Analysis of potential materials for local production of a rail car component using additive manufacturing

Rumbidzai Muvunzi, Khumbulani Mpofu, Ilesanmi Daniyan, Festus Fameso

Department of Mechanical & Automation Engineering, Tshwane University of Technology, Pretoria 001, South Africa

Research article

1. Introduction

In the rail industry, unavailability of spare parts timeously can lead to financial losses (Han et al., 2017). When a critical part breaks down, the train can be rendered out of service until it is replaced. Some of the parts can have lengthy delivery times, especially if they are not locally produced (Killen et al., 2018). Thus, a lot of downtime is experienced while waiting to replace the part. It can be costly to produce the part in-house because of the associated tooling costs (Killen et al., 2018). Also, considering the lengthy service time of trains, some of the parts might have become obsolete and it becomes difficult to replace them. Proper maintenance and functionality of vehicles requires spare parts to be available timeously.

On the other hand, Additive Manufacturing (AM) is a promising technology for spare parts production (Li et al., 2019a,b). This is because AM allows parts to be produced directly from digital models in a short period without the need for tooling (Schmidt et al., 2017). The use of AM to print spare parts on demand is a quicker and flexible approach. This eliminates the tooling costs and time for producing parts using conventional methods or the logistical costs and downtime associated with outsourcing the part. The distinct characteristics that make spare parts suitable for production with AM include variable demand, need for reducing delivery lead time and low volume production (Savolainen and Collan, 2020). Based on previous studies, AM can be an economic method of producing spare parts when compared to conventional methods. (Savolainen and Collan, 2020) evaluated the economic viability of using AM to produce spare parts. In the study, they identified manufacturing strategies that are economically viable to produce spare parts using AM. In their conclusion, it was stated that AM would be most beneficial for spare parts that are approaching the end of life stage of the product lifecycle. Kostidi and Nikitakos (2018) conducted a study to investigate the application of AM to produce spare parts for the maritime industry. In their study, it was concluded that AM would be economical for low volume parts. Beiderbeck et al. (2018) investigated the business implications of producing AM spare parts on demand and on-location for the automotive industry. The outcome of the study highlighted the potential benefits of AM in the automotive aftermarket to revolutionise the business landscape through the production of individualised spare parts on demand and on location without the need for costly tooling. Nonetheless, the study also indicate that some AM concepts are not feasible.
from the technical perspective, Cerutti et al. (2019) evaluated the impact of incorporating Augmented Reality into the AM technique to produce spare parts for the aeronautics industry. The outcome of the study indicated that the incorporation of AR into the AM technique can enhance maintenance operations. AR can provide support for the AM operators with instructional manuals and virtual models which depicts the real world. As such, it could minimise the workload, and manufacturing error with improvement in the process reliability and manufacturing time. As part of the study, a benchmark spare part component, a bracket for an extension mechanism was produced using AM. The produced part had a more efficient design with lower mass and had the potential to reduce carbon emissions by 4.583 tonnes. According to a study by Muir and Haddud (2018), AM is a suitable technology for producing spare parts in the medical and mechanical engineering fields. Westerweel et al. (2021) developed an approach for using AM to produce spare parts in remote locations for the army. The proposed approach was validated using a case study of the Netherlands military. According to the results, applying AM can reduce the operational cost through reduced inventory and increased asset availability. So far, there is limited research that focuses on the use of AM to produce spare parts for the rail industry yet other companies in this sector have shown interest in adopting AM (Kilien et al., 2018). Alston, a French railway company has exploited AM to produce lightweight components (StationOne, 2021). A project known as RUN2Rail was launched in Europe to investigate the application of AM to produce rail components with efficient designs that are lighter and more reliable (RUN2Rail, 2021). Dubai’s road transport authority has utilised AM to produce railway components (Dubai National, 2021). According to their analyses, using AM can reduce the time taken to source a part by 90% and reduce the original cost by 50%. Webtech, a rail company, is developing metal AM parts using the Binder Jet AM technology (Molitch-Hou, 2020) Duettsch Bann, a German railway has started producing parts using AM (Duetsch Bahn, 2021).

Existing works have also reported on the analysis of materials using the modelling and simulation approach vis-à-vis their service requirements. For instance, Singh (2018) performed the comparative analysis of the carbon steel and composite materials for the sidewall of a light rail vehicle using the FEA approach in the ABAQUS environment. The study showed that the composite materials show promising potential for the development of the sidewall of a light rail vehicle when compared with the carbon steel in the quest to achieve lightweightness, energy conservation, and environmental friendliness. Daniyan et al. (2020b) employed the FEA technique to establish the suitability of the ASTM (A) cast steel for the development of the rail car bogie frame. Compared to other materials, ASTM (A) cast steel was found to meet the service requirement of high strength that will ensure sufficient rigidity under the required service conditions.

