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MARAGING STEEL AS A MATERIAL CHOICE FOR ROCKET MOTOR CASINGS

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1. Abstract

Delivering critical spatial infrastructure like satellites efficiently and without accidents requires reliable and cost-effective design of rockets including its significant subsystem called rocket motor casings. Rocket motor casings require high strength materials, but often times high strength also means low fracture toughness leading to brittle fractures of material well under the material's strength. In this article, we present maraging steel application as a suitable material, and discuss its mechanical properties that make it ideal for the design of rocket motor casings.

Keywords: *Maraging Steel, Fracture Toughness, Rocket Motor Casings, Brittle failure, LEFM*

2. INTRODUCTION

The importance of satellites goes well beyond the common public knowledge of powering TVs and broadband connections. They are used to protect and sometimes save humans, touching our everyday lives in numerous and profound ways. They are used in meteorology, farming, construction, mining, supply chain management, security and more[1]. They are also used in addressing 21st century issues like climate change. While their importance cannot be stressed enough, it is also as important that the rocket motors that are used to deliver these satellites into their appropriate orbits are adequately designed so that they can be relied upon consistently. In this article, we will discuss the material selection aspect of the design of rocket motor casings along with a discussion on suitability of maraging steel for this application.

3. Considerations of Material selection

The rocket motor casing material should be able to withstand the thermal, structural and creep loads and must possess high specific strength[2]. General considerations for rocket motor casing material selection include modes of failure, fabrication method and the operating environment. In this section we will discuss each of these considerations in further detail.

3.1. Modes of Failure

3.1.1. Brittle Failure:

Under load, a few of the high strength material types may fail under the design stress level due to presence of defects that can increase the stress concentration around them. This leads to slow progressive or quick propagation of that defect and eventual failure[3]. To address this, an ideal design approach for designing fracture prone materials can be to utilize linear elastic fracture mechanics (LEFM)[4]. For appropriate application of LEFM design approach, it is required that the designer is equipped with knowledge related to temperature effect on fracture toughness, geometry and location of the defects, directionality and magnitude of the stress applied, presence of corrosive environments and magnitude of residual stresses.

3.1.2. Ductile Failure:

Design for materials that are determined to undergo ductile failure is relatively straightforward as it is based on the actual material strength[5]. The material strength can be determined by material testing in uniaxial/biaxial mode or by performing either a full scale or sub scale burst test.

3.2. Fabrication Method

The choice of fabrication method for a chosen material can induce properties that may be beneficial or undesirrable based on the intended use. Therefore, adequate consideration must be given while chosing the fabrication method to maximize on the potential benefits of the material in reaction to the process and to minimize the adverse effects. For instance, work hardening associated with the forming process can increase the material strength but degrades the material's fracture toughness. In another case, welding processes like gas tungsten arc welding (GTAW), although takes longer welding time, produces highest quality weld with better fracture toughness. Periticularly for rocket motor casings fabrication, high strength steels are used with detailed consideration for the fabrication methods to maximize the material's fracture toughness. Hence, fabrication considerations are significantly important during the material selection process of the rocket motor casings.

3.3. Operating Environment

The rocket motor casings may encounter different operational environments during their life cycle from production of structural casings through to its service use. A few instances of exposure include the use of dye-penetrant fluid with high chlorides and sulfide content that could induce cracking[6]. Other examples include the use of hydro-static fluid on certain steels could induce stress corrosion cracking, conducting welding and heat treatment operations in uncontrolled atmospheric conditions can lead to entrapped gases and carburization and ultimately result in stress corrosion cracking. Therefore, consideration of operating environment is one of the critical factors affecting the choice of material for rocket motor casings.

4. Maraging Steel for Rocket Motor Casings

In this section we will explore the benefits of using maraging steel for rocket motor casings, and discuss their specific mechanical properties that make them ideal for this application. For comparison purposes we will also detail the mechanical properties of other competing alloys to make the case for maraging steels for rocket motor casings.

4.1. Alternative materials for Rocket Motor cases:

4.1.1. Steels

Conventional quench and temper steels have been traditionally used due to extensive understanding of their mechanical properties and their reaction to the known fabrication processes. The 9-Ni-4-Co quench and temper steels, available in 0.250 and 0.450 carbon grades possess tensile strengths of up to 1520 MPa and 2070 MPa respectively. Traditional steels, however, have low fracture toughness and stress corrosion resistance which are highly desired properties for designing durable rocket motor casings[7].

