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Modern High Alloy Steels in Aerospace Industry – Challenges and Resolutions

Hitesh Ashwin Narsia[1] and Surendra M. Vaidya[2]

[1]Deputy Manager – Welding and Fabrication, Godrej Aerospace, Mumbai, India
[2]Executive Vice President and Business Head, Godrej Aerospace, Mumbai, India
Email: [1]hiteshnarsia@gmail.com, [1]narsia@godrej.com; [2]smv@godrej.com

ORCID : Hitesh Ashwin Narsia : http://orcid.org/0000-0002-5640-04555.
ORCID : Surendra M. Vaidya : http://orcid.org/0000-0001-6652-6089

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Abstract

Modern High Alloy steels – The category of purposely developed advanced steels to meet the desired requirements in respected sectors. Due to their excellent properties which are compatible with exotic aerospace grade materials, these materials are widely adopted in aerospace sectors mainly in defence and space applications. These materials are the future of space programmes developing by LPSC-ISRO. As an industry, there are many day-to-day practical challenges related to welding and fabrication mainly with new materials. With considering the fact, more examples that are practical tried to cover in this paper with case studies related to welding and metallurgy.

Keywords: Godrej Aerospace, High Alloy Steels in Aerospace, Aerospace Welding Requirements, Maraging Steels, Precipitation Hardenable Stainless Steels, Case Studies in Aerospace Welding

1.0 Introduction

The materials used in aerospace components are miscellaneous and having exceptional qualities. The alloys which are used from decades are aluminium alloys, titanium, nickel base alloys, cobalt base alloys, austenitic stainless steels. After research and adequate experience on these materials, required details of these materials are available in AWS, ASME or EN standards. However, with the time and requirements, aerospace Materials are upgrading in Space, Defence and Aviation Sectors to meet the quality upgradation, cost, easy to operate, etc. To meet the requirements, required alloys are developed, designed and finalized for production. These materials are not designated in any AWS, ASME or EN standards, nor their relevant grade is available to know their metallurgy, welding and heat treatment properties. To understand these materials, there were lot of practical challenges and these challenges are overcoming gradually with experience. Some alloys include in this paper are maraging steel and precipitation hardenable SS, which are also known as secondary hardening steels and Ultimate product cost is very less as compare to conventional exotic aerospace materials with satisfactory operational requirements. These specialty alloys are upgradation of conventional stainless steels and high strength alloy steels. Conventional SS can provide good corrosion resistance but lack of desired mechanical properties and poor fabricability (High Ovality, Distortions). On the other side, high strength alloy steel can provide good mechanical properties with lack of corrosion resistance. Maraging and PH Steels considered a high strength steels with meeting of several key requirements. Welding of these materials need special care like minimum heat input, welding in proper fixturing condition, minimal weld rework and welding techniques. Complex aerospace components require complex heat treatments. Vacuum furnaces are ideal for hardening and strengthening aerospace components because parts cannot oxidize. This allow metallurgists to design the complicated treatment cycles necessary for complex aerospace components. In addition, the process controls required very precise, very specific treatment to fulfil the industry's strict specifications. This is crucial: In aerospace, there is no room for error.

2.0 Aerospace Industry Requirements

Aerospace industry comprises of aviation, space and defense expanses. All sectors referring different standards and specifications with respect to their operations and applications.

E.g., Aviation sectors follows AWS D17.1 – Specification for Fusion Welding of Aerospace Applications and customer (GE, Boeing, Honeywell) specific requirements. In Space, ISRO-LPSC VIKAS, CRYO, SEMI CRYO codes and standards are available for qualifying welders are procedures. In Defense sectors Brahmos, LRSAM, MRSAM QAP (Quality Assurance Plan) need to follow to qualify WPS, PQR and WPQ. However, AS9100 (International Quality Management Standard for the Aviation, Space and Defense Industry) and NADCAP (National Aerospace and Defence Contractors Accreditation Programme) standards are essential for aerospace industry. Special Processes Welding, Heat Treatment, Surface Treatment, Chemical Processing, Coatings, Non-Destructive Testings required perodical renewal which is carried out by highly qualified individuals, having experience in the aerospace industry conduct the actual process. Special qualification SCA (Source Certifying Authority) examination is essential to certified the product. Likewise, in welding, CWI-AWS Certified Welding inspectors will train, qualify, certify and maintain continuity of welders and welding operators. Before welding on actual hardwares having critical joint, mock up and simulation welding is a part of the process. NDT Requirements are also very stringent due to less factor of safety, so rework cost a lot in aerospace product, to maintain that FPY (First Pass Yield) and FTR (First Time Right) concepts are very much important.

