Design of Welding Fixture for Head End Sub-Assembly of Motor Case

Naveen A M, V A Girish

Abstract—This paper deals with the design of the welding fixture for the head end sub-assembly of a rocket motor case. The head end sub-assembly consists of four parts namely Y-Ring, Dome, Igniter Boss and the Fore skirt ring that have to be welded to each other with a specified tolerance and weld quality. The material used in the manufacture of different parts of head end sub-assembly is Maraging steel which is one of the most commonly used material in the field of aerospace. All the welding processes are carried out in the presence of the Copper Arsenic back-up support bar to ensure the quality of weld is as per the requirement. The optimum thickness of the back-up support bar is determined and with in-process purging facility in the copper-arsenic bar ensure sound weld. Modeling of all the parts of head end sub-assembly and the welding fixture is carried out using UNIGRAPhICS NX8.0.

Index Terms—Welding fixture, Maraging steel, Motor Case, Copper-Arsenic, Weld back-up support, head end sub-assembly.

1 INTRODUCTION

A fixture is a device for locating, holding and supporting a work piece during a manufacturing operation. Fixtures are essential elements of production processes as they are required in most of the automated manufacturing, inspection, and assembly operations. Fixtures must correctly locate a work piece in a given orientation with respect to a cutting tool or measuring device, or with respect to another component, as for instance in assembly or welding. Such location must be invariant in the sense that the devices must clamp and secure the work piece in that location for the particular processing Operation. Fixtures are normally designed for a definite operation to process a specific work piece and are designed and manufactured individually.

The correct relationship and alignment between the components to be assembled must be maintained in the welding fixture. To do this, a fixture is designed and built to hold, support and locate work piece to ensure that each component is joined within the specified limits. A fixture should be securely and rigidly clamp the component against the rest pads and locator upon which the work is done.

Fixtures vary in design from relatively simple tools to expensive, complicated devices. Fixtures also help to simplify metalworking operations performed on special equipments. Fixtures play an important role on reducing product cycle time and ensuring production quality, by proper locating and balanced clamping methods [1]. Therefore to reduce production cost, fixture design, fabrication and its testing is critical.

Generally, all fixtures consist of the following elements:

- Locators: A locator is usually a fixed component of a fixture. It is used to establish and maintain the position of a part in the fixture by constraining the movement of the part.
- Supports: A support is a fixed or adjustable element of a fixture. It maintains the relationship between the fixture elements namely Locator, clamps, supports, and the machine tool on which the part is to be processed.
- Spatter grooves must be provided below the line of welding to prevent the work piece from getting welded to the base plate.
- Care should be taken to check that the joined work piece do not get locked in the fixture after welding.
- For work piece requiring welding from a number of sides, a provision for easy tilting or rotating the fixture should be made to ease welding from the various sides.
- To protect the weld from the atmosphere, the purging facility can be designed.

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• To have rapid cooling to achieve less defects in weld, the backup bar facility must be designed. (Copper-Arsenic bar has been used in this paper)

2 INTRODUCTION TO ROCKET SYSTEM

Solid rocket systems are used extensively in situations in which the total impulse is known in advance and restart is not required. Structurally, a solid rocket motor (see Fig. 1) consists of the solid propellant grain itself, the liner, whose primary purpose is to provide an adhesive bond between the propellant grain and the case insulation; the case insulation which provides thermal protection to the case from combustion products and also structurally supports the propellant grain with the motor case. Any one of these structural elements may become the weakest link in the propellant grain structure. A rocket motor case is used only for a short duration during flight[2].

![Head End Sub-Assembly](image)

Fig 1 Cross-section of a typical rocket motor: (A) chamber; (B) head end dome; (C) nozzle; (D) igniter; (E) nozzle convergent portion; (F) nozzle divergent portion; (G) port; (H) inhibitor; (I) nozzle throat insert; (J) lining; (K) insulation; (L) propellant; (M) nozzle exit plane; (N) SITVC system; (O) segment joint.