4.1.2. Titanium

Titanium alloys are sometimes considered for rocket motor casings primarily for their specific strength advantages over conventional steels and its direct impact on increased vehicle performance[8]. However, the buckling resistance of titanium alloys is considered to be subpar in relation with their high strength steel counterparts which counts against their choice for certain applications of rocket motor casing designs.

4.2. Maraging Steels for Rocket Motor casings

Maraging steels are ultra-high strength steels with tensile strengths up to 2070 MPa and are a preferred choice of steel for rocket motor casings primarily due to its high specific strength- which is strength per unit weight of the material. Other characteristics of maraging steel include its better forging and forming characteristics along with low temperature heat treatment options[9]. Maraging steels differ from conventional steels in that they harden by metallurgical reaction that doesn’t involve carbon. These steels also contain a high percentage of nickel, cobalt, and molybdenum with a very low percentage of carbon which minimizes the formation of titanium carbide (TiC) which adversely affects the strength, ductility, and toughness. Due to its unique inter metallic precipitation process to achieve hardening, maraging steels can be fabricated in soft condition with minimum distortion during the age hardening process.
A different grade-Grade 250- of maraging steel alloy with low carbon, iron-nickel, and with a small amount of titanium is most commonly used in the aerospace industry due to its abundance, cost, and high strength.

Table 1 Maraging Steel Grades and their Chemical compositions

Element	*Grade 200*	*Grade 250*	*Grade 300*	*Grade 350*
Nickel	17.0-19.0	17.0-19.0	18.0-19.0	18.0-19.0
Cobalt	8.0-9.0	7.0-8.5	8.5-9.5	11.5-12.5
Molybdenum	3.0-3.5	4.6-5.2	4.6-5.2	4.6-5.2
Titanium	0.15-0.25	0.30-0.50	0.50-0.80	1.3-1.6
Aluminum	0.05-0.15	0.05-0.15	0.05-0.15	0.05-0.15
Carbon	0.03	0.03	0.03	0.03
Manganese	0.10	0.10	0.10	0.10
Silicon	0.10	0.10	0.10	0.10
Phosphorous	0.01	0.01	0.01	0.01
Sulphur	0.01	0.01	0.01	0.01

All values in percentage

The austenite to martensite transformation temperature (Ms) for maraging steel is 200-300°C and is fully martensite at room temperature. The age hardening for maraging steels is achieved by heat treating at 455-510°C for 3-9 hours[10]. This low temperature heat treatment allows for easy processing of maraging steels making them ideal choice for rocket motor casings.

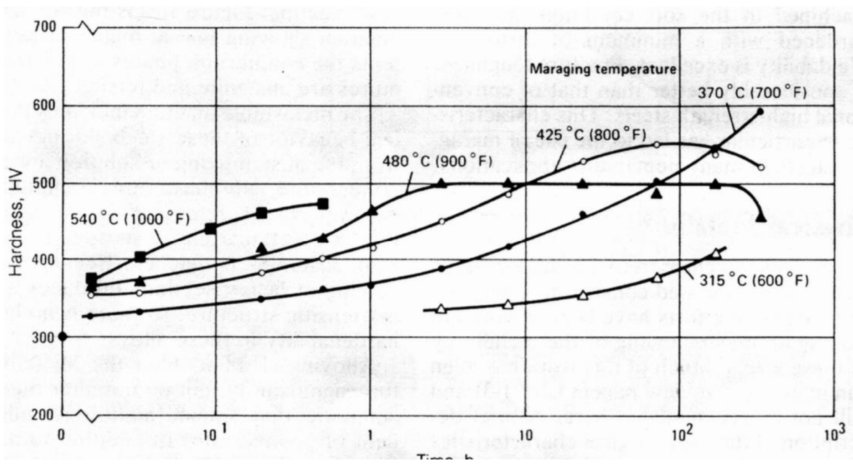

Figure 1 Temperature vs Time vs Hardness

Maraging steels are typically solution annealed and then heat treated for age hardening. They are required to be heat treated in dry hydrogen or dissociated ammonia to minimize the surface damage for use in rocket motor casings. The cooling rate after annealing process is observed to have minimal effect on microstructure or material properties. However, it is required that they are cooled down to room temperature before the age hardening process to avoid presence of untransformed austinite which could cause the steel to be much softer than desired.

