Fatigue Lifetime of 3D Printed Landing Gear

Anusha Begur

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3D printed landing gear has become a novel technology due to issues with the longevity of traditionally manufactured landing gear. Currently, aerospace company Safran is developing landing gear printed from a titanium alloy to potentially increase the part's fatigue resistance. This study determines the projected fatigue lifetime of this landing gear and how it compares to the lifetime of a steel alloy. The discovered fatigue lifetime of the titanium alloy Ti6-Al-4V was 2.8×10^{15} cycles, which is an iterated value from lifetimes calculated at several stress amplitudes using an equation relating stress and cycles. According to this calculation, landing gear printed from Ti6 would long outlast the lifetime of the aircraft carrying it. However, the lifetime of 17-4 PH steel was discovered to be much longer than that of the titanium alloy, prompting further investigation into various other material attributes of both metals. The material property data used was found in manufacturers' datasheets. Significantly, the strength-to-weight ratio of the Ti6 was found to be nearly twice that of the steel at 264.11 $\mathrm{MPa}\times\mathrm{cm}^3/\mathrm{g}$. This, along with other material factors, justified Safran's original choice of the titanium alloy to develop their 3D printed landing gear. Further research may be conducted on the efficiency of this part in order to understand the practicality of larger applications of this technology in commercial aircraft.

Introduction

Landing gear failure accounts for a large portion of all accidents and malfunctions in aviation. According to Wang and Long, they made up 9% of failures on the Boeing 737[1]. NASA also found that almost 30% of accidents due to system/component failure/malfunction involved landing gear failure specifically[2]. Taxi, takeoff, and landing are the most critical parts of a flight, and all three ultimately come down to the landing gear, making it a crucial factor in aircraft safety[3]. Due to the extreme stress put on these parts, they are prone to wear and cracks. In an effort to help deal with this issue, Safran, an aerospace manufacturing company, has developed nose gear casing using titanium additive manufacturing. Using the titanium alloy Ti6-Al-4V under Selective Laser Melting (SLM) additive manufacturing (AM) technology, they've produced landing gear suitable for regional or business jets. While 3D printing may have its benefits in terms of the potential reduction of lead time and complexity as well as an increase in durability, using metal AM also invites the major concern of failure due to fatigue, which is what this study aims to understand. Additively manufactured parts can have microscopic discrepancies that can become crack initiation sites when put under cyclic stresses. SLM technology in particular uses metal powders that are then melted together with lasers to form parts. One of the main drawbacks with this is that issues with uneven melting can lead to cracks, which can be potentially fatal during a landing. Therefore, it is crucial to determine the best materials to maximize fatigue lifetimes and efficiency for landing gear. It is not currently clear what the application of this technology would look like in terms of fatigue resistance or if the titanium alloy is truly the best material for this landing gear. Accordingly, this study aims both to identify whether additively manufactured landing gear is really a safe option for aircraft as well as to determine the best metal to use for the 3D printing of this component. It is important to note that this study does not heavily weigh cost efficiency when determining the superior metal to use. Fatigue lifetimes of the landing gear are also compared to those of a regional jet, not a commercial one, as that would be the application of the specific landing gear analyzed in this study. This narrows the scope of the findings. Yield strength data was used to obtain fatigue lifetimes which were then compared to both the lifetime of a regional plane and to an alloy of steel. Material properties of both the titanium alloy and the steel alloy were also compared in order to determine the best metal with which to 3D print landing gear.

Results

Analyzing the Fatigue Curve for the Titanium Alloy

Engineers often design parts such as landing gear to undergo stress only until about 2/3 of their yield strength. This precautionary measure provides a margin to prevent a material hitting maximum yield strength and undergoing plastic deformation. Furthermore, an important quality in landing gear is stiffness. However, stiffer materials often break soon after hitting maximum yield strength, making the cautionary margin increasingly vital for safety. The yield strength for Titanium 6 is 1030 ± 70 megapascals, 2/3 of which is 687 ± 46.7 MPa[4]. Using the SN curve for this alloy, described by the following equation [Eq 1],

$$\sigma(N) = 1700(N-4900)^{-0.2} + 440 \tag{1}$$

in which σ is equal to stress amplitude and N is equal to the number of cycles, this material will be able to sustain around 20000 cycles at this stress amplitude[5]. For a landing that would undergo less stress, say 1/2 yield strength, the Ti6-Al-4V would be able to sustain about 6000000 cycles.

