A Steely-Eyed Man: The History of Stainless Steel in Rocketry

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The early 2000s were a series of rather boring years for space travel. NASA plans listed just a few shuttle launches here and there to service telescopes and send crew to the International Space Station. However, on a bright spring day in 2002, a young entrepreneur hailing from South Africa aimed to change this. It was none other than a rising Elon Musk, freshly flushed with funds from selling his business PayPal to Ebay for hundreds of millions. Backed by his newfound wealth, he set his eyes on space exploration and tourism, founding SpaceX in May of 2002 [1].

As with any startup, particularly ones dealing with rocketry, the initial years were turbulent. Although Musk initially planned to buy retrofitted ballistic missiles from the Soviets to launch his first passengers into low earth orbit, the plan swifty deteriorated into a bureaucratic nightmare [1]. Yet, Musk would go on to realize that developing a launch system in-house would be magnitudes easier, while also maintaining full control over the production process. This concept of vertical integration would be a mantra that SpaceX would devoutly follow even today. However, with its recent goals shifting towards more ambitious targets like Mars, SpaceX will need a new rocket system to fulfill these needs. Its secret weapon: stainless steel.

The Rise and Fall of Steel in the '50s-'60s

Although SpaceX is pioneering a new era for stainless steel rocketry today, the usage of this material also has a rich and extensive history in spaceflight. Beginning in the 1950s, an infantile NASA began the construction of America's longest lasting family of rockets, the Atlas. Initially functioning as the nation's first intercontinental ballistic missile, the SM-65 Atlas was refurbished to transport satellites and humans into low Earth orbit. While functionally identical to their counterparts, Atlas rockets were compositionally unique compared to vehicles like the popular Soviet R-7. They were constructed using extremely thin stainless steel rather than more advanced aluminum-based alloys [2]. American engineers reasoned that while aluminum alloys would be more suitable for welding purposes due to its highly ductile nature, stainless steel had a much greater hardness — the ability to resist deformations. This property was of the utmost importance as NASA aimed to greatly minimize the weight of the Atlas, going as far as to make the shell of the rocket too thin to be structurally stable when unpressurized. However, when filled with propellant, the outwards pressure offers a restoring force that counteracts deformations, providing the required rigidity for spaceflight. While this method of pressurized support was effective, it was a flawed process which led to these boosters being named “Balloon Tanks.” This would culminate in an event in 1963 where an unexpected depressurization in the rocket would cause a vehicle implosion on the launch pad, generating an investigation of this issue [3]. Eventually, NASA would revise the design of the Atlas rocket and begin using various reinforcements, later retiring the use of steel Balloon Tanks as a whole for more reliable systems. As materials science and aerospace manufacturing evolved in tandem, steel rocket bodies were slowly phased out in favor of new advanced alloys and composites. Thus, a period of stainless steel dormancy in rocketry would ensue for several decades.

Figure 1: SM-65 Atlas–Agena depressurization failure [3]

The Birth of Starship

Well rested, stainless steel has awoken from its slumber and is now the driving force directing the future of rocket development. The company behind this movement is SpaceX, which has not only risen as the only private agency to launch a vehicle to orbit, but is the only organization ever to have produced rapidly reusable rockets. Its fleet consists of Falcon 1, the first commercial rocket to have ever reached orbit, Falcon 9, SpaceX's workhorse and most reused vehicle, Falcon Heavy, the world's most powerful modern rocket, and now Starship, potentially the most powerful spacecraft ever constructed [4]. While the Falcon lineup falls under the aluminum alloy family of rockets, Starship proposes to revive the use of stainless steel, which SpaceX believes is capable of outperforming its alternatives at a fraction of the cost. Let's discuss these considerations.

Figure 2: Fully stacked Starship rendering in flight [4]

<u>Strength at desired temperatures:</u> Starship, much like the Falcon family, utilizes cryogenically chilled liquid oxygen as a propellant oxidizer. This fuel reaches temperatures of -207°C during ascent and maintains this supercooled state throughout flight. Considering this, austenitic stainless steel 304L was a prime candidate for Starship's construction as unlike many other metals, this form of stainless steel does not become brittle at cryogenic temperatures, rather it actually strengthens. This is because of its high

chromium-nickel content and face-centered-cubic structure, which allows its dislocations to maintain adequate levels of slippage at these temperatures, thereby increasing ductility without compromising its yield strength [5] [6]. Moreover, stainless steel 304L, while possessing a lesser yield strength than materials like carbon-fiber composites at these temperatures, is more than sufficient at handling the maximum stresses of launch [7].