In the South African rail-manufacturing sector, most spare parts are imported (Oyesola et al., 2020, 2021; Muvunzi et al., 2021). Amidst the emerging materials, the comparative analysis of the appropriate material for the development of the traction link frame of a railcar via the additive manufacturing process has not been fully explored by the existing literature. There is need for further investigation on the use of AM as an enabling technology for local manufacturing of rail components. This will eliminate the costs and downtime associated with procuring the parts elsewhere. Also, local manufacturing is a sustainable drive for creating employment and increasing competitiveness (Kleer and Piller, 2019). Thus, the aim of the study is to investigate the potential materials for employing AM to produce a traction link, which is a typical safety part of a rail car. To take advantage of the design freedom offered by AM, three high performance materials (Aluminium 7075, Titanium Ti6Al4V, and Stainless steel A36) are investigated for potential reduction in weight and improvement in the functional performance of the part. The reason for selecting these materials stems from their excellent mechanical properties such as high strength and lightweight properties which are necessary for achieving weight reduction and improvement in the mechanical performance of the traction link. The novelty of this study lies in the fact that the analysis of potential materials that can be used to produce a rail car component with focus on weight reduction and functional performance has not been sufficiently highlighted by the existing literature. The paper is structured as follows; section 2 describes the component and the proposed AM manufacturing process. The FEA analysis of the component with the alternative materials is also provided. Section 3 presents the results and discussion. Finally, a conclusion is provided in section 4.

2. Materials and methods

As mentioned earlier, the paper aims to identify potential materials that can be used to manufacture a rail component locally using AM. To achieve this aim, a quantitative research design was used. This is because the study involves analysing the mechanical and thermal performance of the potential materials under loading conditions. Hence, the parameters under investigation are measurable. Finite Element Simulation was used for predicting the mechanical and thermal behaviours of the component when different materials are used to produce the part. The reason for using this approach is that it depicts the physical phenomenon thereby reducing the costs associated with physical experiments while allowing for design optimisation (Boulbes, 2010; Daniyan et al., 2020a). Secondly, Finite Element Simulation allows for varying physical conditions such as stress, vibration and applied force etc. Also, Finite Element Simulation allows prediction of potential design challenges that can be addressed before producing the physical product (Koutromanos, 2018). On the other hand, the challenge of using FE analysis is that it makes approximations since the analysis is made on a model and not the real structure (Koutromanos, 2018), hence, it is necessary to perform physical experiments at a later stage to further evaluate the simulation results. A comparison table and existing literature are used to decide the most suitable AM process based on the size of part, technical limitations and cost of available metal AM processes. The steps involved in the study can be highlighted using Figure 1.

As shown in Figure 1, the first step involves specifying the component. This is followed by selection of the suitable AM process. The next
step involves conducting the FE analysis to determine the performance of the material under conditions similar to real life.

2.1. Case study part

The traction link, shown in Figure 2 is a component used to transmit force and isolate vibration. It was modelled and simulated in this study using high performing materials viz: aluminium alloy (7075), titanium alloy (Ti6Al4V) and stainless steel (A36).

The traction link is an auxiliary component of the railcar bogie system for force transmission and provision of acoustic and vibration isolation. The traction link is designed purposely for the transfer of the traction and braking forces between the railcar system and its body (Daniyan et al., 2021). This is to reduce dynamic vibration, which can cause ride discomfort and wear of the components of the rail car suspension system. Hence, the design of the traction link must take into consideration high strength to weight ratio to ensure structural integrity, corrosion resistance, cost effectiveness, formability and the end of life requirements to meet the service requirements.

2.2. Selection of AM process

Initially, the component is manufactured using casting with cast steel material. The challenge of using casting as a local manufacturing process lies in the high tooling investment costs required. Also, considering that the part is required in low volumes, the production cost per part becomes very high. Additive Manufacturing (AM) is considered as the most suitable technology for producing the part because it is more economic when compared to casting since no tooling is required (Wu et al., 2018). Table 1 shows a brief comparison of metal AM processes.

