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Welding High Strength Steels to Ultra High Strength Steels for Commercial Vehicle Chassis

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Abstract: In commercial vehicles, to suit design needs and to have economic balance, combination of high and low strength steels becomes necessary with high strength being used only in critical areas. To have such a combination, appropriate joinery is used. The objective of this work is to achieve high strength welding joints of dissimilar steel grade to be used in commercial vehicle chassis. Welding, for its wide usage on fields, least modification requirement and minimum increase in weight is chosen as the joining process. This paper gives an insight into the detailed procedure used for metal inert gas arc-welding of high strength to ultra-high strength steels which includes material selection, filler selection, choosing of heat treatments if required, setting up parameters of welding and validating those based on testing. The tests carried out include both destructive and non-destructive required to make welding procedure specification. It also aims at developing a guideline for dissimilar high-strength steel welding. Welding procedure specification is provided at the end. Thus, understanding the base metal compositions, considering appropriate factors and end application, immaculate joints of high and ultra-high strength steels of competent weld quality are accomplished.

Keywords* — *carbon equivalent, dissimilar steel grades, filler material, hydrogen induced cracking, metal inert gas welding, overmatching, welding procedure specification

I. Introduction

Designing a component in one piece is seldom possible. It is designed to assemble or joined by various joining processes. These joining processes include welding, bolting, riveting, etc. with each process having its own inherent advantages and disadvantages. Welding is a permanent joining method whereas, riveting a semi-permanent because one part can be destroyed to remove the joint. Bolting and riveting joints essentially need holes which may be, initially drilled as in case of bolting or made during the process of joining as in case of riveting, which leads to stress concentration. Moreover, both processes increase weight and are not suitable methods of joining on field during repairs. For example, welding can be preferred under static loading but is very poor in cyclic or fatigue loading where bolting or riveting is the only option. Based on the application wherever permanent joints are required welding is used. In the automotive industry, high strength steels (HSS) and advanced high strength steels (AHSS) are rapidly getting more demand for their improved performance and crashworthiness. Weight reduction can be achieved by reducing section dimensions with the use of HSS and AHSS. For 10% reduction in weight would lead to 3-7% lower fuel consumption as illustrated by Jeanneau and Pichant [1], [2]. Considerable efforts are thus being employed in the research and development of these materials. The most common steel grades of this categories are Dual Phase (DP), Transformation Induced Plasticity (TRIP), Multi-Phase (MP) and hot stamping boron steels. As these materials are new, their joining processes need to be researched further. To be more specific arc welding processes on quality of dissimilar joints between HSS and AHSS have not been investigated completely. This work is sponsored by Metalsa India Pvt. Ltd. Due to proprietary information materials are specified in codes.

II. Understanding Steel

A. *Basics of steel*

Steel is a complex recipe of pure iron and other alloying elements viz. carbon, manganese, silicon, chromium, molybdenum, vanadium, copper, nickel, aluminium, etc. It also contains contaminants like sulphur, nitrogen and phosphorus. Each alloying element contributes to steel's characteristic physical and chemical property. Carbon acts as a primary hardening element, chromium gives corrosion and oxidation resistance, nickel increases hardenability and impact strength. Molybdenum increases hot and creep strength of low alloy steels at elevated temperature, vanadium increases yield and ultimate tensile strength,

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whereas manganese is beneficial to surface quality. Silicon is one of the main deoxidizers along with aluminium. Tungsten forms hard abrasion resistant particles in tool and high-speed steels. On the contrary contaminants make steel more brittle [3]. These constituent elements affect the microstructure and thus the metallurgy. Complexity further increases with temperatures involved during manufacturing.

Obtaining desired properties for steels essentially requires having proper knowledge of the alloying elements, quantity to be added, controlling temperature, etc. The most common example can be taken for simple carbon steel. Iron-iron carbide diagram explains the behaviour of carbon steels in various phases. But the study of phase diagrams of iron and each other alloying element becomes difficult. Thus, to determine the properties of alloy when more than just carbon is used as an alloying element, the concept of carbon equivalent (CE) is used. The alloying contents other than C are converted to equivalent carbon as the Fe-C phases are properly known. Mostly used for welding, this CE dictates the weldability. Welded region tends to form martensite on cooling. CE also indicates the measure of this tendency. The susceptibility of the material to problems like hydrogen cracking can also be judged by determining its weldability.