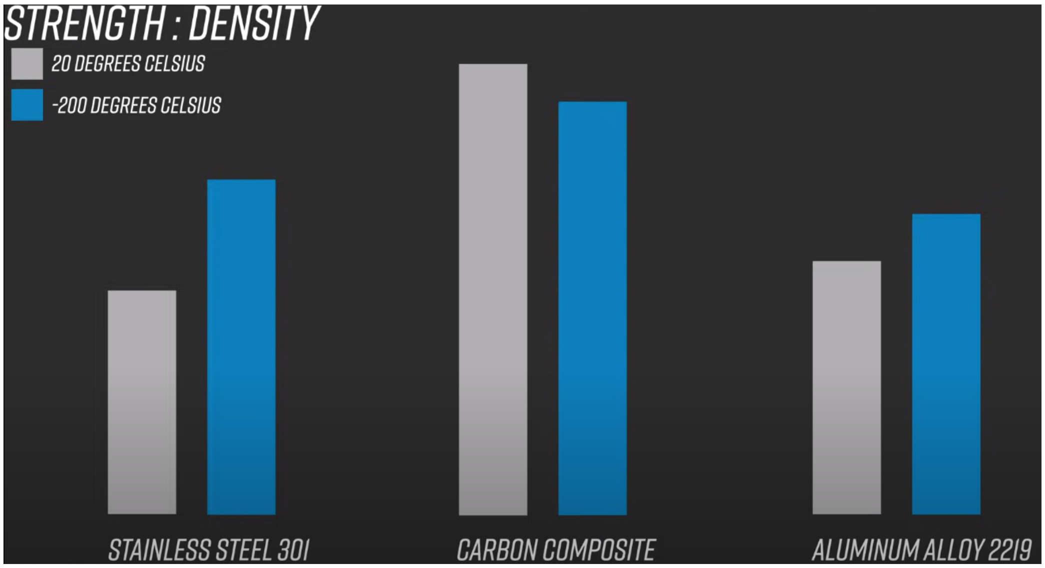

Figure 3: Yield Strength / Density ratio comparison between 3 materials of interest [7]

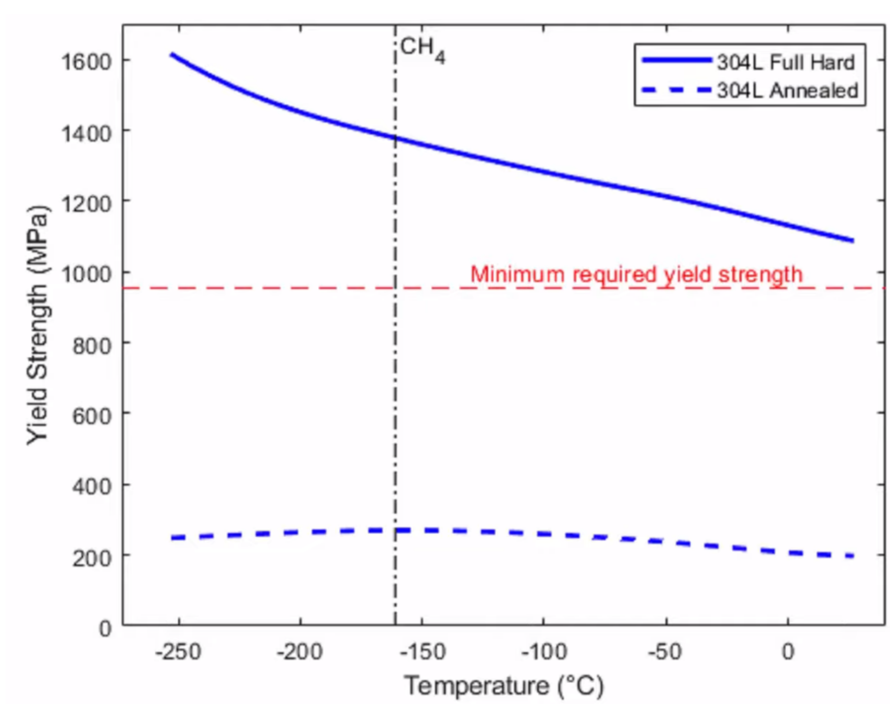

Figure 4: σ_y vs temperature plot demonstrating 304L meeting strength requirements [8]

