Oliveira JP, Godina R. Life cycle assessment of additive manufacturing processes: A review. *J. Manuf. Syst.* **2023**, *68*, 536–559. doi:10.1016/j.jmsy.2023.05.007.
25. Gopal M, Lemu HG, Gutema EM. Sustainable Additive Manufacturing and Environmental Implications: Literature Review. *Sustainability* **2023**, *15*, 150504. doi:10.3390/su15010504.
26. Rejeski D, Zhao F, Huang Y. Research needs and recommendations on environmental implications of additive manufacturing. *Addit. Manuf.* **2018**, *19*, 21–28. doi:10.1016/j.addma.2017.10.019.
27. Peng T, Wang Y, Zhu Y, Yang Y, Yang Y, Tang R. Life cycle assessment of selective-laser-melting-produced hydraulic valve body with integrated design and manufacturing optimization: A cradle-to-gate study. *Addit. Manuf.* **2020**, *36*, 101530. doi:10.1016/j.addma.2020.101530.
28. *ISO 14040:2006*; Environmental management—Life cycle assessment—Principles and framework. International Organization for Standardization: Vernier, Switzerland, 2006.
29. GreenDelta, OpenLCA 1.9—Comprehensive User Manual, no. June. 2020. Available online: https://www.openlca.org/wp-content/uploads/2025/01/Report_PC_PET_Tutorial.pdf (accessed on 25 May 2024).
30. Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Heck T, et al. The ecoinvent Database: Overview and Methodological Framework (7 pp). *Int. J. Life Cycle Assess.* **2005**, *10*, 3–9. doi:10.1065/lca2004.10.181.1.
31. GrantaDesign, "Ansys Granta EduPack: Materials Information Management," Granta Des, 2019. Available online: https://www.ansys.com/products/materials/granta-edupack (accessed on 25 May 2024).
32. Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. doi:10.1007/s11367-016-1246-y.

33. Barrionuevo GO, La Fé-Perdomo I, Ramos-Grez JA, Walczak M, Mendez PF. Microstructural differences and mechanical performance of stainless steel 316L conventionally processed versus a selective laser melted. *Prog. Addit. Manuf.* **2024**, *12*, 1–11. doi:10.1007/s40964-024-00774-y.
34. Kan WH, Chiu LNS, Lim CVS, Zhu Y, Tian Y, Jiang D, et al. A critical review on the effects of process-induced porosity on the mechanical properties of alloys fabricated by laser powder bed fusion. *J. Mater. Sci.* **2022**, *57*, 9818–9865. doi:10.1007/s10853-022-06990-7.
35. Lanzutti A, Marin E. The Challenges and Advances in Recycling/Re-Using Powder for Metal 3D Printing: A Comprehensive Review. *Metals* **2024**, *14*, 1–41. doi:10.3390/met14080886.
36. Barrionuevo GO, Ramos-Grez JA, Sánchez-Sánchez X, Zapata-Hidalgo D, Mullo JL, Puma-Araujo SD. Influence of the Processing Parameters on the Microstructure and Mechanical Properties of 316L Stainless Steel Fabricated by Laser Powder Bed Fusion. *J. Manuf. Mater. Process.* **2024**, *8*, 35. doi:10.3390/jmmp8010035.
37. Barrionuevo GO, La Fé-Perdomo I, Cáceres-Brito E, Navas-Pinto W. Tensile / Compressive Response of 316L Stainless Steel Fabricated by Additive Manufacturing. *Ingenius* **2024**, *31*, 9–18. doi:10.17163/ings.n31.2024.01.
38. Rahmani R, Bashiri B, Lopes SI, Hussain A, Maurya HS, Vilu R. Sustainable Additive Manufacturing: An Overview on Life Cycle Impacts and Cost Efficiency of Laser Powder Bed Fusion. *J. Manuf. Mater. Process*. **2025**, *9*, 18. doi:10.3390/jmmp9010018.