B. Problems involved in dissimilar steel welding

Welding in general is responsible for a metallurgical notch which is present in almost all types of welding. Dissimilar material joining is usually more difficult than that of similar ones. This is owing to the contrasts in physical, chemical and mechanical properties of base metals (BM) welded. The appropriate filler material selection suitable to both the base metals can be tricky and sometimes may even be traded off [4]. Increasing carbon content and alloying element intensifies the vulnerabilities. The manufacturing methods of various HSSs differ as thermal and mechanical control is involved decreasing the probability of one set of welding conditions being applicable to both the metals. A significant increase in the diffusion quantity of brittle component elements during very rapid cooling around fusion zone (FZ) and heat affected zone (HAZ) increases further risk [5]. Factors like carbon migration from the low-alloy side, the microstructure gradient and residual stresses across different regions of the weld metal govern the properties of the welded joints and the feasibility of the welding processes [6], [7]. The microstructure gradient can result in brittle intermetallic compounds. The chemical composition relating to microstructure is very much affected by the thermal cycle [8]. The resultant weldment due to large heat input during welding manifests mechanical properties which are inferior to that of the base materials due to transformations in the microstructures of the weld and its surrounding HAZ. Unlike spot and laser welding techniques, arc welding involves larger heat inputs giving rise to defects like burn through and cracks, excessive heating of parent materials and most important the thermal distortions [9]. Another thermal aspect is, the extent to which the two base materials react to the heat input during welding. This pretty much decides the residual stress scenario post-welding. Hydrogen induced cracking (HIC) is also a common problem associated to welding which is more pronounced in processes having electrode coatings, electrode cores, fluxes namely shielded metal arc welding (SMAW), flux core arc welding (FCAW), electroslag welding (ESW). It is found less in bare metal electrode processes such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). Moisture from uncleaned surfaces mainly due lubricants, paints and from surrounding inert gas environment can also account to some extent [10].

III. MATERIAL SELECTION

A. Base Materials

The materials used for commercial vehicles are ASTM A710, AISI 4130, HR DP 600-UC, S650 MC, etc. In this paper, as stated earlier a combination of AHSS and HSS is used. Steels can be compared based on mechanical and chemical properties [11]. Steels are placed in ascending order of their strengths in grouping method whereas chemical composition and carbon equivalent (CE) is checked in chemical properties. As there is significant amount of difference in the strengths, only chemical properties can be compared. The AHSS is used for load carrying members such as the long member (LM) and HSS for others like gusset. The exact material details cannot be revealed so they are given in Company codes. METIN011 and METIN003 are used where MET designates Metalsa and IN designates India. Weldability of the materials is determined by the following formula which is given by AWS.

$$CE = \%C + \left(\frac{\%Mn + \%\,Si}{6}\right) + \left(\frac{\%Cr + \%\,Mo + \%V}{5}\right) + \left(\frac{\%Cu + \%\,Ni}{15}\right)$$

[12]

The weldability for materials is excellent for CE below 0.35. It is appreciably good within the range of 0.36 to 0.45 and is poor above 0.50. The chemical composition for materials is given in table 1. along- with CE and their strengths.

	METIN011	METIN003	ER110S-G
C	0.043	0.078	0.005
Mn	1.500	0.900	0.480
Si	0.140	0.050	1.530
Cr	-	0.018	0.380
Mo	0.210	0.006	0.360
V	0.060	0.002	0.010
Cu	-	-	0.120

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Ni	-	0.027	1.930
CE	**0.370**	**0.243**	-
Syt	**700**	**460**	**700**
Sut	**800**	**570**	**900**
EL (%)	**21**	**23**	**18**

Table 1. Base and filler materials

CE for METIN003 is 0.243 which is excellent and for METIN011 is 0.37 which is good, and therefore results in good weldability with each other too.