Based on Table 1, WAAM is considered a suitable process because the raw materials are easily available and less costly when compared to other processes. Also, the lead time of manufacturing the part with WAAM is less because of the fast build rates (0.5–4 kg/hr) (Williams et al., 2016). Another reason is that the part to be analysed can be considered as a medium complexity since it does not have internal features and this makes it compatible with the WAAM process. The powder bed-fusion processes (PBFP) are capable of producing highly complex parts, however, they are limited in terms of build size and speed (Williams et al., 2016). Also, the operating costs of PBFP is much higher than WAAM because of the powder and energy required (Williams et al., 2016). The WAAM process accommodates high performance materials which are difficult to process with other conventional manufacturing methods such as machining (Wu et al., 2018). Based on previous studies, the mechanical properties of parts produced using WAAM are comparable to those produced conventionally. However, WAAM is prone to defects such as porosity, residual stresses and distortion which can affect the fatigue performance (Xia et al., 2020). This can be managed through control of process parameters and the use of special post heat treatment procedures (Cunningham et al., 2018).

![Figure 2. Traction link.](image)

| Table 1. Comparison of AM processes. |
|-------------------------------------|
| Process | Powder Bed Fusion | Direct Energy Deposition (powder) | WAAM |
| Size of part | Limited by build volume | Unlimited | Unlimited |
| Cost of raw materials | $80–$120/kg (Simpson Additive, 2020) | $22.05/kg (Production Engineering, 2022) | $10.34–$11.44/kg (Production Engineering, 2022) |
| Complexity of part | High | Medium | Low to medium |
| Common defects | Thermal cracks, Residual stresses (Schmidt et al., 2017) | Porosity, residual stresses (Dass and Moridi, 2019) | Residual stresses, distortion and poor resolution (Wu et al., 2018) |
| Speed/Build rate | $2.93 \times 10^{-6}$ m$^3$/hr (GE Additive, 2020) | $1.41 \times 10^{-5}$ m$^3$/hr (Dutta and Froes, 2017) | $0.54 \times 10^{-5}$ m$^3$/hr (Williams et al., 2016) |

2.3. Analysis of materials

Some authors have reported on the behaviours of certain materials when used as a component of the railcar system under different loading conditions. The use of Finite Element Analysis and simulation tools have shown capability for the determination of dynamic behaviour of railcar components (Kukulski et al., 2019; Nejad, 2014).

Aluminium 7075 has zinc as the primary alloying element and the alloy boasts of high strength to weight ratio, good corrosion and wear resistance, moderate machinability, good fatigue strength, as well as high resistance to stress and strain (Gabrian). These properties makes it a potential material for rail applications where it allows for weight savings over stainless steel. According to previous studies, the aluminium alloy 7075 is prone to solidification cracking and this has limited its application in welding (Dursun and Soutis, 2014). However, recent studies show that aluminium 7075 is weldable and applicable in wire fed additive manufacturing when reinforced with TiC (Oropeza et al., 2020).

The titanium alloy (Ti6Al4V) belongs to the alpha-beta (α-β) alloy class of titanium find extensive application in the industries such as the aerospace, rail, biomedical marine and automotive industries (Liu and Shin, 2019). This is because the alloy is characterised by excellent mechanical properties, such as high tensile strength, high stiffness, good formability and excellent corrosion resistance in addition to its outstanding strength-to-weight ratio (Yadroitsev et al., 2014). The Ti6Al4V alloy is suitable for wire arc additive manufacturing, readily available in wire form and there has been much literature reported on this subject (Kumar et al., 2020).

Stainless steel A36 is a low carbon steel, which boasts of good formability, machinability, excellent strength and corrosion resistance ability (AzoMaterials, 2012). It is readily weldable and has been successfully used in WAAM to make engineering components (Jin et al., 2020).

The selection of aluminium alloy (7075), titanium alloy (Ti6Al4V) and stainless steel (A36) as potential materials were based on their mechanical properties of the materials, which justify their suitability for the development of a rail car traction link.

The material parameters used for the analysis are shown in Tables 2, 3, and 4.
2.3.1. Evaluation of the strength to weight ratio

It was desired to reduce the weight of the traction link, thereby contributing to the reduction of the overall mass of the rail car. This is a sustainable drive for reducing the fuel consumption which translates to the carbon footprint associated with usage of the part (Chatterjee et al., 2020). High-strength materials are suitable for improving crashworthiness and bearing the mechanical load associated with the part (Hasan et al., 2020). Thus, the selected alternative materials are evaluated in terms of their strength to density ratios. The strength to density ratios (r) is the material’s density (kg/m³) while ς is the ultimate tensile strength of the material (MPa).

\[ r = \frac{\rho}{\sigma_U} \]  

(1)

Where, \( \rho \) is the material’s density (kg/m³) while \( \sigma_U \) is the ultimate tensile strength of the material (MPa).