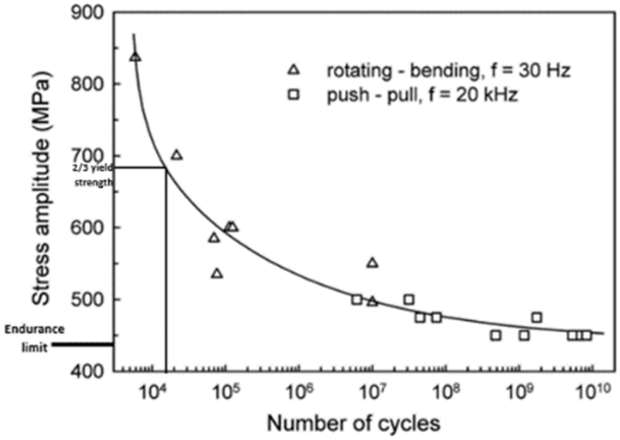

Fig. 1 SN (stress/cycle) curve for Ti6[5]

A more accurate value for the actual number of cycles a regional plane with Ti6 landing gear would be able to sustain can be found using 10% of the cycles at 2/3 yield strength, 70% at 1/2, and 20% at the lowest yield strength of 441 MPa. This comes up with an estimate of 2.8 $\times 10^{15}$ cycles before failure if this titanium landing gear were to actually be used on a plane. The value of 441 MPa was used because it is the lowest stress amplitude Ti6 can undergo before it hits its endurance limit. This endurance limit is essentially the stress value under which the material will no longer experience crack initiation and therefore will not fail due to fatigue[6].

Stress Amplitude (MPa)	Allowable/Actual Cycles	Fatigue Usage
1030	2×10^4	100%
687	6×10^6	67%
515	2.8×10^{15}	50%

Table 1 Fatigue Lifetimes for Ti6

Lifetime of the Part

A standard regional jet of the kind this landing gear would most likely belong to runs about 20000 cycles in its lifetime[7]. According to this data, even at a continuous 2/3 yield strength, Ti6 landing gear would be able to last the entire lifetime of the plane, and longer, without failing. The iterated cycle estimate of 2.8$\times 10^{15}$ cycles for the landing gear would therefore greatly surpass the lifetime of the plane itself and would be at minimal risk for failure due to fatigue throughout the lifetime of the plane. If this type of technology were to be implemented on a larger scale, it could significantly cut back on the number of aviation accidents that occur, as it would clearly cut down on failure due to fatigue in landing gear. This would greatly improve the safety of the aerospace industry overall.

Potential Causes of Crack Initiation

Depending on the cooling process used during SLM, as well as on the presence of subgrains prior to the SLM process, equiaxed grains can be formed. The presence of these grain structures creates grain boundaries which can be symptoms of recrystallization. Recrystallization is known to cause non-uniform grain formations, which often become crack initiation sites.

Inconsistent grain structures also decrease the toughness of materials and make them more susceptible to failure due to fatigue[8]. Additionally, Ostwald ripening, an abnormal grain growth, was observed for Ti6 under SLM, which can also lead to deformities in the part as grains form in variable sizes[9]. The formation of these deformities leads to cracks in the material.