Head end sub-assembly is a part of motor case as shown in the Fig. 2. It consists of four main parts (1) Y-Ring shown in Fig.4, (2) Dome shown in Fig.5, (3) Igniter boss shown in Fig.6 and the (4) fore-skirt ring shown in Fig.7 which have to be welded together with a specified tolerance and quality. It is the main part of the motor case where the actual initial ignition to produce the thrust in the rocket motor case takes place. It is made up of Maraging steel material. It is one of the most popular material used in the aerospace field. The cad model of the Head end sub-assembly is as shown in Fig 2.

In order to keep in track with the tolerance and the quality of weld a proper welding fixture has to be designed. The copper-ar senic back-up support bar with purging facility which blows out the hot gas with the influence of high pressurised inert gas blown into the groove machined exactly below the weld line (a tiny hole is provided for heat to escape during welding) is used in order to maintain the quality of the weld by rapid cooling. The heat evolved during the welding is taken by the copper-ar senic bar due to its property of high thermal conductivity and the provided purging holes will make way for the heat to escape into the atmosphere[3].

3 LITERATURE REVIEW

Siva Sankara Raju R et. al [4] have reported the material properties of the maraging steel and NiDI [7] has been used to work on the welding and its weld parameters of maraging steel.

M C Mittal et al [3] have experimented successfully on the GTA (Gas Tungsten Arc) welding of maraging steel using the copper back-up plate with the purging facility to analyze the fracture toughness.

M. Varul et al [5] have examined the effect of welding fixture to prevent the weld distortion, which are very much taken into consideration while designing the welding fixture.

Hui Wang et al [6] have reported the direct impact of fixture on the product manufacturing quality, productivity and cost. The methodology of building a fixture has been reported, which will be a guideline to design the welding fixture.

Iain Boyle et al [8] have stated the basic fixture design principle, the flow chart of the design steps to design the weld fixture has been stated and 3-2-1 principle of location has been explained in this paper that has been considered while designing the fixture.

According to H. T. Sanchez and M. Estrems. F, the final precision with which work piece are formed strongly depends on good design and correct operation of fixtures [9]. The main errors introduced by fixtures are related to positioning, indentation and structural deformation that has been reported in this paper.

Patricio. F. Mandez et al [10] has given the different types of welding techniques and their parameters that are used in the Aeronautical industry. The paper has been studied and the required weld parameters have been extracted before designing the fixture.

F. Sikstrom et al [11] reported in his paper the influence of the clamping force on the structural integrity of the GTAW welded work piece. The paper has been studied and considerable clamping force calculations have to be carried out in designing of the welding fixture.
R. Scott Funderburk [12] has reported the key concepts in welding operation and in his paper the expression for heat input has been stated.

G. R. Stoeckinger et al [13] have conducted a successful experiments on computerized prediction of heat distribution in welding tool and they have used the expressions of thermodynamics to arrive at the heat transfer efficiency and heat energy.

4 METHODOLOGY

The design of the welding fixture for head end assembly is carried out as per the flow chart given in fig3.

Fig 3 Flow Chart to design the fixture

In this flow chart, the initial step starts with the material information, machine specifications, geometric dimensions and tolerances required to be achieved on the component, and different parts of the head end sub-assembly and their cad drawings which are modeled using the software UNIGRAPHICS NX 8.0.

Before the design of the welding fixture the fixture requirements have to be considered. Some of the requirements are stated below.

Generic requirement: Abstract sub-requirement examples.
- Physical: The fixture must be physically capable of accommodating the work piece geometry and weight. The fixture must allow access to the work piece features to be machined.
- Tolerance: The fixture locating tolerance should be sufficient to satisfy part design tolerances.
- Constraining: The fixture shall ensure work piece stability (i.e., ensure that work piece force and moment equilibrium are maintained). The fixture shall ensure that the fixture/work piece stiffness is sufficient to prevent deformation from occurring that could result in design tolerances not being achieved.
- Affordability: The fixture cost shall not exceed desired levels. The fixture assembly/disassembly times shall not exceed desired levels. The fixture operation time shall not exceed desired levels.
- Collision prevention: The fixture shall not cause tool path-fixture collisions to occur. The fixture shall cause work piece-fixture collisions to occur (other than at the designated locating and clamping positions). The fixture shall not cause fixture-fixture collisions to occur (other than at the designated fixture component connection points).
- Usability: The fixture weight shall not exceed desired levels. The fixture shall not cause surface damage at the work piece/fixture interface. The fixture shall provide tool guidance to designated work piece features. The fixture shall ensure error-proofing (i.e., the fixture should prevent incorrect insertion of the work piece into the fixture). The fixture shall facilitate chip shedding (i.e., the fixture should provide a means for allowing machined chips to flow away from the work piece and fixture) [8].