Cold working: While the process has existed for several decades, cold working/strain hardening stainless steel has been an elusive task until recently. This is because properly introducing dislocations into stainless steel without compromising its structure is far more difficult than with other metals like copper or brass. However, in 2018, Outokumpu, a British industrial engineering company, had successfully developed an efficient means of cold forming austenitic stainless steels. While not disclosing their method, one can assume the process generates an increase in dislocation density which increases the yield strength of stainless steel rolls. SpaceX is currently contracting Outokumpu to form stainless steel rolls for their Starship prototypes [8].

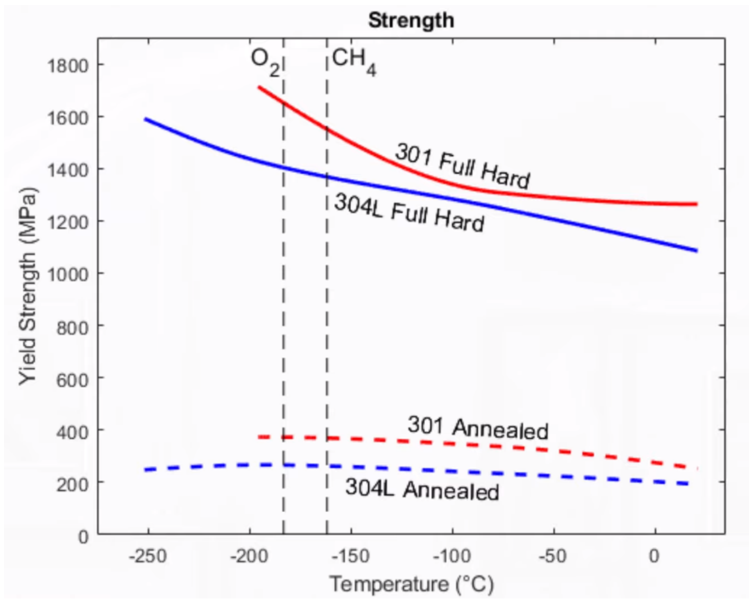

Figure 5: 301 and 304L yield strength following cold working vs annealing [8].

Figure 6: Outokumpu manufactured full-hard stainless steel 304L [9]

Ease of use and price: When comparing the costs of manufacturing Starship, the decisions regarding material selection become quite straightforward. The material that SpaceX had initially intended to use for construction was carbon-fiber composites, satisfying all yield strength requirements while being easily shapeable before curing. However, it quickly became clear that in order to fulfill the SpaceX standard for rapid iterative testing, the lengthy and prohibitively expensive nature of purchasing and processing the material for use. Plainly put, carbon composites would cost approximately $180/kg, while stainless steel 304L costs at most $3/kg [7]. It is simply not rocket science to understand why selecting a product that not only offers nearly all the same benefits, and with a 60 fold decrease in price, is a vastly superial financial decision. Furthermore, viewing this from an engineer's lens, stainless steel is a far more historically understood material with lengthy documentation and endless man hours of usage experience.

The Materials Science Paradigm

As of now, SpaceX has conducted 9 tests of the starship vehicle, with the most recent one demonstrating full flight, flip, and landing capabilities. At this point, SpaceX has exceeded all expectations. It would be logical to fall into skepticism when considering that a company days away from bankruptcy would be able to revive itself and continuously create the most revolutionary rockets in all of history. In doing so, SpaceX has silenced its doubters, becoming a leader in an industry dominated by the world's most powerful government agencies. The methodology that has driven all of these accomplishments is one of "failing fast," one that reflects the materials science paradigm. SpaceX's belief in rapid iterative testing, testing different materials and mechanisms without bias or attachment to prototypes, is what allows the company to make so much progress in so little time [4]. With an engineer's mindset, they consider material properties first (toughness, ductility, corrosion resistance) and then conduct performance testing to narrow the materials of interest. Only after these steps are completed do they seek to understand the structure and processing (machinability, weldability, price), allowing them to make a speedy yet informed material choice. In the end, the choice of selecting stainless steel truly reflected this paradigm.

Figure 7: Starship Serial-Number 15 post successful flight and landing [9]

Citations

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