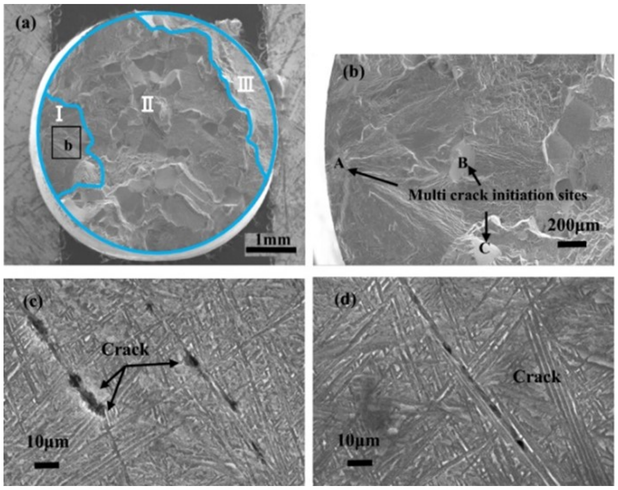

Fig. 2 Development of cracks at grain boundaries[10]

These cracks grow as the metal sees more wear, eventually causing the material to fail. As the part is exposed to increased stress amplitudes, it fails faster, as cracks begin to develop and grow more quickly. Although this creates opportunities for failure due to fatigue in 3D printed parts, the timeline and progression of that failure, proven through fatigue lifetime calculations, demonstrates that this is not a concern when used in regional aviation-related applications.

Analyzing the Fatigue Lifetime of 17-4 PH Steel

The yield strength for 17-4 PH steel is 1000 MPa, which is about 30 MPa less than the Ti6 alloy[11]. 2/3 of this yield strength is 667 MPa. The number of cycles to failure at this stress amplitude is roughly 13.8 million, as can be seen in Figure 3. For a stress amplitude of lower than about 621 MPa, the steel alloy hits its endurance limit. Half of the yield strength for this metal is 500 MPa, which is lower than the endurance limit. It can therefore be determined that the steel can endure a greater number of cycles at a greater stress than the titanium can, as it hits its endurance limit at a higher stress amplitude.

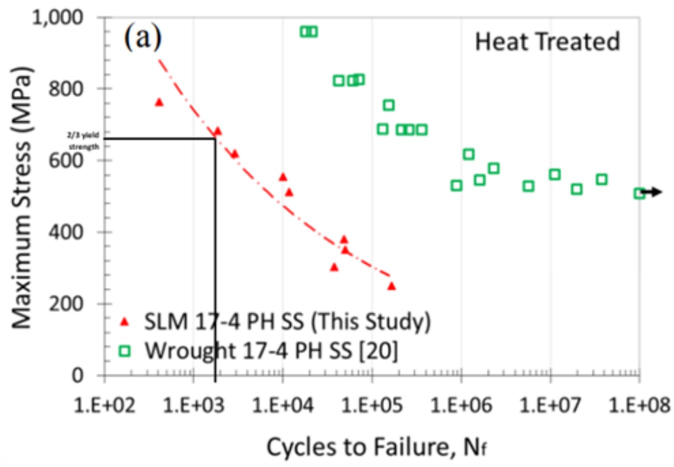

Fig. 3 SN (stress/cycle) curve for 17-4 PH Steel[12]

Comparing the Material Properties of Titanium and Steel

Table 2 Material Properties

Property	Ti-Al-4V Titanium	17-4 PH Steel
Ultimate Tensile Strength (MPa)	1170[13]	1103[14]
Density (g/cm^3)	4.43[15]	7.8[16]
Specific Strength ($\text{MPa}\times\text{cm}^3/\text{g}$)	264.11	141.41

While steel may be more fatigue resistant than titanium, other material properties are important to consider as well. For example, knowing the strength-to-weight ratio, or specific strength, of a material is crucial to understanding how practical it will be in application. As seen in Table II, the titanium alloy used to make Safran's landing gear has almost double the specific strength of stainless steel. This is important for the efficiency of the actual plane, as a material with a higher specific strength will be much stronger at a lower weight. In comparing solely the densities of the two materials, it is apparent that steel is also a much denser material than titanium, meaning that the same amount of material will be heavier. This can affect the performance of the plane, meaning that titanium is a better material in terms of lightweighting. Lightweighting is an important factor to consider in aircraft manufacturing and design due to its connection to energy consumption and material cost[16].