4.1 MARAGING STEEL

Maraging steels are leading members of the ultra high strength steel family and derive their superior properties like high strength and toughness due to a combination of two solid state reactions: “MAR + AGEING” meaning martensitic transformation and subsequent ageing. These steels are primarily based on the Fe–Ni system. The composition is so balanced that on cooling from the austenitic region it transforms to soft martensite and on ageing, precipitation of inter-metallic compounds occurs on a fine scale to increase strength. These steels have attracted material scientists and aerospace structural designers because of their unique strength-toughness combination, ease of fabrication and heat treatment, good weld ability and minimum dimensional distortion. Eighteen percent of Ni maraging steel is the most widely used ultra-high tensile strength maraging steels. It is classified into M-200, M-250, M-300 and M-350 grades according to their 0.2% proof stress levels, namely 200, 250, 300 and 350 ksi. Weld ability is one of the most important properties of ultra-high tensile strength steels and consequently steels with poor weldability cannot be applied to practical use. The weldability of 18% Ni maraging steel differs greatly from that of the other martensitic ultra-high tensile strength steels in that the former does not need preheating or post-heating, has little hardening in the heat affected zone and produces few cracks during welding. In addition, the ageing temperature after welding is low, and therefore the contraction on ageing is very little [2].
The composition used in head end sub-assembly is MDN-250 which has a composition of 18%Ni and the properties of MDN-250 is as stated below:[14]:

- Density: 8.1 g/cm³ (0.29 lb/in³)
- Specific heat, mean for 0–100 °C (32–212 °F): 813 J/kg K
- Melting point: 2,575 °F, 1,413 °C
- Thermal conductivity: 25.5 W/m K
- Mean coefficient of thermal expansion: 11.3×10⁻⁶
- Yield tensile strength: typically 1,030–2,420 MPa
- Ultimate tensile strength: typically 1.6–2.5 GPa
- Grades exist up to 3.5 GPa
- Elongation at break: up to 15%
- K IC fracture toughness: up to 175 MPa m¹⁄²
- Young's modulus: 210 GPa (30,000,000 psi)
- Shear modulus: 77 GPa (11,200,000 psi)
- Bulk modulus: 140 GPa (20,000,000 psi)
- Hardness (aged): 50 HRC (grade 250); 54 HRC (grade 300); 58 HRC (grade 350)

4.2 DESIGN OF WELDING FIXTURE

The given information about the head end sub-assembly are as given below:

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Component to be welded</th>
<th>Welded to</th>
<th>Quantity</th>
<th>Type of Weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dome</td>
<td>Y-ring</td>
<td>1</td>
<td>Circular Manual TIG welding</td>
</tr>
<tr>
<td>2</td>
<td>Igniter Boss</td>
<td>Dome and Y-ring</td>
<td>1</td>
<td>TIG welding</td>
</tr>
<tr>
<td>3</td>
<td>Fore Skirt ring</td>
<td>Igniter Boss, Dome and Y-ring</td>
<td>1</td>
<td>TIG welding</td>
</tr>
</tbody>
</table>

Table-2 Sequence of weld

The model of the welding fixture for the head end sub-assembly is shown in the fig 8. This fixture is casted with aluminium considering the casting does not have a major effect due to the temperature rise because of the welding. Since, the heat evolved during welding is thrown out as soon as it is produced because of the purging facility provided under the weld bead. The critical part of the casting is the profile. This casted round profile has to match the profile of the dome, Y-Ring and also some part of the igniter boss. Hence, the fixture has to be inspected to match this profile to produce the required accuracy and tolerance of the welding on the components of head end sub-assembly. This has been stated in one of the paper by M. Estrems et al. [15] that the dimensional accuracy of the welding fixture has a direct impact on the dimensional accuracy of the part being welded. Hence, to have a control over the required accuracy of
the welding fixture is carefully casted and inspected before it is finalized to use as a welding fixture.

