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Materials and Manufacturing Process Selection for Pressure Vessel Construction Using Ansys Granta EduPack

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Abstract

Pressure vessels play a pivotal role in numerous industrial applications, as they are engineered to contain fluids or gases at pressures significantly above atmospheric levels. Ensuring their safety and efficiency is critical across sectors such as chemical processing, aerospace, and oil and gas. Over centuries, pressure vessel designs have evolved from simple forms in the 15th century to sophisticated constructions governed by the ASME Boiler and Pressure Vessel Code, established in 1911. However, pressure vessel failures still pose substantial risks, primarily due to issues like corrosion, fatigue, and inadequate maintenance protocols. The selection of suitable materials is fundamental to pressure vessel safety, emphasizing the "leak-before-break" criterion to prevent catastrophic failures. Materials such as carbon steel and stainless steel are often preferred for their ability to withstand mechanical stress and temperature fluctuations. Using the CES EduPack software, this study provides a structured approach to identifying appropriate materials and manufacturing techniques, focusing on attributes such as yield strength, fracture toughness, and corrosion resistance. Stainless Steel AISI 304, an austenitic and half-hard alloy, emerged as the optimal material due to its excellent balance of structural integrity and resistance to environmental degradation. Additionally, Manual Metal Arc (MMA) welding was selected as the most versatile and economical manufacturing method, suited to manage various thicknesses and tolerances effectively. This study concludes that integrating high-quality materials with precise manufacturing processes is essential for developing pressure vessels that meet rigorous safety and performance standards, enhancing reliability and efficacy in demanding industrial environments.

Keywords
Pressure Vessel, Ansys Granta, Materials Selection, Manufacturing Process Selection

1. Introduction
Pressure vessels are integral to numerous industrial processes and applications, designed to contain fluids or gases at pressures significantly different from atmospheric pressure. Their design and construction are pivotal in ensuring safety and operational efficiency across various sectors, including chemical processing, power generation, aerospace, and oil and gas. The key characteristics of pressure vessels that distinguish them from standard containers include their robust construction, ability to withstand high internal pressures, and adherence to stringent safety regulations.

This introduction delves into the historical evolution, safety considerations, and material selection for pressure vessels, drawing on a range of sources to provide a comprehensive overview.
Historically, the concept of pressure vessels can be traced back to Leonardo da Vinci's sketches from 1495, which, while rudimentary, laid the groundwork for modern designs. The Industrial Revolution marked a significant advancement with the development of early pressure vessels, primarily boilers, which were critical yet prone to catastrophic failures due to inadequate materials and construction methods. The catastrophic boiler explosion at the Grover Shoe Factory in 1905, resulting in substantial loss of life, under-scored the need for stringent safety standards, leading to the establishment of the ASME Boiler and Pressure Vessel Code (B&PVC) in 1911. This code has since become a benchmark for pressure vessel safety, ensuring adherence to rigorous standards that mitigate risks associated with high-pressure operations.

Despite these advancements, pressure vessel failures continue to pose significant hazards. An analysis of industrial incidents involving pressure vessels revealed that failures often stem from both technical and organizational factors. Technical failures, such as rupture and leakage, are frequently caused by issues like corrosion, fatigue, and improper maintenance (M. Esouilem, 2022). Organizational failures, including lapses in procedures and inadequate training, further exacerbate these risks. Addressing these issues requires a multifaceted approach, incorporating preventive measures such as strict adherence to design codes, regular inspections, and effective training (T. Ladokun, 2010).

In terms of material selection, the design of pressure vessels necessitates materials that can withstand significant mechanical stresses and temperature variations. The principle of "leak before break" (LBB) is critical, where materials are chosen to allow leakage rather than catastrophic failure (M. F. Ashby, 2005). Materials such as carbon steels, low alloy steels, and stainless steels are commonly employed due to their favorable properties regarding ductility, toughness, and fatigue resistance. The CES EduPack software, developed by Michael F. Ashby and collaborators, plays a crucial role in material selection by providing a systematic approach to evaluating materials based on performance indices and application-specific requirements. This tool facilitates the selection of materials that best meet the operational demands of pressure vessels while ensuring safety and efficiency.

