Comparison of CO_2 and Nd:YAG Laser Welding of Grade 250 Maraging Steel

IIW Doc. II-A-173-06

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Abstract

Laser welding trials were performed on thin walled cylindrical Grade 250 maraging steel tubes to determine its suitability as a joining process for rocket motor casings. Bead-on-plate (BOP) and butt welded samples were produced utilising a 5 kW Trumpf TLF5000HQ CO_2 laser ($M^2 = 1.82$) with a 5-axis TLC1005 Lasercell and 200 mm focal length off axis parabolic mirror welding head. The samples were subjected to tensile testing after an aging post weld heat treatment was performed at 480ºC for 3 hours. Acceptable results were obtained although some concerns emerged regarding the ability of the welding jig to ensure repeatability of joint fit-up and alignment of the laser beam with respect to the seam. Alternative techniques such as dual focus (twin spot), scanner welding, addition of filler material and pulsed Nd:YAG welding were investigated to increase the operating window compared to autogenous single spot laser welding by making the process less sensitive to fit up and alignment. Metallurgical investigations were also performed to compare the microstructures produced by the various welding techniques. Twin spot and pulsed Nd:YAG welding increased the tolerance with regards to laser beam offset to 0.5 mm compared to 0.2 mm for single spot autogenous welding. The higher heat input of twin spot resulted in a higher fraction of reverted austenite after PWHT at 480ºC for 3h and reduced mechanical properties compared to pulsed Nd:YAG welding. The presence of contamination and misalignment has been found to have a profound impact on weld integrity. Pulsed Nd:YAG welding is the preferred process due to the large operating window, small amount of reverted austenite and excellent weld geometry.

Keywords: Maraging steel, laser welding, weld scanner, twin spot

Introduction

Maraging steel is commonly welded with TIG and PAW with the addition of filler material. Originally the rocket motor casings were manufactured with a combination of PAW and TIG. PAW was used for the first run and TIG with the addition of filler material for the second run. An investigation into the laser welding of Grade 250 maraging steel tubes for rocket motor casings was performed. Advantages of laser welding over conventional arc welding processes include lower heat input, excellent repeatability, control of welding parameters, increased welding speed and reduced dependence on operator skill. Fit-up and alignment tolerances for laser welding are however much more stringent compared to arc welding processes. To reduce process sensitivity to these well known limitations of conventional laser welding alternative laser welding techniques such as twin spot welding, scanner welding, the addition of filler material and pulsed Nd:YAG welding were investigated.

During post weld heat treatment (PWHT), precipitation of $Ni_3(MoTi)$ occurs which is responsible for the increase in strength and hardness. Previous studies regarding the mechanical properties of 18% Ni maraging steels indicated that for a PWHT time of 3 hours, optimum mechanical properties were obtained at a aging temperature of 510ºC [1]. In Grade 250 maraging steel, austenite reversion usually requires prolonged exposure to temperatures in excess of 650ºC for the parent material. This is only true for the base material and does not apply to welded structures. Maraging steels subjected to welding processes result in weld metal with a typical cast structure. After PWHT, a second phase commonly referred to as reverted austenite is formed in the interdendritic areas of the weld metal. Previous studies indicated that the segregation of Ti and more importantly, Mo is responsible for increasing the tendency for austenite reversion in the interdendritic regions [2, 3]. Segregation of Ni and Co across the dendrite regions was not pronounced. Lower Mo and Ti contents will reduce the segregation effect during solidification and will result in less reverted austenite after aging heat treatment of the weld metal. Lower aging temperatures also resulted in less reverted austenite in the weld metal. The amount of reverted austenite will have a significant influence on the weld metal properties due to the lower strength of this phase. These considerations imply that a balance needs to be found between the PWHT required to produce the required precipitation hardening and the need to avoid the formation of excessive levels of reverted austenite.

Experimental procedure

Bead-on-plate (BOP) and butt welds were performed on Grade 250 maraging steel tubes with a wall thickness of 1.2 mm and an outer diameter 160 mm. The chemical composition of the base material is shown in **Table 1**. Welding tests were performed with a 5 kW Trumpf TLF5000HQ CO_2 laser ($M^2 = 1.82$) with a 5-axis TLC1005 Lasercell and 200 mm focal length welding head. Nd:YAG welding was performed with a Rofin DY044 diode pumped Nd:YAG with a 300 mm focal length welding head coupled to a Kuka KR60L30 HA articulated arm robot. A 400 micron step-index fibre and a 200 mm collimator were used in the beam delivery system. Helium was used as a shielding gas. Relatively good weld joint fit-up was obtained for butt welds with gaps typically less than 0.1 mm and joint face misalignment of less than 0.3 mm. This was achieved with the assistance of a specially designed welding fixture. The welding fixture could not always be relied on to produce an optimum set-up and the fit-up often had to be manually adjusted. Joint preparation consisted of sandblasting the areas adjacent to the weld joint with glass beads and cleaning with acetone prior to welding. Both the outside and inside of the tubes were prepared in this way.