Based on Eq. (1), the strength to density ratio shown in Table 5.

According to Table 1, Ti–6Al–4V has the highest strength to density ratio followed by the aluminium 7075 alloy. The ASTM steel has the lowest strength to density ratio. Thus, the Ti–6Al–4V and aluminium 7075 materials are more sustainable in terms of weight reduction. The next stage involves FE analysis of the materials under loading conditions. The appropriate material should satisfy the condition of fatigue resistance, lightweight, and stress resistance. This is because existing works on the railcar suspension systems have linked the failure of the suspension system and its components under dynamic loading conditions to fatigue, stress and uncontrolled vibrations (Zhi et al., 2020).

2.3.2. Finite element analysis of traction link

The FE analysis was conducted at the initial design stage to obtain foresight on the dynamic response of the materials under loading conditions. FE analysis allows the traction link to be analysed in detail and desired comparative investigations carried out, based on how it will react under real-world conditions. It reduces casualty in the development of essential components and speeds up the process of discovering the minimum and most influential considerations, materials and parameters needed to produce the component even before a prototype is generated (Koutromanos, 2018). It thus in essence, reduces the number of physical prototypes, testing and experiments and optimization and redevelopment of the components right in their design phase to, saving a whole lot on resources and expenses (Boulbes, 2010). However, the limitation of FE analysis comes with its wrong application and implementation which leads to inaccurate results and erroneous design decisions. This can be expensive to correct later in the design process.

The comparative response and performances of the three materials to in-operation conditions was evaluated using commercial finite element analysis software, ABAQUS CAE. The three different materials (Titanium Ti6Al4V, Aluminium 7075 and Stainless steel) were analysed using the ABAQUS software. This specific software was used because of its wide application in the modelling and analysis of mechanical components and systems (Zhang, 2015). Also, the software is capable of analysing stress and vibration of loaded components (Vani and Jayachandraiah, 2015). The response of the traction links to forces and heat were simulated in static and thermal loading analyses respectively. The CAD model of the traction links was produced on the complete ABAQUS environment. The geometric model was discretized at the shank with 3-dimensional 8-node continuum hexagonal (C3D8R) mesh elements. These give the best results for minimum computational cost. At the grooves, 3-dimensional 10-node continuum tetrahedron (C3D10R) mesh elements were employed. This was done on the non-linear geometry of the grooves in anticipation of relatively large strains that will occur in this region and to improve visualization of the stresses on the part. It also helps to overcome shear and volumetric locking during computation. Quick mesh convergence checks produced mesh size of 0.4 mm as the optimal element size to mesh the parts, providing the required level of accuracy and validity of the computations and balancing the computational time and size constraints. The choice of the right mesh element description and convergence of the mesh in FE is vital if computational accuracy and cost is to be optimum (Kim et al., 2018). Mesh convergence relates to how small the elements need to be to ensure that the results of an analysis are not affected by changing the size of the mesh. Mesh refinement by virtue of the mesh convergence leads to a significant reduction in errors and increase in the convergence of solutions without increasing the size of the overall problem being solved (Boulbes, 2010). The meshed model is shown in Figure 3.

Static general and heat transfer analyses steps with step periods of 1s were created for the mechanical and thermal evaluation of the response of the traction link to applied loading. These scaled step timescales where applied instead of the natural time for the quasi-static process. This was

| Table 2. Materials properties of Aluminum 7075 (Matweb, 2021). |
|----------------|----------------|
| Property        | Value          |
| Density (kg/m³) | 2823.3         |
| Brinell’s hardness (BH) | 150         |
| Yield strength (MPa) | 503          |
| Ultimate tensile strength (MPa) | 572          |
| Modulus of elasticity (GPa) | 71.1         |
| Elongation at break (%) | 11            |
| Poison’s ratio | 0.33           |
| Shear modulus (GPa) | 26.9          |
| Shear strength (MPa) | 331           |

| Table 3. Materials properties of Titanium Alloy (Ti–6Al–4V) (US Titanium Industry, 2017). |
|----------------|----------------|
| Property        | Value          |
| Density (kg/m³) | 4420           |
| Yield strength (MPa) | 880           |
| Ultimate tensile strength (MPa) | 950          |
| Bulk modulus (GPa) | 150           |
| Modulus of elasticity (GPa) | 113.8        |
| Poison’s ratio | 0.342          |
| Shear modulus (GPa) | 44            |
| Shear strength (MPa) | 550           |