B. Filler Material

Both the materials are high-strength low alloy (HSLA) steels. After determining weldability based on chemical composition, strengths do need to be considered for filler material selection. There exists mechanical heterogeneity with respect to elastic-plastic deformation in structural welded joints, in case of dissimilar materials after welding [13]. The dissimilarity of both the base materials can be expressed in terms of mismatch with the filler material (FM) strength which is the ratio of FM strength to BM strength. The resulting weldment is overmatched if this mismatch is greater than 1 and under-matched when the ratio is less than 1 [5]. Undermatch is used in case of higher strength steels to avoid defects like cold cracking. While, overmatch is used for applications subjected to tension for an efficient transfer of strength. Any weldment be it similar or dissimilar, has a transition of chemical as well as mechanical properties in the fusion zone (FZ) and heat affected zone (HAZ) between BM and FM. That is the strength in FZ will lie between the BM and FM strengths. In an already under matched weld the FZ strength will be lesser than the both BMs increasing the probability of failure in weld region. For this reason, overmatching seems to be more practical. Hence ER110S-G with strength of 900 MPa in the form of metal core wire is selected as filler. The composition and strength of the filler material is given in table 1. Metal core wires produce broad cone shaped arc with higher rate and depth of penetration and are preferred for single pass welds, weldments subjected to burn throughs, jobs where aesthetics are important. The diameter of wire used is 1.2 mm.

GMAW is selected for its suitability for high deposition rate, faster welding speed, variable thicknesses and its incessant nature. It can also be operated semi-automatically and automatically making it advantageous for mass production. Furthermore, cold cracking phenomenon is less pronounced in GMAW with inert gas atmosphere. The only care to be taken is cleaning the surfaces from any source of moisture [14].

IV. WELD HEAT TREATMENTS

Rapid cooling rate, which leads to martensitic microstructure, assisted by hydrogen diffusion and other complicated phenomena, causes cold cracking. Pre-heating (PH) is generally done to remove moisture and other contaminants, to reduce the cooling rate and hence cold cracking [10]. Maintaining Interpass temperature (IP) also has the same reason. Post weld heat-treatment (PWHT) however, along with reducing cold cracking has objectives of reducing residual stresses, increasing toughness of the weldment. Subsequently this residual stress relaxation increases resistance to brittle fracture, fatigue cracking and stress corrosion cracking [15]. The PH and IP requirements depend on the code. METIN003 is an ASTM A1018 HSLA Grade 60 equivalent. According AWS D1.1/D1.1M Table 3.3 [16], this material PH and IP requirements are for thickness above 38 mm. The thickness of materials used is 5 mm in our case, so no PH and IP needed. PWHT depends on the microstructure of the weld and surrounding HAZ after completion of weld. On the other hand, materials manufactured by cold working process to achieve higher mechanical properties are not suitable for PWHT. It is not imperative for any wall thickness except multi-pass welding is employed for wall thicknesses greater than 5 mm and preheat to 95°C (min) for wall thicknesses greater than 25 mm. Thus, PWHT also is not employed in our case.

The type of joint to be made is butt joint because complete joint penetration (CJP) for groove welds qualifies for any size of fillet or partial joint penetration (PJP) for any thickness and 1G (flat) position, according to AWS D1.1M table 4.1 and 4.2 [16]. A fixture plate was made to serve the purpose of reducing thermal distortion and providing backing plate for the penetrated material since single V groove was used. The base plate dimensions are 510X180mm as specified by the code AWS [16] with thickness of 5mm. Edge preparation is carried out on the base plates in the form of single V groove with groove angle of 60°, root opening of 2mm and root face thickness of 1mm. The backing plate on the fixture is of non-fusing metal type (*copper*).

V. WELDING PROCEDURE SPECIFICATION (WPS)

The process of WPS involves a draft WPS, procedure qualification record (PQR) and the final WPS. Draft WPS is an estimation of the parameters by the qualified welder based on experience which are preliminary. Some trial welds are carried out by the welder until he is satisfied with quality of weld. Then actual welding is carried out on the base plate. These parameters recorded while welding is PQR as these are actual parameters used. The welded base plate undergoes non-destructive (NDT) and destructive testing (DT) which will be described later. If the weldment fails any of the tests, it is rewelded by changing the parameters and retested until it passes all the tests. The final parameters are used for WPS document.

We carried out three iterations of welding. The first one failed as it did not have proper penetration. This was

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improvised by increasing the current. Following iteration lacked the reinforcement on the face side which attributed to higher welding speed and was rectified in the later iteration. The third one succeeded and its criteria for passing are described in following section.