It was found that optimum parameters for single spot BOP welds resulted in poor butt welds. The welding speed for single spot BOP welds had to be reduced by 30% to obtain acceptable butt welds. Proper alignment of the laser beam and weld joint was also required to obtain acceptable joints. Offsets larger than 0.2 mm resulted in lack of fusion in some areas along the seam for single spot welding. Twin spot, scanner welding, the addition of filler material and pulsed Nd:YAG welding were investigated to increase the operating window with regards to joint fit-up and misalignment. The focus of this paper will be on the comparison of twin spot and pulsed welding. Acceptable results were obtained with offsets of up to 0.5 mm. Twin spot welding was performed with a spot separation of 0.7 mm (centre to centre) and focal length of 200 mm. The spots straddled the seam and were equally spaced with respect to the weld seam. Pulsed Nd:YAG welding was performed with a diode pumped 4.4 kW Rofin DY044. Focal length of 300 mm with a 200 mm collimation unit was used to obtain a spot size of 0.6 mm. 1200W at 0.5 m/min (15Hz, 30% duty cycle) with 20 l/min He (off axis shielding nozzle) was used to obtain full penetration. Optimum welding parameters for the twin spot and pulsed Nd:YAG welding processes were determined for BOP samples. These parameters were found to be optimum parameters for BOP as well as butt welds. Optimum welding parameters for the BOP and butt welds are shown in **Table 2**. Post weld heat treatment (PWHT) at 480ºC for 3 hours was performed as per internal specification requirements of Denel Land Systems, Western Cape, South Africa. Weld geometries of the single spot and pulsed Nd:YAG butt welds were superior to the twin spot weld due to more sagging. Butt weld samples are shown in **Figure 1**.

Table 1 - Chemical composition of Grade 250 maraging stee

Element	**C**	**Mo**	**Ni**	**Co**	**Ti**	**Al**
Grade 250 (spec)	0.03 max	5	18	8	0.5	0.1

Table 2 - Optimum welding parameters for BOP and butt welds

Material	**Power (kW)**	**Thick ness (mm)**	**Focus position (mm)**	**Welding speed (m/min)**	**Welding head (mm)**	**Wire feed speed (m/min)**	**Weld joint gap (mm)**	**Shielding gas**	**Gas flow rate (l/min)**	**Remarks**
Gr 250	4.2*	1.2	0	9.0	200	0.0	n.a	He	14	Single spot, BOP
Gr 250	4.2*	1.2	0	6.0	200	0.0	0.1	He	14	Single spot, butt
Gr 250	4.2*	1.2	0	4.0	200	0.0	0.1	He	14	Twin spot, separation 0.7 mm
Gr 250	1.2	1.2	0	0.5	300	0.0	0.1	He	20	Pulsed Nd:YAG, 0.6 mm spot size, 15 Hz, 30 % DC