| Table 4. Materials properties of ASTM (A36) steel (American Metal Co, 2021). |
|----------------|----------------|
| Property        | Value          |
| Density (kg/m³) | 7850           |
| Poison’s ratio | 0.26           |
| Young modulus (GPa) | 200          |
| Shear modulus (GPa) | 79.3          |
| Tensile strength (MPa) | 550          |
| Yield strength (MPa) | 250           |
| Bulk Modulus (GPa) | 160           |
| Elongation (%) | 20%            |

| Table 5. Strength to density ratio. |
|----------------|----------------|
| Material        | Strength to density ratio (MPa * m³/kg) |
| Ti–6Al–4V       | 0.199           |
| ASTM (A36) steel | 0.0318         |
| Aluminium 7075  | 0.1781          |
done to regulate the cost of computation since the solution remains nearly the same as the true static solution which can be extrapolated into natural time if need be, given that dynamic effects in this case in question remain insignificant. In-situ mechanical and thermal loading profiles where imposed in the analyses to predict the suitability of the materials in performing the task of transmitting the applied loads and isolating non-linear variations in distributed forces associated with in-service vibrations, while also observing the effects of heating on the morphology and mechanical potential of the material of the component.

Non-rotational mechanical boundary conditions were applied on the left and right edges of the part in the static general analysis. This was done to constrain the component from rotating in any of the 3 rotational axes because when the part is in service, it links the car and the body, providing translational traction. This causes the part to be constrained from rotating in any direction. The mechanical loading and constraint regime is shown in Figure 4.

In the thermal analysis, the boundary conditions defining the ambient operating temperature of the component, pegged at a magnitude of 313 K, were imposed on the outer surfaces of the component. This was done in accordance with the principles of thermal equilibrium under no-slip conditions causing a zero-temperature gradient at the physical boundary between the surface of the traction link and the surrounding current of ambient air around it. Thermal interactions in the form of surface heat transfer at ambient air were considered as a combination of three separate shapes. These include the two outer sections, which are circular in shape and the mid-section, which has a rectangular section and they are calculated using Eqs. (4) and (5) respectively.

![Meshed model of component.](image)

**Figure 3.** Meshed model of component.

3. Results and discussion

The results for the stress distribution are shown in Appendix 1. For the aluminium 7075 alloy, the vibrations and forces acting on the part can cause the stress to vary from 2.248 kPa to 33.77 MPa. Much of the stress is concentrated on the grooves. This is because the grooves are a point of connection with other components that transmit forces and vibration. This is different from the other regions of the traction link, which has lower levels of stress. The range of stresses acting on the part (2.248 kPa–33.77 MPa) is way below the maximum yield strength (503 MPa) of the material. Thus, the material will not have permanent deformation under normal loading conditions. In the case of the ASTM (A36) steel, the instantaneous vibrations and forces cause the stresses acting on the part to vary between 3.445 kPa to 33.86 MPa. Accordingly, the part will not yield to permanent deformation since the stress levels are below the Von Misses stress was the key parameter used to validate the evaluated performance of the materials under loading conditions. The evaluation was conducted by comparing the von misses stress and the yield strength of the materials. The Von Misses stress calculations were obtained by using Eq. (2) (Dupen, 2014).

$$\sigma = \frac{F}{A}$$  \hspace{1cm} (3)

To calculate the cross-sectional surface area \((A)\), the traction linked is considered as a combination of three separate shapes. These include the two outer sections, which are circular in shape and the mid-section, which has a rectangular section and they are calculated using Eqs. (4) and (5) respectively.

$$A_1 = 2 \frac{\pi}{4} (d_2 - d_1^2)$$ \hspace{1cm} (4)

$$A_2 = LW$$ \hspace{1cm} (5)

The elastic and plastic strains were calculated using Eqs. (6) and (7) (Dupen, 2014).

$$\varepsilon_e = \frac{\sigma}{E}$$ \hspace{1cm} (6)

$$\varepsilon_p = \varepsilon - \varepsilon_e$$ \hspace{1cm} (7)

To calculate the deflection, the traction link is considered as a simply supported beam, which is supported at both ends and calculated using Eq. (8) (Khurmi and Khurmi, 2019).

$$\delta = \frac{5wL^4}{384EI}$$ \hspace{1cm} (8)