3.0 High Alloy Steel in Aerospace

3.1 Frequently used and accustomed grades

3.1.1 Titanium Alloys

Titanium alloys are widely known for their very good strength to weight ratio and good corrosion and creep resistance in high temperatures as well. Ti-6Al-4V is widely used alloy in Boosters, Missiles, Fuel Pumps and Landing Gears. The weldability of titanium is most challenging and extra care is required in welding. There are lots of fabrication challenges like chances of crack formation in forming, challenges in set-up and rolling as well.

3.1.2 Nickel Alloys (heat Resistance Super Alloys)

After Austenitic SS, Nickel alloys are widely used in aerospace and space sectors in cryogenic engines, Jet engines, Exhaust systems, Turbo Pumps. The weldability is similar to ASS except special precautions to be taken to minimize heat input and crack formation. Nickel alloys having very good corrosion resistance and high strengths at Room and higher temperatures with addition of alloying elements due to its stabilized structure. Grades 625 and 718 are most commonly used Super alloys.

3.1.3 Cobalt Base Alloys (Stellite)

The cobalt-base super alloys or also widely known as Stellite alloys, designed for their excellent wear resistance. These alloys are widely used in VIKAS Engines. Special care to be taken during welding to prevent crack formation in HAZ area. These alloys having 900-1000 MPa UTS with 40-45%Elongation in as received condition. No Post weld heat treatment is required for these alloys.

3.1.4 Austenitic Stainless Steels

Most widely used material in cryogenic engines, gas generators, gas turbines. 316L and 321 grades are used in thickness ranges of 0.6mm to 10mm. challenges in fabrication and welding due to lesser thickness and larger diameters. The successful performance is obtained by freezing optimum welding parameters, proper tooling, fixturing, expansion and planishing processes. In these materials, in sheet metal parts solution annealing is carried out after forming and welding.

3.2 New generation grades developed with intent and purpose for required design and applications

3.2.1 Maraging Steels

- **MDN250, MDN300 Grades.**

Maraging steel is used in aircraft, defence applications, mainly rocket motor casings applications that require high strength-to-weight materials. Maraging steel contains low-carbon martensite and it is strong, tough, which contains hard precipitate particles formed by thermal ageing.

3.2.2 Precipitation Hardenable SS

- **06X15H6MB (15-5PH Steel)**
- **03X12H10MTP (12-10PH Steel)**

Very good mechanical properties can be obtained with good-moderate corrosion resistance with these alloys. UTS of 850-1700MPa and 0.2% PS of 500-1500MPa is achievable with selecting alloys and heat treatment processes. Generally, these grades of steels consist of martensitic structure with precipitates formation after heat treatment. Copper, molybdenum, aluminium and titanium either singly or in combination are forming precipitates in these grades of steels.

3.2.3 Martensitic SS

- **SS410**

Martensitic Stainless steels are iron-base alloys category having10.5% or more chromium with higher C% used in aircraft parts requiring high yield strength. Mainly used for structural aerospace components.

In this article, case studies covered mainly on these new generation high strength alloys developed with intense and will be widely used in space and defence applications in future and are not familiar to the other industries.

4 Details and Case Studies on New Generation Grades Developed for Required Design and Applications

4.0 Maraging Steels

Maraging steel, as the name describes, is the combination of words Martensite and Aging. Hard precipitates formed by aging. Maraging steel contains an extremely low amount of carbon (0.03% Max.); other important alloying elements are Ni, Co, Mo, Ti & Al (**Table 1**). Maraging steel is heat-treated at 480–500 °C for 3-4 hours to form a fine dispersion of hard precipitates within the soft martensite matrix. Over-ageing causes a loss in strength owing to precipitate coarsening and decomposition of the martensite with a reversion back to austenite (**Fig. 1**). The strength of maraging steels (**Table 2**) is much greater than that found with most other aerospace structural materials, which combined with ductility and toughness, makes them the material of choice for aircraft.