*Power at workpiece

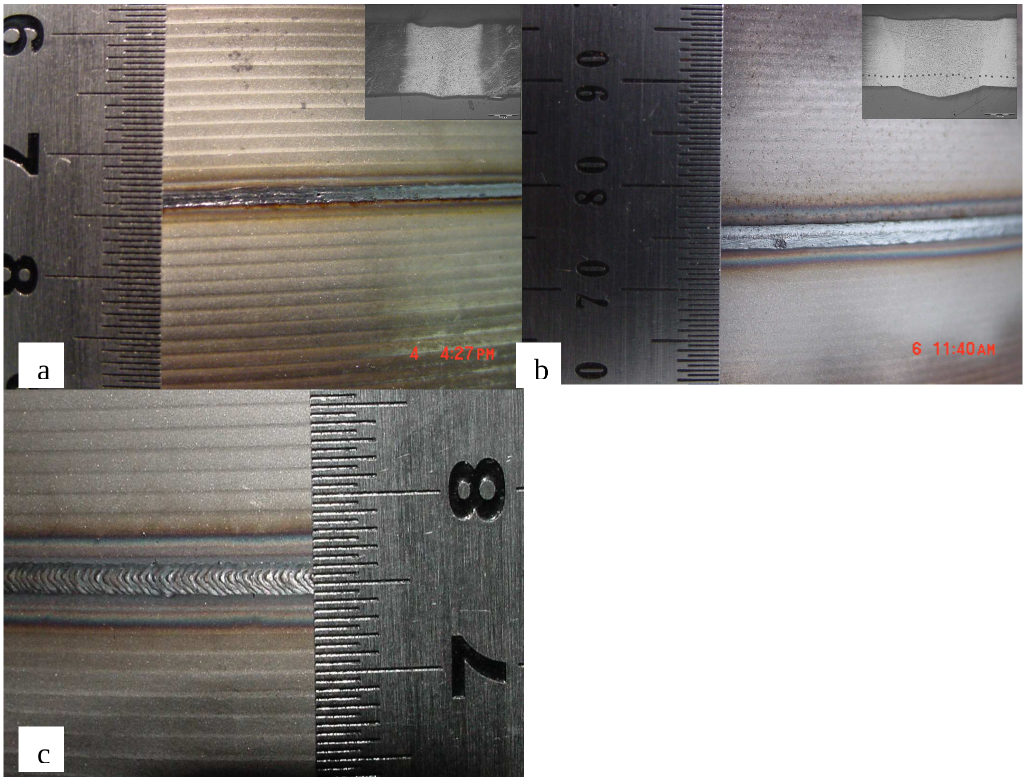


Figure 1 - Laser welded butt joints. a) Single spot, b) twin spot, c) pulsed Nd:YAG weld

Results and discussion

Metallurgical investigation

The microstructures of the as-welded butt welds exhibit a cellular-dendritic morphology, as shown in **Figure 2**. With 15 % Nital, etching occurs preferentially along the alloy-rich interdendritic areas revealing the solidification structure. No significant differences in the solidification structure could be observed between the weld centre line area and the areas near the fusion line, weld root and weld face of the as-welded CO_2 laser welded samples. This is attributed to the geometry of the solidification front during welding. The single spot welds revealed a finer microstructure in comparison to the twin spot weld. The finer microstructure of the single spot butt weld is due to the lower heat input (42 J/mm) and therefore higher cooling rate compared to twin spot welding (63 J/mm). The solidification structure of the pulsed Nd:YAG weld exhibit a cellular morphology in the weld centreline and columnar near the fusion line. Cellular structure of the pulsed Nd:YAG weld metal centreline is due to constitutional supercooling (liquid metal temperature is lower than the liquidus temperature) of the remaining liquid [4].

Shown in **Figure 3** are the microstructures of the single spot, twin spot and pulsed Nd:YAG welds after PWHT at 480ºC for 3 hours respectively. The formation of reverted austenite is clearly visible in the interdendritic regions. The finer microstructure of the single spot and pulsed Nd:YAG welds (**Figure 3a,f**) resulted in a lower fraction of reverted austenite which is also more evenly distributed. Although no significant differences could be observed between the solidification structures in the weld centre line and the areas near the fusion line for the CO_2 laser welds, different fractions of reverted austenite were evident.