Where: \(\sigma\) is the stress induced on the traction link (MPa), \(F\) is the force applied on the link (N), \(A\) is the cross-sectional surface area of the link (mm²), \(d_2\) is the outer diameter of the link (mm), \(d_1\) is the inner diameter (mm), \(L, W\) are the length and the width of the traction link (mm), \(E\) is the Young’s modulus of the material (MPa), \(\varepsilon, \varepsilon_e, \varepsilon_p\) are the total, elastic and plastic strains respectively (dimensionless quantities), \(\delta\) on the traction link (mm), \(w\) is the uniformly distributed load acting per length on the traction link (kN/m), \(L\) is the length of the traction link (mm), \(I\) is the moment of inertia of the traction link crosssectional area (mm⁴).
maximum yield stress of the material (250 MPa). Just like the aluminium 7075 alloy, high stress levels are experienced at the grooves although, the stresses are generally higher for the ASTM (A36) steel. For the Ti6Al4V, the stress range is from 2.764 kPa to 33.76 MPa under normal loading conditions. Just like all the other materials, this is well below the yield stress of 880 MPa. Thus, there is no permanent deformation which is expected. When comparing the stress maps of all the three materials, the ASTM steel has the least deviation and the aluminium 7075 alloy has the most deviation.

Appendix 2 shows the displacement maps for the three materials. All the maps show that the highest displacement was experienced on the right side of the traction link. This could be caused by the amount of load experienced in that region, making it more susceptible to deformation. The deformation ranges for the aluminium 7075 alloy, ASTM steel and Ti6Al4V are 0.286 mm–0.507 mm, 0.0338–0.1548 mm and 0.0131 mm–0.3228 mm respectively. Accordingly, all the materials show very little displacement. Based on the figures, ASTM steel gives the least displacement followed by Ti6Al4V and aluminium 7075 alloy respectively.

The elastic and plastic strains are shown in Appendix 3 and 4. Based on the analysis of the maps, there is no plastic strain under normal loading conditions. Thus, all the materials show the capacity to revert back to their original state after deformation. According to the maps, the elastic strain ranges of the aluminium 7075 alloy, ASTM steel and Ti6Al4V are 1.706 × 10–8 to 4.439 × 10–4, 9.224 × 10–10 to 1.560 × 10–4 and 1.306 × 10–8 to 3.002 × 10–4 respectively. Generally, these are very low values, however, the ASTM steel shows the least elastic strain while aluminium 7075 alloy shows the highest plastic strain.

Much of the studies in literature have focused on the application of Ti6Al4V and aluminium 7075 in the aerospace industry (Naveen Kumar et al., 2018; Kumar et al., 2020). These materials have not yet been fully explored in the railway industry which has mainly been dominated by steels. Jiru (2015) conducted a structural analysis of a high speed steel rail car vehicle body. In their study, the steel was able to withstand the mechanical and thermal loads. However, they recommended the use of high performance materials with lightweight and high strength for improved functionality. Veiga et al. (2020) used WAAM to produce Ti6Al4V specimens and tested them for tensile strength, elastic limit and elongation. According to the results, the samples were able to meet the required standards for the aeronautic industry.

Figure 5 presents the stress-strain distribution for the three materials considered (aluminium 7075, Ti6Al4V and stainless steel). All the materials show linear proportionality, which indicates an increase in the rate of strain as the magnitude of the stresses increase. Although their elastic limits were not exceeded under the loading condition, there is evidence of strains and displacements from the results obtained. This implies that the stress induced in the material is not sufficient to cause plastic or permanent deformation. This is an indication that the materials were not subjected to stress beyond their yield limits. Figure 5 indicates that titanium alloy has the highest stress-strain ratio followed by stainless steel while the least stress to strain ratio was observed in the 7075 aluminium alloy. This means that for the required service condition, the 7075 aluminium alloy shows the highest resistance to stress and strain which makes it a potential material for the traction link of the railcar most especially in this situation where weight savings from steel will ultimately lead to a reduction in the carbon footprint.

The thermal analysis showed that all the materials were able to withstand the thermal loads exposed to the traction link. However, the 7075 aluminium alloy has the highest heat flux and the Ti6Al4V had the least heat flux compared to the other materials. Stainless steel had the highest temperature and Ti6Al4V had the lowest.

As expected, the aluminium 7075 alloy and Ti6Al4V are considered as suitable for producing the component with WAAM. However, further studies are required on the production of nanoparticle enhanced Aluminium 7075 parts since there is limited information in literature.