4.3 ARSENIC COPPER WELD BACUP

Backup supports are used for welding of significant thickness for easy penetration control where welding is carried out from one side only. The role of backup support is also essential to protect the under bead from atmospheric oxidation. This is achieved by gas purging and ensures that the under bead is smooth and of high quality. The backup support can be divided into three categories depending on type of welding:

1. Back-up support for L-seam welding
2. Back-up support for cir-seam welding
3. Back-up support for planetary welding

The width (w) of the back support is the sum of the distance between two clamps, width of pressure exerting area of the clamps and additional width to hold the joint properly. Additional rigidity to the back support is provided by peripheral aluminum Alloy or mild steel ring, which is lighter in weight. All the above categories of back support can be sub divided on the basis of type of grooves provided.

- The groove type (iii) is generally deployed to AC weld where the purging call from both top and bottom faces of weld, and the gas used is Argon (specific gravity is 1.69 kg/chum). The groove width, depth and radius are variable factors with respect to the sheet thickness.

With reference to the papers [12] and [13], the expressions are extracted from these papers and are used in determining the mass of the back-up support bar using the specific heat of both Maraging steel and Copper Arsenic.

Calculation For Finding Out The Mass Of Weld Back Up Tool:

The weld parameters have to be established by doing Weld trials on the test specimens. The number of iterations are carried out before proceeding with the actual process of welding the components. These iterations are carried out and the results of each iteration are documented and the feasible weld parameter among the different iteration is finalized to proceed with the actual component welding using welding fixture.

The results of all the iterations that have been carried out on the test specimen has been shown in the below table. In this table the optimum welding parameters of the TIG welding is also established and it is further used.

<table>
<thead>
<tr>
<th>SL.NO.</th>
<th>E(V)</th>
<th>I(AMP)</th>
<th>Travel Speed, v</th>
<th>Heat Input, H</th>
<th>Mass Of Weld Back Up Tool</th>
</tr>
</thead>
</table>
| 1      | 12   | 180    | 280 mm/min     | 462.85 J/mm  | 71745.33 kg/
| 2      | 12   | 180    | 280 mm/min     | 462.85 J/mm  | 71745.33 kg/
| 3      | 10   | 100    | 280 mm/min     | 462.85 J/mm  | 71745.33 kg/
| 4      | 10   | 200    | 280 mm/min     | 462.85 J/mm  | 71745.33 kg/
| 5      | 12   | 200    | 280 mm/min     | 462.85 J/mm  | 71745.33 kg/
| 6      | 12   | 180    | 280 mm/min     | 462.85 J/mm  | 71745.33 kg/

Table 3 Welding parameters iterations

The feasible one out of the above iteration is taken and the theoretical calculation for the same is carried out below:

Welding parameters:

- Voltage, E = 12 V
- Current, I = 180 Amps
- Travel speed, v = 280 mm/min = 4.66 mm/s

Heat Input [H]:

\[ H = EI/V \] in J/mm

Where,

\[ E = \text{Voltage} = 12V \]
\[ I = \text{Current} = 180A \]
\[ V = \text{Travel Speed} = 280/60 = 4.66 \text{ mm/s} \]

Therefore, the heat input:

\[ H = (12 \times 180)/4.66 = 462.85 \text{ J/mm} \]
Let $H_n$ be the actual heat transferred to the work piece considering small electrical losses in arc. Then,

$$H_n = \frac{(f_1 \times E \times I)}{v} = f_1 \times H$$

Where, $f_1 = \text{Heat transfer efficiency} = 0.7$ for TIG Welding (considered as 70% efficient)

$$H = 0.7 \times 462.85$$

$$H = 324 \text{ J/mm}$$

**Heat Energy Used To Melt Maraging Steel ($H_m$):**

The expression for heat energy is given by:

$$H_m = \left[ H_f (T_m - T_0) \right] \frac{W}{L}$$

Where,

- $H_f = \text{Heat of fusion} = 1126 \times 10^3 \text{ J/kg (for M-250)}$
- $C = \text{Specific heat of weld metal} = 0.813 \times 10^3 \text{ J/kg (for M-250)}$
- $T_m = \text{Melting temperature of base metal} = 1413^\circ C$
- $T_0 = \text{temperature of base metal prior to weld} = 20^\circ C$
- $W = \text{Weight of the deposited weld metal} = \rho x V$
- $L = \text{Length of weld metal deposited} = \pi \times \frac{d}{2}$