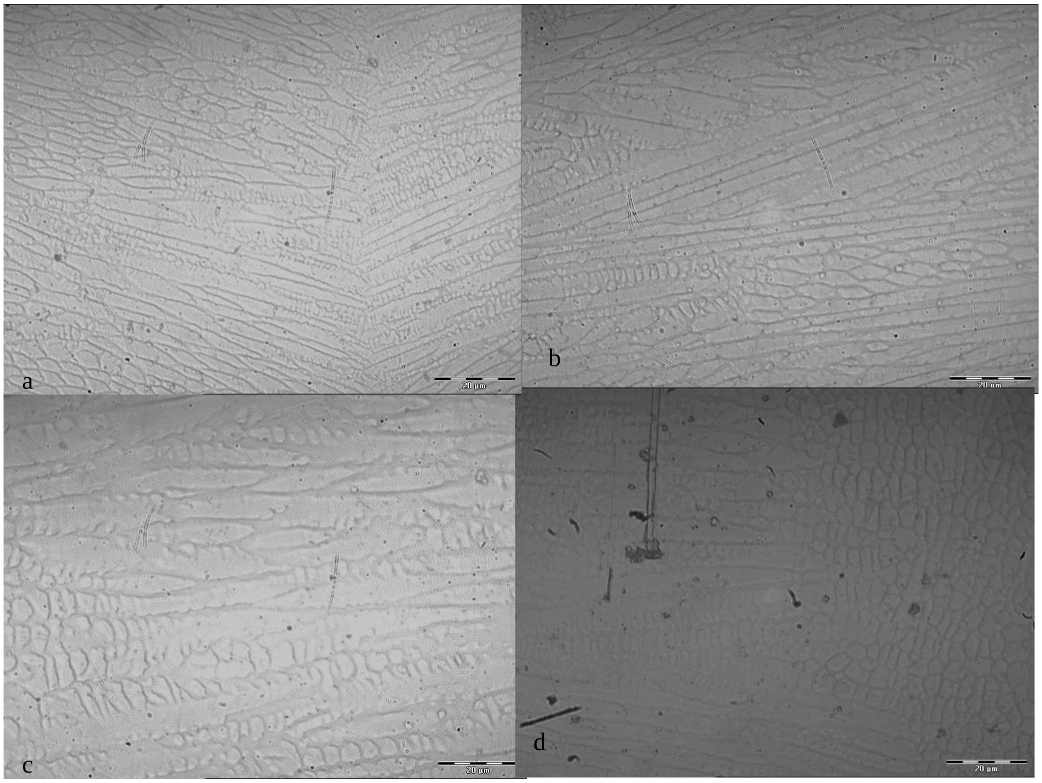


Figure 2 - Microstructure of weld metal, as-welded, 1000X, 15% Nital. a) Single spot BOP weld, b) single spot butt weld, c) twin spot butt weld, d) Pulsed Nd:YAG butt weld

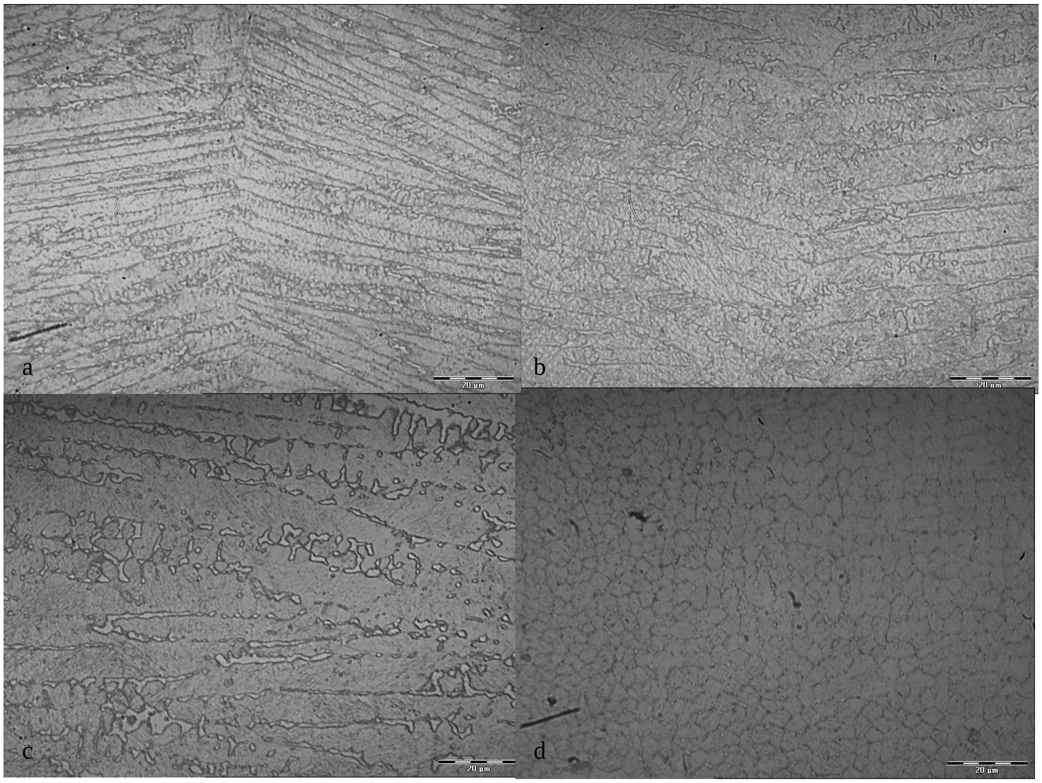


Figure 3 - Microstructure of weld metal centre line after PWHT @ 480ºC for 3h, 1000X, 15% Nital. a) Single spot BOP weld, b) single spot butt weld, c) twin spot butt weld, d) pulsed Nd:YAG butt weld

Figure 4 shows the microstructures of the weld metal near the fusion line after PWHT. The weld metal near the fusion line will be lower in alloying elements (Mo, Ti) and the tendency for formation of reverted austenite is therefore greatly reduced. Segregation of Mo and Ti will increase with the rapidly growing solidification front. More reverted austenite is therefore expected in the weld centre line. Very little reverted austenite was observed in the weld metal near the fusion line for the CO_2 laser welded samples with almost none for the single spot butt weld. However, more reverted austenite was observed near the fusion line for the pulsed Nd:YAG welds. This is a result of the re-solidification of the weld metal due to the overlapping spot welds. Little grain growth occurred in the high temperature heat affected zone due to the extremely low heat input of the laser welding process.