The challenge with the use of FE analysis is that it is based on approximations. Hence further studies will include physical experimentation to evaluate the mechanical and thermal parameters of the part since the FE analysis is mainly based on assumptions.

Figure 5. The stress-strain plot of the aluminium alloy, stainless steel and titanium alloy.

4. Conclusion

The aim of this paper was to investigate potential materials that can be used for local manufacturing of a traction link. This is a typical critical component of the rail car which is not currently being produced locally. Additive Manufacturing was considered as an economic approach for producing the part locally because it does not require tooling investment and the part is required in low volumes. The WAAM process was considered viable for producing the part considering the large size and medium complexity of the part. Also, WAAM is a sustainable approach in terms of material usage since the part is produced additively rather than using subtractive methods. The potential materials investigated for this study include aluminium 7075 alloy, titanium alloy Ti6Al4V and ASTM steel A36. These specific materials were selected with the aim of producing a more sustainable part in terms of reducing the carbon footprint associated with the usage of part and increasing the functional performance. The following conclusions can be drawn from the study.

- The aluminium 7075 alloy and Ti6Al4V are necessary materials for increasing the strength to weight ratio of the part. This tends to contribute towards reducing the overall weight of the railcar and ultimately leads to a reduction in the carbon footprint.
- In terms of mechanical performance, all the materials showed the capability to withstand the load associated with the rail car with no plastic deformation. However, the aluminium 7075 alloy exhibited the lowest stress levels under the considered operating conditions.
- The thermal analysis showed that all the materials were able to withstand the thermal loads exposed to the traction link. However, the 7075 aluminium alloy has the highest heat flux and the Ti6Al4V had the least heat flux compared to the other materials. Stainless steel had the highest temperature and Ti6Al4V had the lowest.
- Both the Aluminium 7075 alloy and Ti6Al4V are considered as suitable for producing the component with WAAM. However, further studies are required on the production of nanoparticle enhanced Aluminium 7075 parts since there is limited information in literature.
- The challenge with the use of FE analysis is that it is based on approximations. Hence further studies will include physical experimentation to evaluate the mechanical and thermal parameters of the part since the FE analysis is mainly based on assumptions.
• Although WAAM is capable of producing parts with mechanical properties that compete with those conventionally produced, the challenge of residual stresses and distortion still needs to be addressed. There is need for further studies on optimizing the process parameters to ensure improved quality and fatigue performance.
• The next stage of the study involves investigating the effects of the WAAM process on the performance of the parts through FE analysis and physical experiments. This is because WAAM is prone to residual stresses, porosity and distortion. Hence there is need for further study to confirm the most applicable material.

Declarations

Author contribution statement

Rumbidzai Muvunzi: Conceived and designed the experiments; Wrote the paper.
Khumulwini Mpoku: Conceived and designed the experiments. Ilesani Daniyan: Analyzed and interpreted the data. Festus Fameso: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Funding statement

This work was supported by Technology Innovation Agency (TIA) South Africa, Gibeila Transport Consortium (GRTC), National Research Foundation (NRF grant 123575) and the Tshwane University of Technology (TUT).

Data availability statement

Data included in article supplementary material/referenced in article.

Declaration of interests statement

The authors declare the following conflict of interests: Author name; [details of issue]. The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.helyon.2022.e09405.

References

AmericanMetalCompany, 2021. A36Steel Technical Datasheet. Available at: https://www.metalshims.com/a-36-steel-technical-datasheet.aspx. (Accessed 8 June 2021).
AzoMaterials, 2012. ASTM A36 Mild/Low Carbon Steel. Available at: https://www.azom.com/article.aspx. (Accessed 8 August 2021).
Beiderbeck, D., Deradjat, D., Minshall, T., 2018. The Impact of Additive Manufacturing Technologies on Industrial Spare Parts Strategies. Centre for Technology Management working paper series, University of Cambridge, UK, pp. 1–59.
Boulbes, R.J., 2010. Troubleshooting Finite-Element Modeling with Abaqus. With Application in Structural Engineering Analysis. Springer Nature, Cham.
Ceruti, A., Marzocca, P., Liverani, A., Bil, C., 2019. Maintenance in aeronautics in an online at https://doi.org/10.1016/j.heliyon.2022.e09405.
Cunningham, C.R., Flynn, J.M., Shokrani, A., Dhokia, V., Newman, S.T., 2018. Invited review article: strategies and processes for high quality wire arc additive manufacturing. Addit. Manuf. 22, 672–686.
Daniyan, I.A., Mpoku, K., Daniyan, O.L., Fameso, F., Gyosela, M., 2020a. Computer aided simulation and performance evaluation of additive manufacturing technology for component parts manufacturing. Int. J. Adv. Manuf. Technol. 107, 4517–4530.
Daniyan, I., Mpoku, K., Fameso, F., Adeodu, A., 2020b. Numerical simulation and experimental validation of the welding operation of the railcar bogie frame to prevent distortion. Int. J. Adv. Manuf. Technol. 106 (11), 5213–5224.
Oyesola, M.O., Mpofu, K., Mathe, N.R., Daniyan, I.A., 2020. Hybrid–additive manufacturing cost model: a sustainable through-life engineering support model for maintenance repair overhaul in the aerospace. Procedia Manuf. 49, 199–205.