4.2.1. Maraging Steel Mechanical Properties:

To compare the mechanical properties of maraging steel with those of competing steels, Table 2 lists the mechanical properties such as yield strength, modulus of elasticity and density along with the choice of heat treatment method.

Table 2 Comparing Mechanical Properties of Maraging Steels with Other Alloys

Material	*Design Yield Strength, MPa*	*Modulus of Elasticity, GPa*	*Density Gm/cc*	*Heat Treatment*
Low Alloy Steel				
4130	1035-1240	199.95	7.83	
4335V	1240-1380	199.95	7.83	Quench and Temper
D6aC	1240-1660	199.95	7.83	
15CDV6	1080-1280	199.95	7.83	
Maraging Steel				
Grade 200	1380	189.61	8.00	Solution Anneal and age
Grade 250	1660	189.61	8.00	
Grade 300	1930	189.61	8.00	
Titanium				Solution Anneal and age
Ti-6Al-4V	1035	110.32	4.62	

Maraging steel's most distinguishing feature from the conventional grades of steel is its superior fracture toughness. Table 3 lists the fracture touchness (K1c) values as a function of material's tensile strength. Figure 2 also illustrates the fracture toughness of different grades of maraging steels compared to other materials. It can be inferred from the data presented that the fracture toughness of maraging steel increases as its purity increases. In other words, greater the carbon and sulphur levels lower the fracture toughness. Therefore, to optimize the maraging steel's mechanical performance with respect to fracture toughness, the impurity levels should be maintained low[11].

Table 3 Fracture Toughness of Maraging steels as function of Tensile Strength

Grade	*Tensile Strength, MPa*	*Yield Strength, Mpa*	*Elongation in 50mm, %*	*Reduction in area, %*	*Fracture Toughness, $MPA\sqrt{m}$*
18Ni(200)	1500	1400	10	60	155-240
18Ni(250)	1800	1700	8	55	110
18Ni(300)	2050	2000	7	40	73
18Ni(350)	2450	2400	6	25	32-45

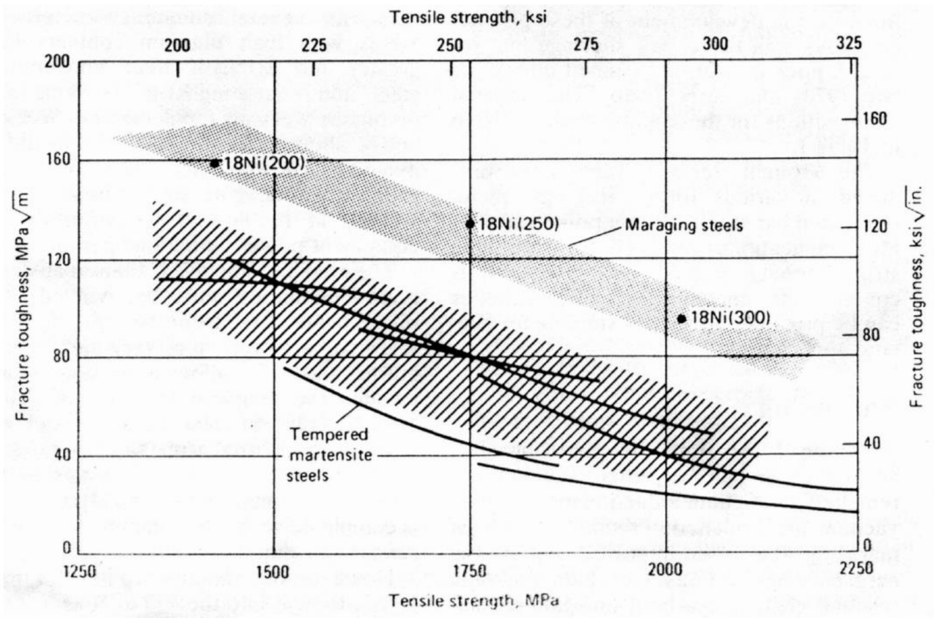

Figure 2 Maraging Steels Fracture Toughness comparison with other alloys

5. Conclusion

In conclusion, the data related to mechanical properties such as high yield strength, tensile strength, specific strength, fracture toughness and high dimensional stability with age hardening, makes maraging steel a preferred choice of material for the design of rocket motor casings. However, judicious fracture-based design approach, appropriate choice of fabrication process and quality control method for identification and remedy of material defects is also required to produce reliable, cost effective and efficient rocket motor casings that are used to deliver critical infrastructure related to satellites to the outer space.

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