Table 1 : Composition of maraging steel

Element	Composition (%)
Ni	17
Mo	4.6
Co	7.0
Al	0.05-0.15
C	0.03 Max.
P&S	0.01 Max.
Ti	0.3-0.5
Fe	Bal (68%)

Table 2 : Properties of maraging steel

Mechanical Properties	Before Aging	After Aging
UTS	950 MPa	1800 MPa
0.2	750 MPa	1700 MPa
%E	7.0	3

CASE STUDIES ON MARAGING STEEL WELDING

4.1 Preventing Heat Input In Dissimilar Welding

- Dissimilar Material Welding (MDN250 to SAE4130) **(Fig. 2)**.
- SAE4130 material is very weak compared to MDN 250; Minimum UTS not obtained in SAE4130.
- Heat Ban Paste and Copper Cooling ring with water circulation applied on SAE4130 side.
- After Application of Heat Ban paste, Cu Cooling ring and water circulation, minimum UTS achieved in tensile testing.

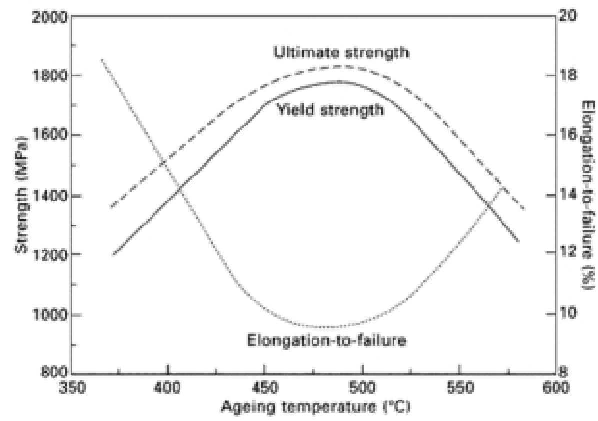


Fig. 1 : Plot of variation of strength and elongation with ageing temperature of maraging steel

Fig. 2 : Photograph of dissimilar welding carried out

4.2 Eliminating Arc Blow in Welding

- Welding of MDN Shell to Flange
- Arc Deviation During TIG Welding
- Checked earthing connection and Magnetism prior to welding (**Fig. 3**)
- Magnetism >3 gauss causing arc deviation
- De-Magnetization of flanges prior to welding
- After De-Magnetization, satisfactory welding results observed.

Fig. 3 : Checking magnetism prior to welding

4.3 Minimising Ovality During Weld Repair

- Repair Welding in Dissimilar (MDN250 to SAE4130) material motor casings .
- End ring to minimize ovality at the exit end
- Copper cooling ring and Jacking from ID to minimize ovality at weld joint
- After rework ovality maintained <0.5mm. If ovality >0.5mm, there will be trouble in machining and maintaining dimensions within tolerance.

5.0 PH Steels

- Martensitic PH steels is weldable in annealed condition although the best results will be achieved with the TIG (GTAW) process as this provides the cleanest weld metal
- Special care and Standard Operating procedures are required during welding because of the high levels of alloying elements.
- These alloys are welding in annealed condition, weldability is good and providing excellent properties after post weld heat treatment.
- Arc should be kept as short as possible to minimize loss of required elements
- Low welding current combined with slow travel contributes to the heat problem. Overheating increases grain growth of parent metal near the weld, resulting in lower ductility and lower strength. It is better to use higher welding current and fast travel. These conditions permit the weld metal to cool through the transformation range at a faster rate, thereby resulting in a stronger Joint.
- High-quality joints are made by TIG welding as this process permits excellent concentration and control of heat and gives high-quality weld metal. Proper weld back up (Fixturing and Tooling) is required to minimize distortion.
- On heavier-gage metal, metal-inert-gas (MIG) welding may be considered; MIG welding are readily mechanized and permit high travel speeds resulting in Less Heat Input and Distortion.

Fig. 4 : Photographs of repair welding done in dissimilar (MDN250 to SAE4130) material motor casings

Table 3 : Composition of 12-10 PH Steel

Element	Composition (%)
Ni	10
Mo	0.8
Cr	12
Al	0.05-0.15
C	0.03 Max.
Mn	0.25 Max.
Ti	0.15-0.25
Fe	Balance

Table 4 : Composition of 15-5 PH Steel

Element	Composition (%)
Ni	5-6
Mo	0.8 - 1.0
Cr	13 - 15
Nb	0.15 Max.
C	0.03 Max.
Mn	0.6 Max.
V	0.15 - 0.25
W	1.0
Fe	Balance

Table 5 : Mechanical Properties of 12-10 PH Steel

UTS	980 MPa
0.2	835 MPa
%E	16
[**PWHT Cycle:** Solution Annealing + Sub Zero Treatment + Tempering]	

Table 6 : Mechanical Properties of 15-5 PH Steel

UTS	1180 MPa
0.2	980 MPa
%E	12
[**PWHT Cycle:** Solution Annealing + Tempering]	

CASE STUDIES ON PRECIPITATION HARDENABLE STEEL WELDING

5.1 Joint configuration

- Heavy beads are less susceptible to stress cracking and lead to less distortion than do small beads. Also, multiple small beads that extend the length of the joint have a serious cumulative shrinkage effect. In a V-joint, for example, the greater shrinkage across the face of the weld will increase tension on the root bead and may cause it to crack.