Oyesola, M.O., Mpofu, K., Mathe, N., Fatoba, S., Hoosain, S., Daniyan, I.A., 2021. Optimization of selective laser melting process parameters for surface quality performance of the fabricated Ti6Al4V. Int. J. Adv. Manuf. Technol. 114, 1585–1599.

Production Engineering, 2022. Advantages of Wire AM vs Powder AM. Comparing Sciaxy’s Wirefeed 3D Printing Process. Available at: https://www.productionengineering.com/additive-manufacturing/wire-vs-powder.html. (Accessed 25 February 2022).

RUN2Rail, 2021. Run2rail Consortium. Available at: http://www.run2rail.eu/. (Accessed 20 April 2020).

Savolainen, Jyrki, Collan, Mikael, 2020. Industrial Additive Manufacturing Business Models—What Do We Know from the Literature? Technical, Economic and Societal Effects of Manufacturing 4.0Automation, Adaption and Manufacturing in Finland and Beyond. Springer.

Schmidt, M., Merklein, M., Bourell, D., Dimitrov, D., Hausotte, T., Wegener, K., Overmeyer, L., Vollertsen, F., Levy, G.N., 2017. Laser based additive manufacturing in industry and academia. CIRP Annal. 66 (2), 561–583.

Singh, D., 2018. Comparison of Carbon Steel and Composite Side wall of Light Rail Vehicle by Finite Element Analysis. Doctoral dissertation. The University of Texas, Austin, Texas, USA.

Songmene, V., Khettabi, R., Zaghbani, I., Koaam, J., Djebara, A., 2011. Machining and machinability of aluminum alloys. Alum. Alloys Theory Appl. 377–400.

StationOne, 2021. New on StationOne! 3D Printing Service from Alstom. Available at: https://www.station-one.com/en/printing. (Accessed 20 April 2020).

U. S. Titanium Industry, 2017. Titanium Alloys - Ti6Al4V Grade 5. Available at: https://www.azom.com/articles.aspx. (Accessed 5 March 2021).

Vani, A., Jayachandraiah, B., 2015. Crashworthiness of a railway vehicle to reduce overriding effect by using Abaqus Software. Int. J. Eng. Sci. Invent. 4 (7), 14–22.

Veiga, F., Gil Del Val, A., Suárez, A., Alonso, U., 2020. Analysis of the machining process of titanium Ti6Al4V parts manufactured by wire arc additive manufacturing (WAAM). Materials 13 (3), 766.

Westerweel, B., Basten, R., den Boer, J., van Houtum, G.J., 2021. Printing spare parts at remote locations: fulfilling the promise of additive manufacturing. Prod. Oper. Manag. 30 (6), 1615–1632.

Williams, S.W., Martina, F., Addison, A.C., Ding, J.I., Pardal, G., Colegrove, P., 2016. Wire+ arc additive manufacturing. Mater. Sci. Technol. 32 (7), 641.

Xia, C., Pan, Z., Polden, J., Li, H., Xu, Y., Chen, S., Zhang, Y., 2020. A review on wire arc additive manufacturing: monitoring, control and a framework of automated system. J. Manuf. Syst. 57, 31–45.

Zhang, Z., 2015. Finite Element Analysis of Railway Track under Vehicle Dynamic Impact and Longitudinal Loads.

Zhi, P., Li, Y., Chen, B., Shi, S., 2020. Bounds-based structure reliability analysis of bogie frame under variable load cases. Eng. Fail. Anal. 114, 104541. https://www.gabrian.com/7075-aluminum-properties/, 2020. (Accessed 3 February 2022).

https://www.additivemanufacturing.media/articles/why-does-my-3d-printed-part-cost-so-much, 2018. (Accessed 26 February 2022).