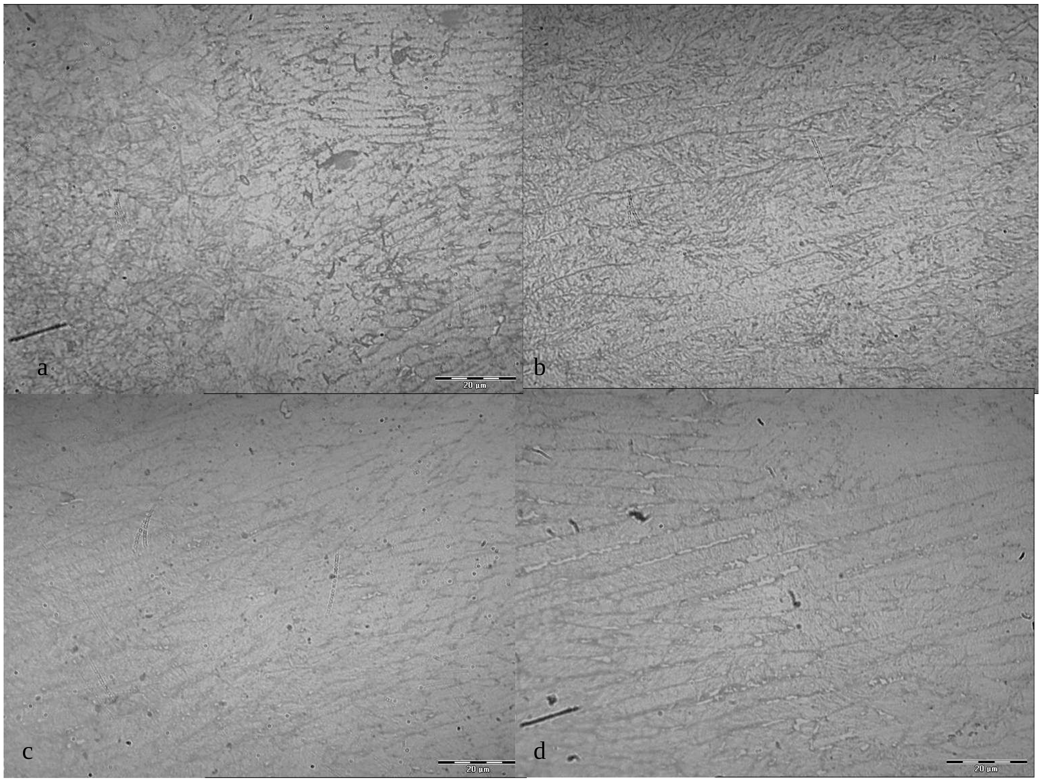


Figure 4 - ***Microstructure of weld metal near fusion line after PWHT @ 480ºC, 3h, 1000X, 15% Nital. a) Single spot BOP weld, b) single spot butt weld, c) twin spot butt weld, d) pulsed Nd:YAG butt weld***

SEM analysis

Scanning electron microscopy was performed to verify the segregation of Ti and Mo responsible for the formation of reverted austenite after PWHT. Shown in **Figure 5** are the SEM images of the single spot (SS/6), twin spot (TS/4) and pulsed YAG (PY) butt welds after PWHT. More reverted austenite was observed in the twin spot weld compared to the single spot and pulsed Nd:YAG welds. EDS (energy dispersive spectroscopy) analysis was also performed.