Where,

$$d = \text{Diameter of the component to be welded.}$$

$$\rho = \text{Density of M-250} = 8.1 \times 10^3 \text{ Kg/m}^3$$

$$V = \text{Volume} = \frac{\pi}{4} (418.4^2 - 413.4^2) \times 0.15$$

Therefore,

$$H_m = \left[ H_f (T_m - T_0) \right] \frac{\pi \times 418.4}{\pi \times \frac{d}{2}} = \frac{324 \times 10^3}{1314.44}$$

$$H_m = 266.54 \text{ J/mm}$$

Heat dissipated to component and tool is given by the expression:

$$Q = \frac{H_n - H_m}{\text{In J/mm}}$$

Also,

$$Q = \text{Heat absorbed by component} + \text{Heat absorbed by tool}$$

$$Q = (m C dT)_{M-250} + (m C dT)_{As\ Cu}$$

$$= H_{M-250} + H_{back}$$

Where,

- $M_{M-250} = \text{mass of maraging steel,}$
- $H_{back} = Q - (H_{M-250})$
- $m_{back} = m_{back} \times 380 \times (113-38)$
- $m_{back} = H_{back}/ (380 \times 75 )$
- $m_{back} = 2.5025 \text{ Kg}$

Considering the weld parameter the mass of the backup tool is approximated as 2.5Kgs. Rise in temp in back up tool is 93° and hence it is recommended not to touch the backup tool after welding. Allow the tool to cool and then disassemble the tool set up used for welding.

From the above calculations, it can be concluded that for 12V & 180A, a minimum of 2.5025Kg of back-Up mass is sufficient to dissipate the heat satisfactorily. But, the thickness will be very less, arising the strength & rigidity concerns. Hence, a nominal 20mm thick minimum is sufficient to address the thermal as well as strength requirements as for the calculations.

### 4.4 MINIMUM GAP BETWEEN WELD EDGE AND CLAMP EDGE

The thickness of the weld between each of the parts is 5.67mm. Using this thickness value the minimum gap between the weld edge and the clamping edge has to be determined using below expressions.

An examination of bead shape(weld pool), welded with direct polarity shows the bead width ‘d’ to a depth of penetration ‘p’ relationship of the form:

$$d = 1.7p$$
This is the normal polarity for TIG process.

It "t" is the thickness of the material to be welded, then the safe gap (a) between one edge of weld bead to the clamp is 1.25t.

Hence,

Required gap to RH clamp = 1.25 x 5.67 = 7.08 m
Required gap to LH clamp = 1.25 x 55.67 = 7.08mm

The distance between the clamps for DC direct polarity weld

\[ d = 1.7 \times 5.67 \]
\[ d = 9.63 \text{ mm} \]

\[ \text{Required gap to RH clamp} = 1.25 \times 5.67 = 7.08 \text{ m} \]
\[ \text{Required gap to LH clamp} = 1.25 \times 55.67 = 7.08 \text{ mm} \]

\[ \text{Hence,} \]
\[ d = 9.63 \text{ mm} \]

\[ \text{The distance between the clamps for direct (DC) polarity weld} \]
\[ = d + 2a \]

\[ \text{Here, } t = 5.67 \text{ mm} \]

Therefore the distance between the clamps for direct (DC) polarity weld

\[ = 9.63 + 2 \times 7.08 \]
\[ = 23.79 \text{ approximately } 24 \text{ mm} \]

Thereby, the minimum gap between the clamp edge and the weld edge is half of the total distance i.e \(24/2 = 12\text{mm}.\)

4.5 WELD SETUPS

1st Weld set-up

The first weld setup in the sequence stated in the above Table-2 is Y-Ring to Dome and the setup of fixture for the same is as shown in the sequential figures below

In this setup all the welding parameters, minimum gap between the clamp and the weld edge has been considered as per the arrived results in the earlier stage of this paper.