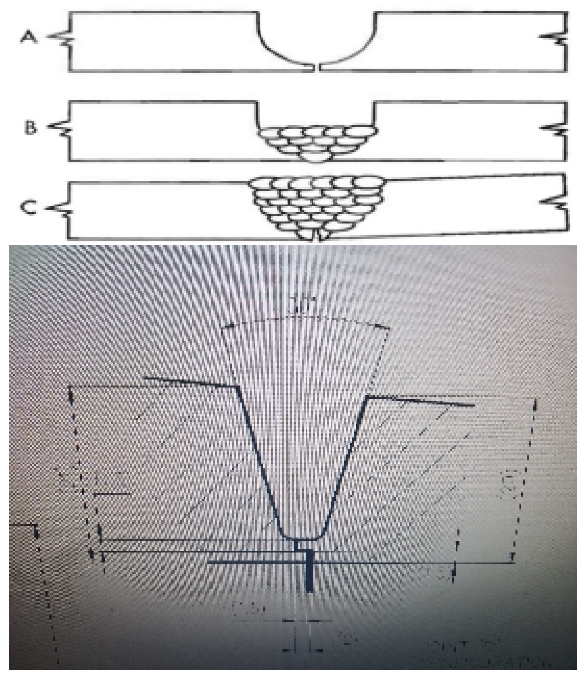


Fig. 5 : Joint configuration and multipass welding

5.2 Welding Technique – Multipass Welding

- Two types of welding shown in **Fig. 6 (A & B)**
- A Welded with weaving with less passes and B Welded in more passes with no weaving
- Type B Welding cleared in DP and RT in First time, thus welding technique plays important role.

5.3 DP/RT repair after PWHT– selection of welding filler wires

- Linear Indication (Faint Transverse Crack) in DP and RT observed in HAZ **(Fig. 7)**
- Very difficult to attend crack with Precipitation Hardened filler wire after Heat treatment.

- Discussed with design team and welding carried out with 316L grade filer wire
- Rework done successfully and met the design requirements as well.

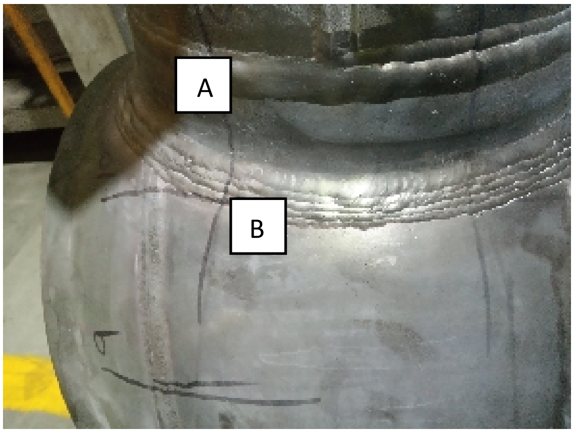


Fig. 6 : Two types of multipass welding done

Fig. 7 : Indication of faint transverse crack in HAZ

5.4 Importance of start-end point/ deciding welding sequence

- Dimensions are important and it shall meet the specification after welding also.
- Checking the run-out values near the joint and on basis of that welding sequence is decided.

5.5 Proper tooling and fixturing

- Fixturing (**Fig. 9**) from penetration side and out side to prevent mismatch near to weld joint, minimize ovality at the fabricated part.
- While attending weld repairs also, job is welded in fixture only if repair is critical.

Fig. 8 : Welding in progress

Fig. 9 : Typical fixturing

5.6 Difficult to access joints– welder's skill

- Joint is 70mm away from the edge, not proper access to the welder (**Fig. 10**)
- One patch of 80mm welded and Radiography taken, on the basis of satisfactory results balance welding carried out.