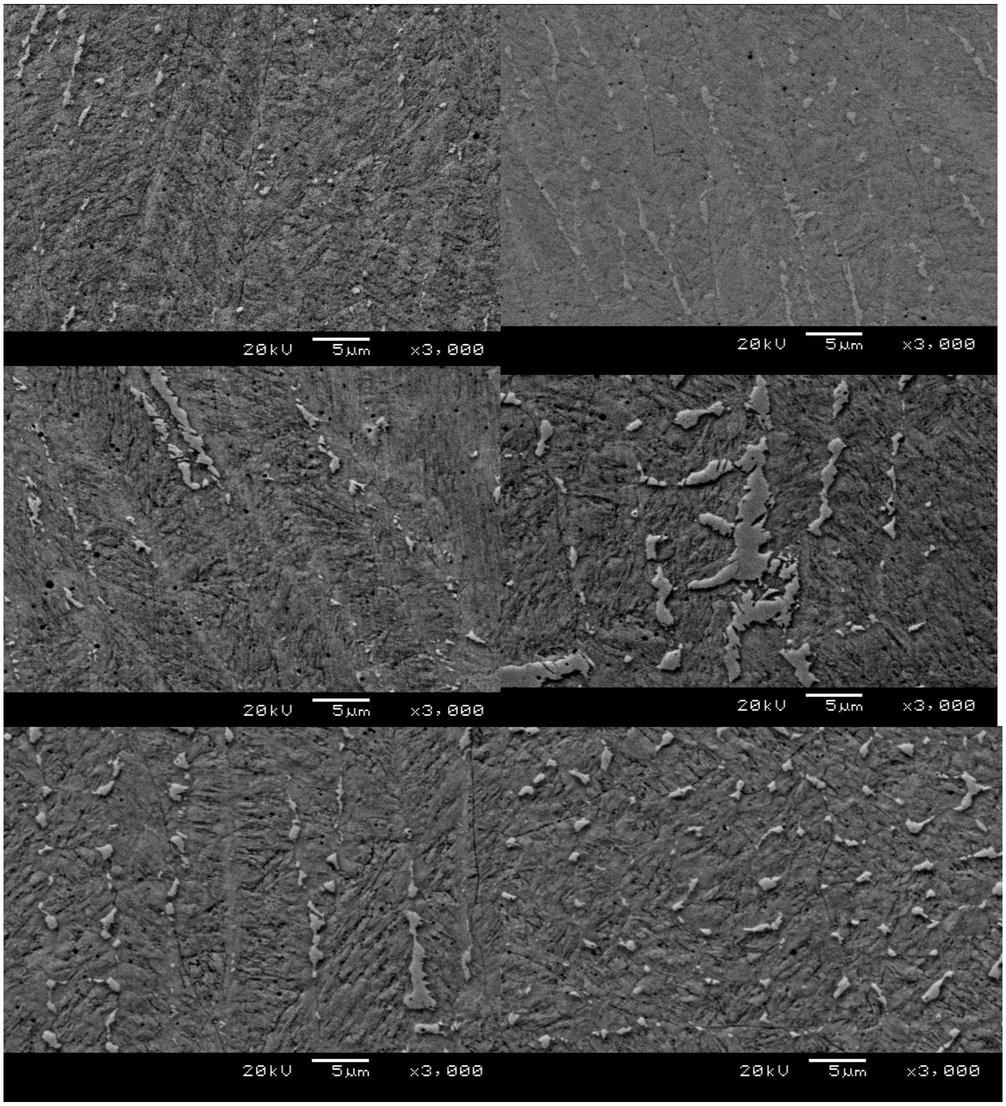


Figure 5 - ***SEM images of butt welds after PWHT, etched 12% Nital, a)SS/6 near fusion line, b) SS/6 weld centre line, c) TS/4 near fusion line, d) TS/4 weld centre line, e) PY near fusion line, f) PY weld centre line***

EDS line scans were performed in the unetched condition. Areas were observed that was enriched in Mo and Ti. Etched samples were analysed in the martensite and austenite and the results are shown in **Table 3**. Higher levels of Mo and Ti were observed in the austenite phase.

Table 3 - ***EDS analysis of butt welds after PWHT @ 480ºC, 3h***

Sample	**Fe**	**Co**	**Ni**	**Mo**	**Ti**
SS/6 – Martensite	70.09	8.47	17.38	3.81	0.18
SS/6 Austenite	66.21	8.57	18.63	5.92	0.6
TS/4 – Martensite	69.17	8.29	17.92	4.27	0.24
TS/4 – Austenite	65.26	8.16	18.72	6.73	1.09
PY – Martensite	69.37	8.27	18.07	4.06	0.18
PY - Austenite	62.61	8.87	19.01	7.75	1.64

Hardness

Shown in **Figure 6** is the micro Vickers hardness traverse across the weld after post weld heat treatment at 480C for 3 hours. Hardness measurements were taken at the weld face 0.2 mm below the surface. Applied load was 300g with an indentation spacing of 0.1 mm. The as-welded hardness of the weld metal and heat affected zone is reduced to below 350HV due to the dissolution of the semi coherent inter-metallic precipitates. The hardness of the base material is in the order of 600 HV_{300g}. After PWHT hardness levels in the weld metal increased to between 470 and 500 HV_{300g}. The lower hardness of the weld metal is due to under aging of the weld metal compared to the base material. The amount of reverted austenite does not seem to have a significant influence on the hardness of the weld metal.