A research in the field of materials and manufacturing discussed the development of a prototype system called MAMPS for selecting materials and manufacturing processes, which is a complex decision-making task involving multiple attributes and uncertainties in early design stages. MAMPS integrates a formal multi-attribute decision model with a relational database, allowing designers to express preferences and assess compatibility between product requirements and available alternatives using possibility theory. It aggregates these compatibility scores into a single rating for each option and outputs a ranked list of suitable alternatives (Giachetti et al., 1998).

Another research highlighted the growing importance of selecting optimal materials, processes, and machines in the context of Additive Manufacturing (AM) due to evolving market demands such as mass customization, complex part requirements, and shortened development cycles. It emphasized the limited existing research on integrating AM product and process data. They addressed this gap by proposing a generic multi-criteria decision-making methodology that aids in identifying practical, design-oriented, and feasible AM solutions (Uz Zaman et al., 2018). Also, some books discussed the Manufacturing process selection from design to manufacture in details (Swift et al., 2003 and 2013). A study done by (Lovatt et al., 1998) pointed out that while material selection methods have advanced significantly, process selection-especially beyond the preliminary design stages-remains underdeveloped. They reviewed current approaches to selection in engineering design, emphasizing the lack of targeted methods for selecting manufacturing processes once a specific task is defined.

One more study by Mançanares et al., 2015 discussed the growing role of Additive Manufacturing (AM) in producing complex parts, as advancements in technology and material options expand its industrial applications beyond rapid prototyping. As the use of AM increases, the complexity of choosing the right manufacturing process also grows due to variations in technology capabilities and machine-specific constraints. Their paper introduced a method based on the Analytic Hierarchy Process (AHP) for selecting the most suitable AM technology and machine according to a part’s technical specifications. The method evaluates key parameters of leading machines on the market, helping manufacturers make informed decisions.

2. Methods

The methodology begins with clearly translating the design specifications, which encompass the functions, limitations, goals, and variables pertinent to the project. This foundational step provides the criteria for all subsequent evaluations. Following this, materials are screened against strict constraints related to their properties, effectively narrowing down the list by discarding those that fail to meet the specified criteria. The remaining materials are then evaluated and ranked according to how well they align with the de-sign's objectives, such as mechanical strength, thermal conductivity, and cost-effectiveness.

Subsequent to this ranking, a thorough investigation is carried out on the top-ranked materials and their types. Ultimately, the selection of the final material involves synthesizing the information gathered from both the ranking and research phases. This decision is based on a holistic evaluation of the materials' properties, performance capabilities, and limitations, ensuring that the chosen material-al best meets the design's requirements and objectives (Figure 1).

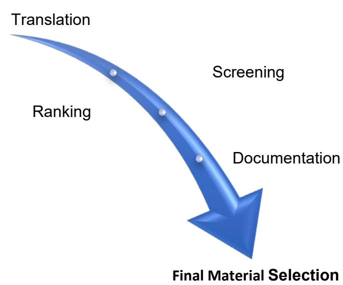

Figure 1. Methodology for Material Selection

2.1 Translation

The following Table 1 illustrates a strength-limited design for a pressure vessel, incorporating constraints related to material properties, processing methods, and temperature tolerance. The primary design goals are to minimize the mass of the vessel while ensuring maximum safety. In this context, thickness is identified as the main variable for optimization to achieve these objectives.

Table 1. Translation

Function	Ability to sustain pressure		
Constraint	Corrosion Resistant Materials can be processed by welding Must leak before break Operating temperature: 25 ºC to 300 ºC		
Objective	**Attribute**		**Maximize / Minimize**
	Mass	Strength-limited design	Minimize
	Safety	Yield Strength	Maximize
		Fracture Toughness	Maximize
		Leak-Before-Break	Maximize
Free Variables	Thicknes		

2.2 Screening

After conducting a comprehensive screening of materials based on their weldability, compatibility with fresh water, and ability to withstand service temperatures ranging from 25°C to 300°C, a selection of 462 materials (excluding grey) was identified from the 4249 materials available in the Ansys Granta Level 3 database. This selection process is illustrated in Figure 2 below.