The NDTs included visual inspection, dye penetrant (DPT) and radiography test (RT). As either of Ultrasonic Test (UT) or RT should be used only the latter is carried out [16]. Visual inspection was carried out to check for any porosity, excessive reinforcement, undercut and overlap. DPT was performed to check for discontinuities such as cracks, porosity, incomplete fusion and lack of fusion, which cannot be perceived by naked eye.

Macro-etch test conforming to AWS D1.1M 4.9.4 [16] was done. A specimen for macro-etch test should have proper finish.

DTs included tensile, hardness and bend test. The specimens for these tests were cut according AWS D1.1M figure 4.7 [16] as indicated in the figure below.

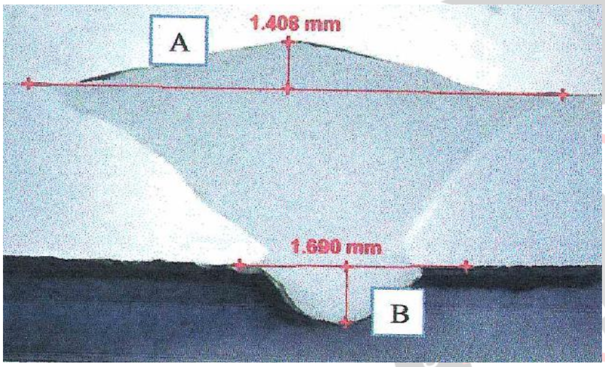

Fig. 1 Specimen cutting from base-plate

Fig 1. shows specimen cutting from welded base plate for completed joint penetration (CJP). The discarded portions are to weld start and end to defects. Two tensile specimens and 4 bend specimens (2 for face bend and 2 for root bend) were cut. Apart from this hardness test specimen which is not shown in the figure was also cut. CVN test was not carried out as the application did not demand.

VI. Results and Discussions

No defects were found in the visual testing.

Fig. 2 DPT of the welded base plate

Fig. 2 shows dye penetrant test of base plate on the weld face side. There is no red patch indicating penetrant which shows no crack near the welded zone. Thus, there is no evidence of any surface discontinuities in the weldment. So, the weldment passes the dye penetrant test. On microscopic level RT ensured no internal cracks or porosity is present in the weldment. Thus, radiography test was also passed.

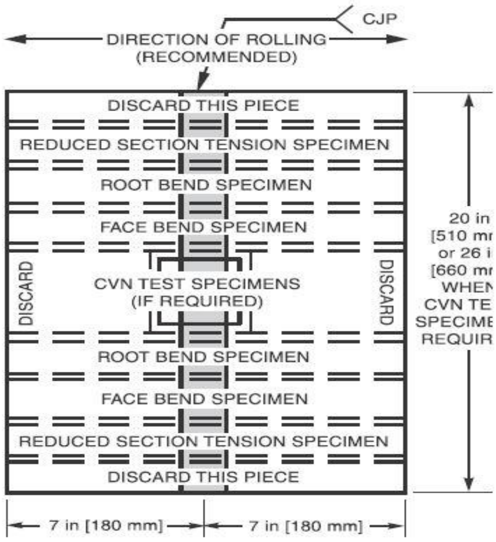

Fig. 3 Macrograph from macro etch test

Macro graphs shown in fig. 3 show that there are no undercuts, underfill, overfill and no excessive reinforcement. The reinforcements were as follows:

Upper (A) :1.408mm

Lower (B) :1.690mm

Upper is the face side of weld and lower is root side. According to AWS D1.1:2006 4.8.1.2 Fig. 5.4 D and E [16] up to 3mm reinforcement is acceptable. Thus, the weldment passed macro-etch test.

For tensile test two samples were tested as shown in Fig. 4. The fracture took place at the base material METIN003 side as its strength is the least among the base material and the filler material. The details are given below.

Tensile strength (S_{ut}) : 560MPa
Test standard : ASTM A370-17.