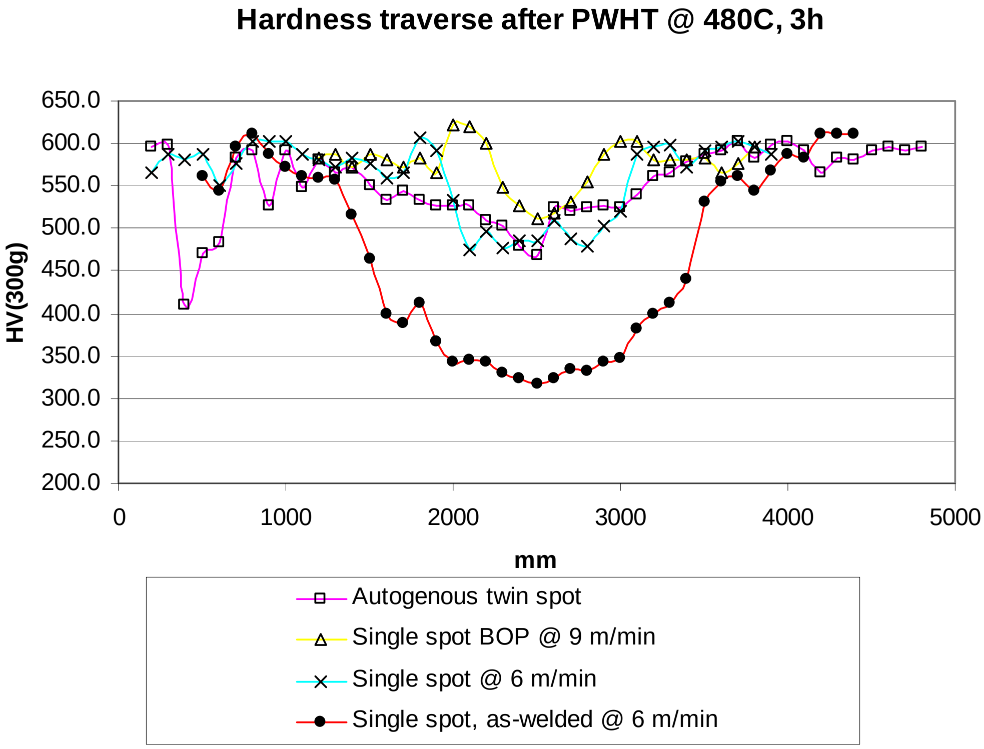
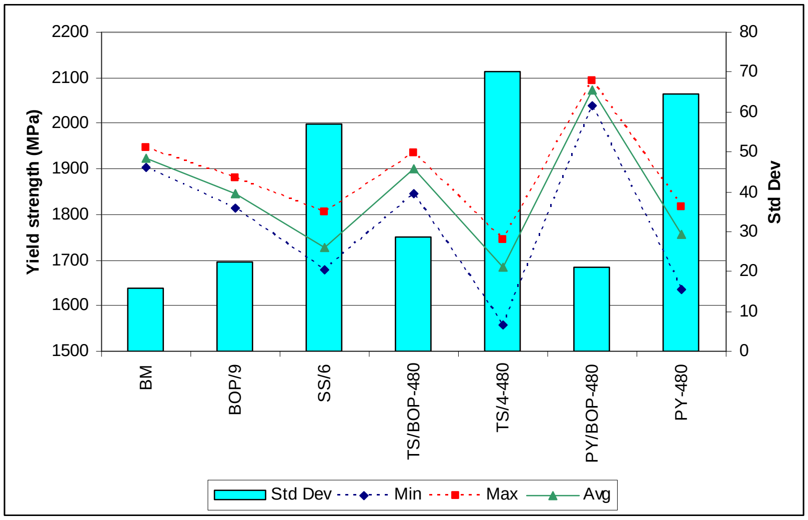


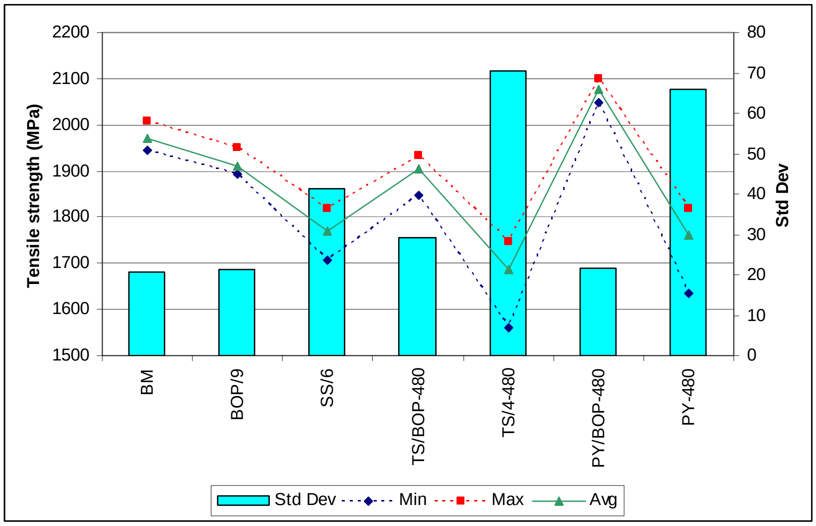
Figure 6 - Micro Vickers hardness traverse of butt welds after PWHT @ 480ºC, 3h

Tensile testing

Transverse tensile testing was performed after post weld heat treatment of 480ºC for 3 h. Tensile specimens were laser cut from the cylindrical test pieces. Yield strength, ultimate tensile strength and elongation results obtained are shown in **Figure 7**. All samples failed in the weld metal except two of the BOP samples @ 9m/min and two of the single spot butt weld @ 6 m/min.