The profile of the fixture helps in positioning of the Y-Ring and Dome.

Step 1: Place the Y-Ring on the fixture and clamp it.

Step 2: Place the dome on the fixture

Step 3: Clamp the Dome using clamp plate.

Step 4: Weld Y-Ring to Dome.

The component after weld is as shown below:

2nd Weld set-up

As per the next sequence in the Table-2, the Igniter boss needs to be welded to the pre-welded Y-Ring and the Dome and the weld setup to weld this sequence is as shown in the figures below:

Step 1: Place the Igniter Boss.

Step 2: Clamp the igniter boss and the pre-welded Dome Y-Ring.
Step 3: Weld Dome Y-Ring to Igniter Boss.

3rd Weld set-up

Until this part the welding fixture had enough flexibility to weld with the Arsenic Copper back-up support bar. In this setup, providing a back-up support needed a special design to fit into the gap between the upper surface of the Y-Ring and the Lower surface of the fore skirt ring is approximately about 40mm. Hence, designing a support back-up is a challenge and the figure below shows the exact problem.

To tackle this problem, design of a collapsible type of back-up support Arsenic Copper ring that has been fastened to the fore skirt ring before the weld setup and after the welding operation the fasteners are removed to eject out the pieces of the Arsenic Copper back-up support. This arrangement shown in the below figure and is the step 1 for the 3rd setup of weld.

Step 1: Fastening the collapsible back-up support to the Fore Skirt Ring.

The 2-D drawings of these collapsible back-up support ring has been shown below:

Step 2: Place the Fore Skirt ring with the collapsible back-up fastened on the pre-welded Y-Ring Dome and Igniter Boss.

Step 3: Clamp the Fore Skirt Ring using the clamp plate and the thrust pad.

Step 4: The final welded head end sub-assembly is as shown in the figure below.
5 ACHIEVING THE TOLERANCE

The specified tolerances on the head end sub-assembly are shown in the figure 12.

To achieve the above tolerances as mentioned in the figure, the top surface of the Igniter Boss is provided with extra material which is machined parallel to the bottom surface of the Y-Ring and the inner radius of the igniter boss is also provided with extra material and this surface is machined in such a way that it is perpendicular to the top surface of the fore skirt ring after the whole welding operation is finished.

6 RESULTS AND CONCLUSION

In this paper, the welding fixture for head end sub-assembly is designed successfully and in this process of designing

- The modeling of each parts of the head end sub-assembly and the welding fixture is carried out for the better visual realization of the components, this modeling of the parts is modeled using the software package UNIGRAPHICS NX 8.0. This method of modeling the parts evolves the better analysis towards the tolerances on the parts and also the fixture design.

- The calculations using the thermal aspects of the arsenic copper and the maraging steel enabled us to arrive at the optimum mass of the back-up support bar, which was found to be 2.5325kg and this ensures that the heat evolved during the welding of the joint is absorbed towards the backup support ring and the mass of this back up support is calculated in order to sustain this hot gas without much of a thermal expansion.

- The minimum gap between the clamp and weld edge is found to be 12mm and this has been followed in the design practice of the welding fixture and at the bottom of clamp plate the arsenic copper backup bar will provide the support so that there is no effect of clamping force on the part head end sub-assembly.

- The sequence of the welding operations is established and is found to be one of the optimum sequence in this head end sub-assembly welding. The each weld setups are stated and are briefed using the figures at each step of welding using the welding fixture.

- The design of the collapsible backup support ring for welding the fore-skirt ring with the y-ring has been successfully executed in this whole design of welding fixture.

- The geometric tolerances that are specified on the head end sub-assembly are very tight and hence this specified tolerance can be achieved up to an extent using the designed welding fixture. Since, in this case the probability of rejection or rework will be more compared with the probability of acceptance a specified method under section 4 will provide the more probability towards the acceptance than rejection.

Hence, this method can be opted for achieving the specified tolerance.

References