Discussion

Through analyzing all these factors, it can be determined that metal AM landing gear such as Safran's is likely a viable option in terms of longevity and resistance to fatigue and that Ti6-Al-4V is the best material to produce it. At average stress amplitudes, it can outlast the lifetime of a regional plane, making it more effective than traditional landing gear that may need to be replaced more often. While the 17-4 PH steel had a much longer projected lifetime than the titanium, they were both found to long outlast the lifetime of a plane, making this a largely irrelevant factor in deciding between the two materials. Moving the weight of consideration to other areas, it was found that the steel was limited where the titanium was not. For example, from analyzing the material properties of the titanium alloy Ti6-Al-4V used to manufacture Safran's landing gear, it is clear that it is a metal more conducive to high-performing aircraft than steel due to its high specific strength of 264.11 $\text{MPa}\times\text{cm}^3/\text{g}$ and low density, both of which are significant factors in lightweighting and therefore greatly impact the efficiency of the plane. As landing gear is critical to safe air travel, it is important to consider the lifetime and properties of each metal. These findings therefore address practical concerns about the security of additively manufactured landing gear. Ultimately, the titanium alloy that Safran originally used to manufacture their landing gear was determined to be more favorable than 17-4 PH steel. The implementation of metal AM landing gear across the aviation industry could be crucial in making air travel safer, as 3D printed landing gear has proven to have a high enough fatigue resistance to mitigate the possibility of accidents due to fatigue failure.

Of course, these calculations are merely estimates, and therefore may be oversimplified versions of real lifetimes. However, given the vast margin between the projected lifetime of the landing gear and the standard lifetime of a regional plane, minor discrepancies should not have a great impact on the conclusions drawn based on the calculated lifetimes. Research into the safety of this landing gear was also limited to the lens of failure due to fatigue. Further research into the other safety and efficiency concerns with 3D printed landing gear, such as control and manufacturing, may be necessary to determine the practicality of implementing this technology on a larger scale. Extrapolating the findings of this study to larger aircraft, which typically have a different fatigue lifetime than regional aircraft, will require a more careful study of cyclical stress on commercial aircraft and the number of flights such planes typically undergo. Getting 3D printed parts approved for mass production could also prove to be an issue, as there is still a relative lack of legal literature regarding this new technology. While certain AM parts have gotten FAA certification within the past few years, any new parts must still undergo a rigorous testing and approval process, making the legal feasibility of the implementation of this technology on a wider scale unclear[17]. Because landing gear is such a critical factor in accident mitigation, regulatory compliance is strictly evaluated in order to maintain safety in air travel. Still, the findings in this paper represent a critical step in understanding the safety of using additively manufactured parts for commercial purposes.

Conclusion

The titanium alloy Ti6-Al-4V analyzed in this study could prove immensely useful to the future of 3D printing in aviation. The minute discrepancies between materials can mean a world of difference in both the performance and the safety of an airplane. In determining the superior material through this study, greater distinctions can be made on a larger scale about optimal materials for metal AM. Because of the impact of materials on aircraft design and construction, these distinctions will help pave the way for a smoother transition to 3D printing in the aerospace industry.

Methods

This quantitative study analyzes material data to form conclusions about the effectiveness and safety of 3D printed landing gear. The data used was taken from datasheets created by respected metal producers in order to obtain the most accurate values. While these values may not entirely represent real-world conditions, they are ideal properties of the materials discussed, and therefore have produced ideal lifetime and fatigue calculations. These values are not necessarily identical to real-world conditions but are instead merely meant to be representative of these conditions and their potential implications in real-world scenarios. The variable being analyzed was cycle numbers, or lifetimes, of each metal. These were calculated by running different increments of yield strengths through Eq 1 and analyzing SN curves and then iterating those values into a single lifetime value that is representative of real-world circumstances and cautionary margins. Material properties of the two metals were also analyzed by a comparison of specific strength, which was calculated using the ultimate tensile strength and the density of each respective metal. Both lifetime and specific strength values were then compared and weighed according to importance to determine the superior alloy for 3D printed landing gear. Though the 17-4 PH steel alloy was found to have a longer fatigue lifetime than the titanium, both fatigue resistances were high enough to give more weight to other considerations in the materials. Specific strength in particular was used as a determining factor in finding the superior alloy, as it is a property indicative of many material traits that are critical in aviation safety.

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