The reduced mechanical properties of the autogenous butt welds result from a combination of misalignment, weld geometry and the presence of reverted austenite in the weld metal. Reverted austenite seems to have a significant influence on the mechanical properties transverse to the weld joint. However, the effect of misalignment is expected to have the greatest influence on transverse strength properties. Misalignment should be closely controlled to maximise weld integrity. The effect of reverted austenite is expected to reduce the mechanical properties with 50 – 100 MPa as shown in Figure 6 (TS/4 and PY). Lower PWHT temperatures will result in less reverted austenite [2]. A temperature of 450ºC and 6h tempering time was used to determine the effect of reverted austenite on mechanical properties. Under aging was however obtained for PWHT @ 450ºC for 6h. Further experiments will be performed with the tempering time increased to 8 h to increase the weld metal strength.





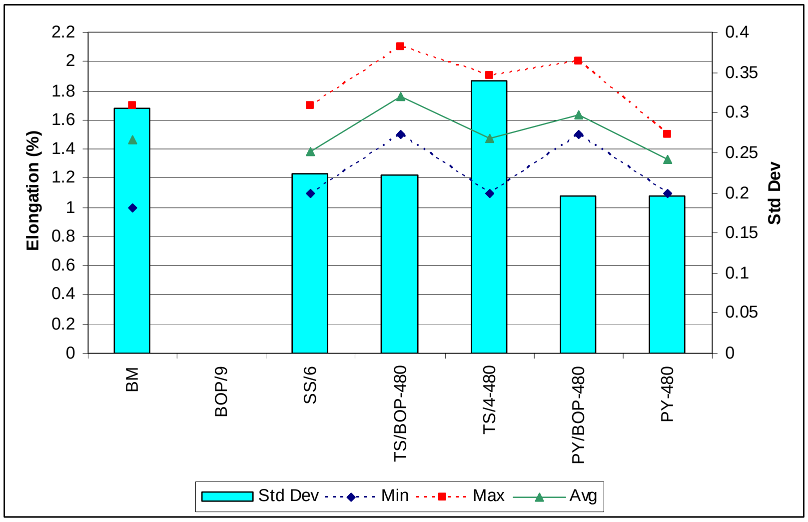


Figure 7 - Weld joint mechanical properties after PWHT @ 480ºC, 3h, ASTM E8-81

Future work

The repair procedure with filler material will be qualified with grade 200 filler wire. The chemical composition of the weld will be lower in Mo and Ti to minimise the levels of reverted austenite in the weld metal. The effect of misalignment on the mechanical properties of the welds will be quantified and the maximum allowable misalignment will be determined.

Conclusion

Laser welded single spot butt welds are very sensitive to joint alignment, joint gap and laser beam offset. Techniques like twin spot and pulsed Nd:YAG welding increased the operating window with regards to laser beam offset to 0.5 mm compared to 0.2 mm for single spot welding. The higher heat input of twin spot resulted in a higher fraction of reverted austenite after PWHT at 480ºC for 3h and reduced mechanical properties compared to pulsed Nd:YAG welding. The amount of reverted austenite does not seem to have a significant influence on weld metal hardness, but affect the tensile properties of the weld joint. The presence of contamination and misalignment has been found to have a profound impact on weld integrity. Pulsed Nd:YAG welding is the preferred process due to the large operating window, small amount of reverted austenite and excellent weld geometry.

References

1 D.G Lee, K.C Jang, J.M Kuk, I.S Kim, The influence of niobium and aging treatment in the 18% Ni maraging steel, Journal of Materials Processing Technology, 2005

2 C.R Shamantha, R. Narayanan, K.J.L. Iyer, V.M. Radhakrishnan, S.K. Sishadri, S. Sundararanja, ,S. Sundaresan, Microstructural changes during welding and subsequent heat treatment of 18Ni (250-grade) maraging steel, Materials Science and Engineering, 2000, pp 43 - 51

3 C.P. Wu, L.W. Tsay, C. Chen, Notched tensile testing of T-200 maraging steel and its laser welds in hydrogen, Materials Science and Technology, 2003, pp 302 – 309

4 RE Reed-Hill, R Abbaschian, Physical Metallurgy Principles, Third Edition, pp 452 - 458