Fig.4 Tensile specimens

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For hardness test 3 values were obtained from the five locations and averaged values are mentioned in the chart. The results of hardness test are as follows:

Hardness test : Vickers (HV)
Indenter : Square base pyramid shape diamond
Test standard : ASTM E92-17

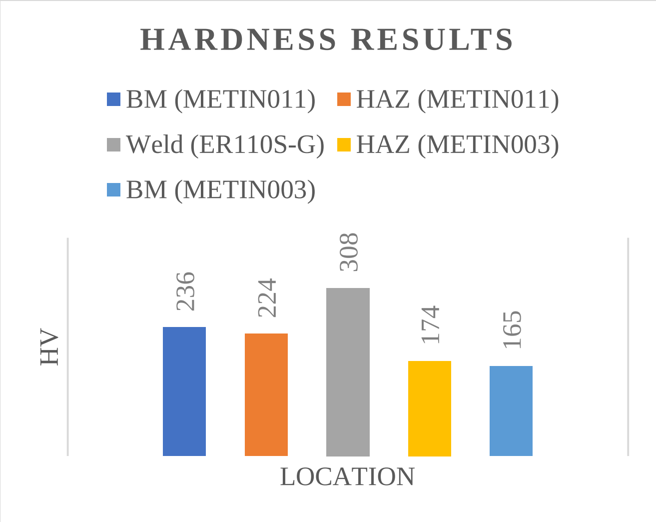

Fig. 5 Hardness test results

Fig. 5 shows the bar graph for hardness testing. The hardness at the weld location is the highest and the difference of hardness between base materials and the corresponding HAZ on either side is not much.

Two samples each for root and face bend were tested. The details of bend test are:

Type : 180° bend
Former bend diameter : 32mm
Test standard : ASTM A370-17

Fig 5. shows face side of the sample of bend test. As can be seen that no cracks are present in the weldment. Other samples also passed the bend test.

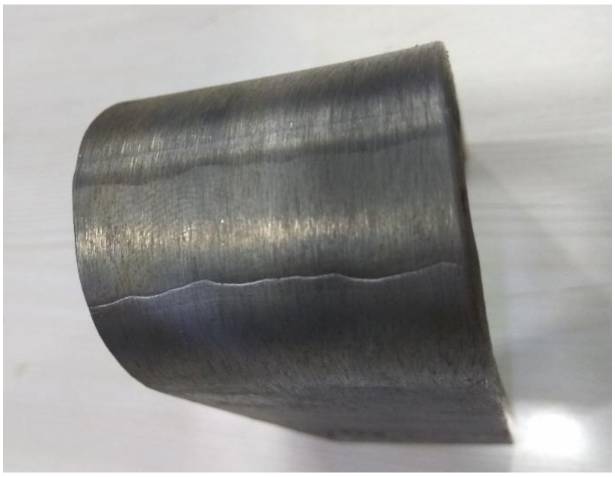

Fig. 6 Bend test sample

So, having passed all the tests, the parameters are freezed and can be used as WPS which is as follows.

WPS parameters

Polarity	DCEP
Weld Pass	Single
Shielding Gas	M21 (CO_2 + Ar) (20% CO_2 80% Ar)
Flow rate (LPM)	15-20
Pre-heat	NA
Amps	220-250
Volts	20-24
Travel Speed (mm/min)	220-250

Table 2. WPS parameters

As mentioned in table 2. DCEP polarity was used as it gives deeper penetration in GMAW. A mixture of CO_2 and Ar provides more arc stability and less spatter. Pre-heat was not applicable as mentioned before.

VII. Conclusion

ND tests witnessed no defects. This warranted that the failure which takes place in DT is not due to welding defect. Macro-etch test confirmed proper penetration and reinforcement. The value of weldment strength i.e. 560 MPa is very near to the minimum of the strengths of BMs which is 570 MPa. Thus, required tensile strength is achieved. The hardness value change of HAZ and base metal on both the sides is within 7% which indicates no abrupt change attributed to brittle martensite formation. No cracks are observed in the bend test which implied adequate ductility was achieved. WPS document was prepared having passed all the tests.

Thus, for HSS and AHSS, we considered the material composition for determining the weldability. Filler material was chosen to theoretically overmatch the joint strength. Following the standards, knowing the grade of material, manufacturing process used and the end application no heat treatment viz. PH, IP and PWHT was employed. Necessary precautions are needed to avoid HIC.

Hence, considering various parameters, understanding end application and carrying out necessary tests welding dissimilar grade steels can be applied for CV chassis attaining the objectives of high strength joint, weight reduction while also keeping check on cost by using AHSS only in load carrying members.

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