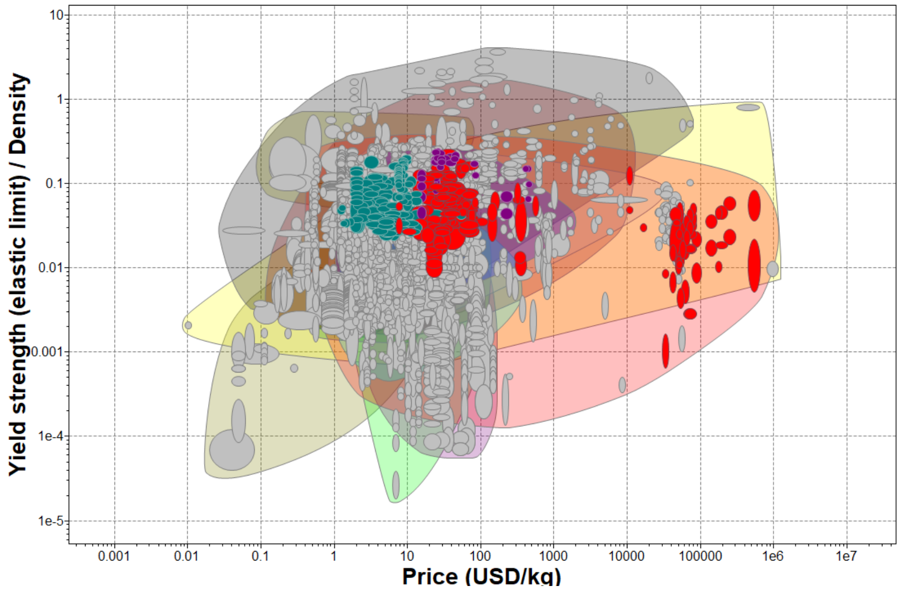

Figure 2. Screening of Materials

2.3 Ranking

Following the screening process, the subsequent phase involves ranking the materials according to the specific objectives outlined in Table 1: Translation Table. During this stage, materials are assessed based on material indices, with those demonstrating the most favorable combinations of properties being assigned higher rankings.

3. Data Collection

To enhance safety through the selection of appropriate materials based on their fracture toughness and yield strength, a graphical representation has been created. This chart includes three lines: M2, M3 (with a slope of zero), and M4 (with a slope of 0.5). Each line represents different material evaluation criteria, illustrating the relationship between fracture toughness and yield strength for various materials (Figure 3).