6.0 Case Studies on Martensitic SS410 Steel Welding

6.1 Difficult joint penetration – joint configuration modified

- SS410 Rib to Casing joint (**Fig. 11**) having dissimilar thickness 1.3mm to 3.5mm.

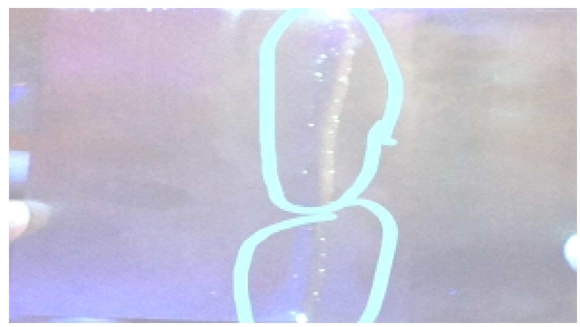
Fig. 10 : Welding at a difficult to access joint

- Full Penetration Joint – Very difficult to penetrate in edges.
- Provide chamfer at both edges and make 0.5mm gap at both edges, i.e. modify the joint configuration to allow the material to penetrate.

6.2 Indications/ Repair in FPI (Flouroscent Particle Inspection) – Modified Welding Technique

- Fluorescent Indication in SS410 material. 2mm Thick, Square Butt Joint
- Welding Technique modified – Welding carried out with low wire feeding in 2 passes instead of single pass.
- Satisfactory Fluorescent Test Results obtained after modifying technique.

Fig. 11. : View of SS410 Rib to Casing joint



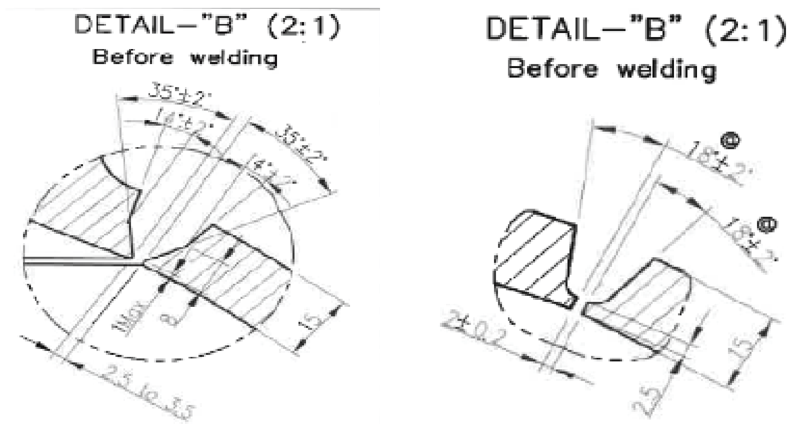
(a) Not Acceptable Joint

(b) Acceptable Joint

Fig. 12 : Inspection using fluorescent test

7.0 Future Developments

MIG Welding is comparatively faster and having very less heat input as compare to conventional TIG Process. Trials for the same are in progress. MIG Welding will replace TIG in many joints of Future Semi-Cryogenic Engine.



TIG Welding	MIG welding
• Welding Area - 161mm2 • No. of Weld Passes - Root + 6 or 7 • Avg. Heat Input - 3.5 kJ/mm	• Welding Area – 119mm2 • No. of Weld Passes – Root + 3 or 4 • Avg. Heat Input – 1.8 kJ/mm

Fig. 13 : Comparison of TIG Welding with MIG Welding

(a) Acceptable Reinforcement

(b) Complete Joint Penetration

Fig. 14 : View of the joint that is accepted

8.5mm Thk Trial plate of 15-5 PH Steel Welded with 12-10 PH Wire with MIG Process using Tri-Mix Gas Ar-He-CO_2

- MIG welded plate having 06X15H6MB Material (15-5 PH)
- Thickness: 8.5mm, No. of Passes: 02
- Welding carried out with Tri Mix Gas Ar+He+Co_2
- Satisfactory LPT and RT (**Fig. 14**).
- Actual Hardware Welding Balance.

8.0 Conclusion

- For Welding of Modern High Strength Materials, Welding technique plays an important role apart from other essential and supplementary essential variables.
- Mechanical properties improving significantly after heat treatment in secondary hardening steels.
- Weldability in annealed condition is very good, but very difficult after PWHT.
- Good Scope of Welding Automation in TIG and MIG in future, trials are in progress.
- Controlling heat input is very important to maintain mechanical properties and to minimise ovality, shrinkage and distortion as well.

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