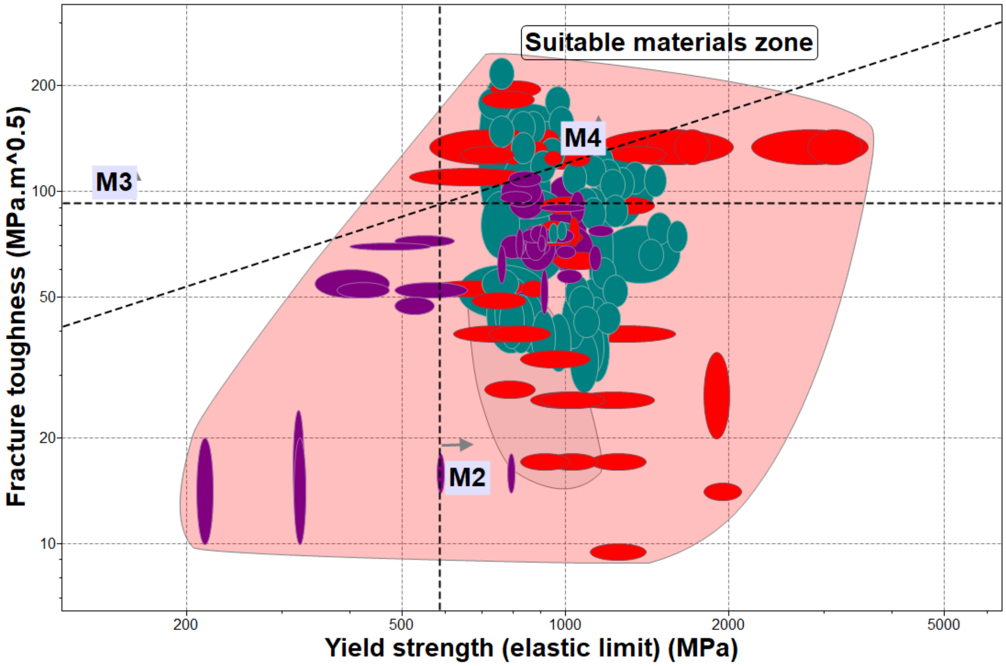

Figure 3. Identification of Suitable materials zone

The "Suitable Materials Zone" denotes the optimal selection area where all critical criteria (M2, M3, and M4) for ensuring the safety of pressure vevssel are satisfied. Materials within this zone are considered ideal choices because they fulfill the essential requirements for both fracture toughness and yield strength, thereby ensuring reliable and secure performance of the vessel (Figure 4).

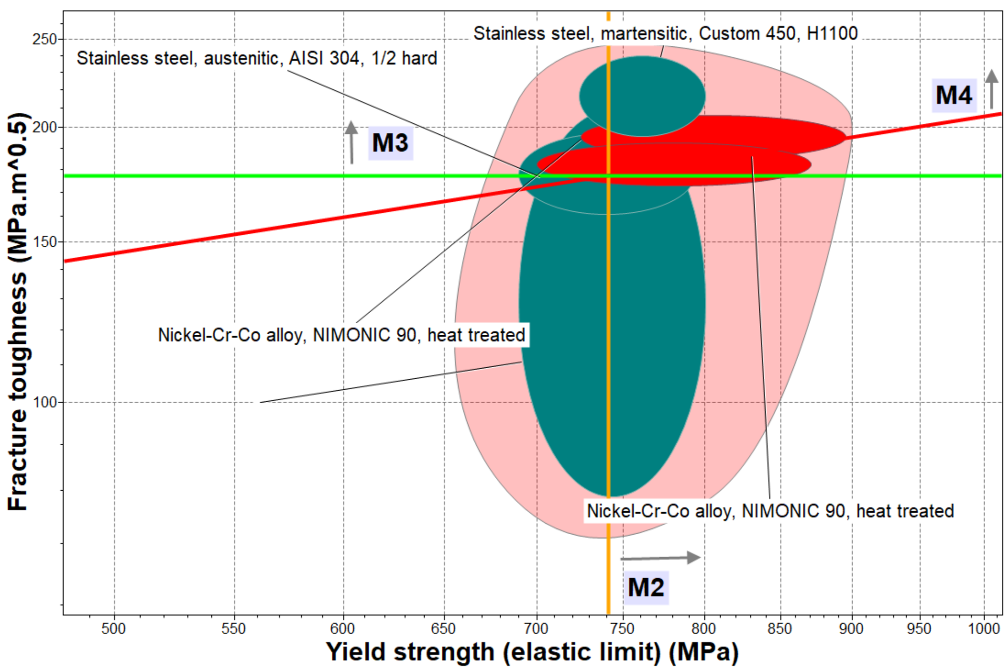

Figure 4. Suitable Materials

Materials that fall within the "Suitable Materials Zone" and satisfy all the specified constraints and objectives for pressure vessel applications are as follows:

1. Nickel-Cr-Co alloy, NIMONIC 90, heat treated
2. Nickel-Cr-Co alloy, NIMONIC PK33, heat treated

3 Stainless steel, austenitic, AISI 304, 1/2 hard
4 Stainless steel, martensitic, 17-4PH, H1150
5 Stainless steel, martensitic, Custom 450, H1100

By adjusting the index lines on the graph to their extreme positions, such that only one material meets all three criteria (M2, M3, and M4), the optimal material can be identified. This approach ensures that the chosen material satisfies the stringent requirements for the pressure vessel, including high fracture toughness, high yield strength, and essential leak-before-break characteristics (Figure 5).

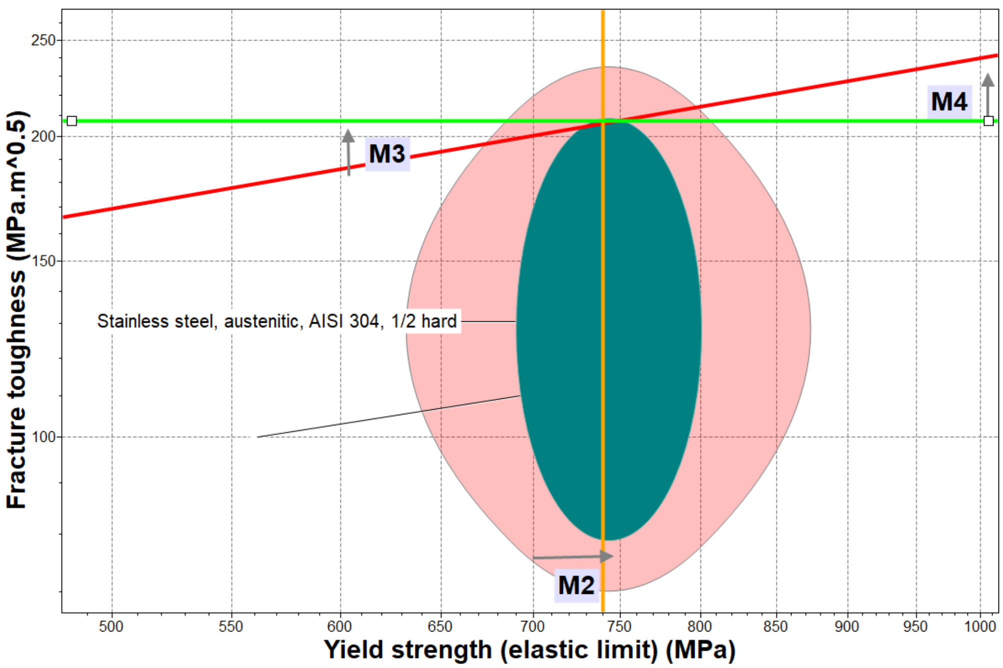

Figure 5. Final Material Selection

Stainless steel, austenitic, AISI 304, 1/2 hard

Stainless Steel AISI 304 is widely used for pressure vessel fabrication due to its excellent corrosion resistance, strength, and formability. This austenitic stainless-steel grade offers good weldability and maintains its structural integrity across a wide range of temperatures, making it a preferred choice for many pressure vessel applications in industries such as chemical processing, food and beverage, and pharmaceuticals. Its versatility is evident from its use in gas turbines, aircraft, and other demanding applications, further validating its effectiveness for pressure vessel and components (Ansys, 2023).

4. Results and Discussion

The Ansys Granta software will be utilized to analyze and compare different approaches for pressure vessel construction using the selected materials. The initial step in developing the design criteria for the pressure vessel involves establishing the necessary requirements and eliminating any methods that fail to meet these specifications.

Table 2. Process Requirements / Specifications

Material	Stainless steel, austenitic, AISI 304, 1/2 hard
Materials to be joined	Metal
Process characteristics	Continuous
Function	Airtight
Joint Geometry	Butt, Tee

From the initial pool of 55 processes, 15 were chosen based on the criteria outlined in Table 2. Following this selection, a of graph comparing section thickness against tolerance ranges are being developed. This graph will be used to assess and identify the most appropriate manufacturing process for the pressure vessel.

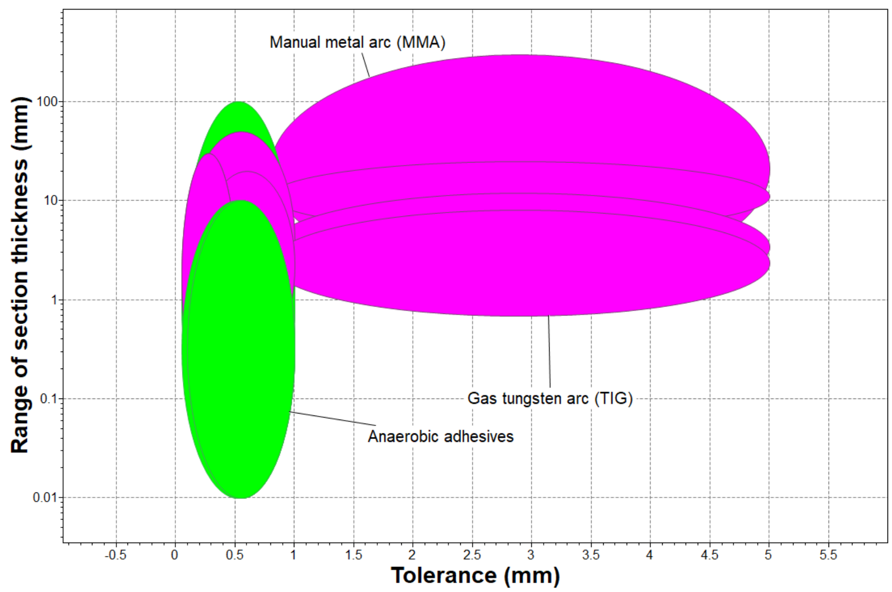

Figure 6. Tolerance vs. Range of Section Thickness

Among various processes, Manual Metal Arc (MMA) welding offers the widest range of manufactural thicknesses and accommodates a broad spectrum of tolerances as shown in Figure 6.

Manual Metal Arc (MMA) welding is highly suitable for pressure vessel manufacturing due to its flexibility and cost-effectiveness. This process, also known as shielded metal arc welding (SMAW), uses a flux-coated electrode to create an electric arc that joins metals. It is capable of handling a wide range of material thicknesses from 1.5 mm to 300 mm, which is crucial for pressure vessels requiring different wall thicknesses. The process achieves tolerances of 0.8 mm to 5 mm, suitable for most applications.

MMA welding works with various metals, including carbon steels, stainless steels, and certain nickel alloys, and is effective for different joint geometries like lap, butt, and tee joints. Despite its manual nature and high labor intensity, MMA is economically advantageous with low setup and tooling costs. Overall, MMA welding provides a versatile and cost-effective solution for pressure vessel fabrication.

5. Conclusion

In conclusion, pressure vessels are essential for various industrial operations, necessitating careful design and material selection to ensure safety and reliability. The material selection process involves rigorous screening and ranking to identify the most suitable options. The principle of "leak-before-break" is crucial for selecting materials that avoid catastrophic failures. Among the materials considered, Stainless Steel AISI 304, austenitic and half-hard, has been identified as the optimal choice. This material was selected for its excellent balance of yield strength, fracture toughness, and corrosion resistance, making it ideal for pressure vessels. Additionally, Manual Metal Arc (MMA) welding was determined to be the most versatile and cost-effective manufacturing process due to its capability to handle a wide range of thicknesses and tolerances. Integrating these materials and processes ensures the development of pressure vessels that meet stringent safety and performance requirements, enhancing their reliability and effectiveness in demanding industrial applications.

References

Ansys Granta, “Datasheet: Stainless steel, austenitic, AISI 304, 1/2 hard,” Ansys Granta, 2023.

Ashby, M. F., Materials Selection in Mechanical Design, 3rd ed. Amsterdam, Boston: Butterworth-Heinemann, 2005.

Esouilem, M., A.-H. Bouzid, and S. Nadeau, “Pressure Vessels and Piping Accident Analysis and Prevention: A Case Study in Canada,” International Journal of Safety and Security Engineering (IJSSE), vol. 12, no. 1, pp. 105–114, Feb. 2022. doi: 10.18280/ijsse.120113.

Ladokun, T., F. Nabhani, and S. Zarei, “Accidents in Pressure Vessels: Hazard Awareness,” 2010.

Lovatt, Andrew M., and Hugh R. Shercliff. "Manufacturing process selection in engineering design. Part 1: the role of process selection." Materials & design 19.5-6, 1998.

Giachetti, Ronald E. "A decision support system for material and manufacturing process selection." Journal of Intelligent Manufacturing 9, 1998.

Mançanares, Cauê G., et al. "Additive manufacturing process selection based on parts’ selection criteria." The International Journal of Advanced Manufacturing Technology 80, 2015.

Swift, K. G., and J. D. Booker. Manufacturing process selection handbook. Butterworth-Heinemann, 2013.

Swift, Kenneth G., and Julian D. Booker. Process selection: from design to manufacture. Elsevier, 2003.

Uz Zaman, Uzair Khaleeq, et al. "Integrated product-process design: Material and manufacturing process selection for additive manufacturing using multi-criteria decision making." Robotics and Computer-Integrated Manufacturing 51, 169-180, 2018.

Biographies

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