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Deposition of Corrosion Resistant Alloy onto Low Alloyed Steel using LAAM for Oil & Gas Applications

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Abstract

In the oil & gas industry, a large number of components are designed with corrosion resistant cladding in order to prevent premature failures, rapid degradation and chemical induced cracking. Most of the surface components are made of carbon steel. However, in order to protect the inner-surface from erosion and corrosion, they are clad with corrosion resistant alloys including stainless steel and Ni-base alloys. Currently TIG/MIG cladding has been widely adopted in the oil & gas industry. However, there are several issues for TIG/MIG cladding. These include low conformance of the clad, lengthy pre-heating and post-weld heat treatment, as well as excessive post-machining time due to undesirable built up of clad material at intersecting holes. Laser aided additive manufacturing (LAAM) has advantages over traditional arc cladding processes for surface modification and repair. The key advantages include lower distortion due to lower heat input to the base material, higher conformance and clad integrity, less materials, manpower and energy needed.

In this paper, deposition of corrosion resistant alloy (CRA) onto low alloyed steel using LAAM was studied. Post heat treatment was investigated to achieve required mechanical properties. The results showed that the quality of the clad CRA can be significantly improved. Pre-heating is not necessary and the post heat treatment time can be reduced 50%. The tensile properties of the deposited material can meet the specifications for oil & gas applications.

Keywords: Laser aided additive manufacturing; inner-surface; corrosion resistant alloy; mechanical properties;

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1. Introduction

The exploration and production of oil and gas is spreading rapidly towards sub-seas and deep-water, largely due to the exhaustion of shallow wells. These new high pressure and high temperature (HPHT) wells are located in deep water and often exposed to unexpected levels of H_2S (hydrogen disulfide) and CO_2 gases, thereby exposing the oilfield equipment to extreme corrosion conditions and rapid degradation, requiring costly intervention. The costs of an unplanned intervention, retrieval and replacement of oilfield equipment can range between US$50m-70m. The oilfield equipment is also subjected to severe slurry and chemical erosion together with particulate and sand abrasion, operating at HPHT, deep-water and sub-sea and Arctic conditions. To prevent corrosion on valves, pipes and other oil field equipment, the exposure area is often protected with a high corrosion resistant alloy (CRA) clad overlay, for example Inconel 625, by cladding. TIG and MIG cladding are the dominant processes for both outer-surface and inner-surface cladding [Craig et al. 2011, Sherman 2013, Madadi et al. 2009]. On one hand, these processes have been already well-established and certified by the classification societies. On the other hand the costs of the equipment and operation are relatively low and the productivity is high, if cladding on flat surface.

There are some further developments of the TIG/MIG cladding techniques to increase the cladding efficiency. TIG hot wire cladding is one of them. The wire is pre-heated to certain temperature before it is fed into the melt pool. Furthermore, TwinArc TIG cladding process was developed, in order to further maximize TIG productivity for fusion and weld overlay of larger components. In this process two torches are attached to the same weld head to produce two individual TIG arcs. The two arcs are positioned diametrically opposite and hence have little heating influence on each other. An important requirement in cladding is that the two arcs produce clad deposits with similar fusion levels, iron content and heat inputs. In application terms, the two arcs can be used to clad at the same or different levels. The cladding time is reduced by up to 50% in bores greater than 4", compared to single arc TIG cladding.

In 2004, as a further development of the TwinArc™ concept, the company Powerelectronics developed the TwinArc™ MIG process. Two MIG arcs with hot-wire configuration are adopted. Meanwhile, pulsed MIG arcs are utilized to make the process better controllable with improved clad quality. This process has been granted approval for use on well head valve overlay applications and is accepted by a number of oil & gas companies. Several of the single and TwinArc™ versions of the SynerMIG™ systems have now been installed. In bores greater than 4 ", welding time has been reduced to less than 30% of that achieved with SingleArc hotwire TIG.

Another development of the arc cladding is the rotary arc cladding developed. Normally the components need to be rotated and the arcs remain stationary. Weld cladding of Oil & Gas industry wellhead valves poses particular problems due to their weights and complex shaped surfaces. In conventional welding of the internal bores of these valves, the component is physically manipulated such that the center of the bore to be welded is aligned to the center of the table rotation point. In multi-bore components, this means that the valve is being turned with its center of gravity 'off center' to the table axis of rotation. This results in accelerated wear of the supporting bearings and drive gears of the turntable.

All the further developments of arc cladding techniques mainly focus on the improvement of productivity. Most important, it is difficult to clad the intersecting bores and bores with ID smaller than 4” using arc cladding. Laser aided additive manufacturing (LAAM) or laser cladding can be a promising alternative technology to overcome these issues. LAAM yields high precision and homogeneity in depositing powder onto the base material. The overlays impart greatly improved performance of the desired characteristics such as wear resistance, impact resistance, sliding wear, corrosion protection, friction modification and specific electrical properties.

Laser cladding has been gaining more and more interests in the research society. There are many research publications related to improve the surface properties using various additive materials. Ocelík et al. 2007 studied laser cladding of Co-base material onto cast iron substrate. Good bonding strength and wear properties of the clad layer have been achieved. Zhou et al. 2010 investigated deposition of WC onto cast iron substrate using laser. Very hard surface coating has been obtained. Zheng et al. 2010 tried depositing Inconel 625 with Ni-coated TiC to improve the surface and mechanical properties of the deposited material. Aghasibeig et al. 2012 clad Fe–8.1Cr–6.4Mn–5.3Si–6.9Mo–3.6C alloy on AISI 1018 steel substrates using a diode laser. Analysis of the clad layers showed that an almost featureless structure was formed at different dilutions between 1% and 4%. The featureless phase shows a high hardness of 1155 HV. Mahmood et al. 2012 reported their work on laser clad corrosion protection for mild and harsh environments. This work examines the performance of protective layers of Inconel 617, laser clad in the form of salvaged machining chips, to protect a corrosive substrate from both mild and harsh environments. The clad layers are investigated for microstructure and phase composition and polarization measurements used to determine their corrosion resistance in neutral and acidified NaCl electrolyte solutions. Ocylok et al. 2010 from Fraunhofer ILT reported functionally graded multi-layers by laser cladding for increased wear and corrosion protection. Nowotony et al. 2007 from Fraunhofer IWS reported the results on laser cladding of materials include metal alloys (Co, Ni, Cu basis, Titanium, and steel), hard metals (e.g., WC/Co, TiC, and VC with metallic binders), and oxide ceramics (Al_2O_3/TiO_2). Similarly, Molian et al. 1989 from Iowa State University studied the laser cladding of Ti-6Al-4W with BN for improved wear performance. Deposition of Inconel 625 using laser was reported by Dinda et al 2009 from Michigan University. Andolfi et al. 2012 reported laser cladding of shafts for oil and gas components.

In recent years laser cladding of inner-surface is a very hot topic. Jung 2010 reported the research progress in inner-surface laser cladding. Bartels et al. 2011 filed a patent on laser cladding of tubes. A lot of efforts have been made to develop the inner-surface laser cladding tools.

In summary, laser cladding has been widely studied by the researchers and has been reported for some industry applications. However, in the oil & gas industry, the process is not well established and only limitedly adopted for outer surface cladding. No reports and publications of inner-surface cladding for oil & gas components can be found. This study aimed to explore laser aided additive manufacturing (LAAM) process to clad Inconel 625 onto steel 4130 for oil & gas applications. The clad integrity, post-clad heat treatment and mechanical properties of the clad samples were studied and analyzed.

2. Experimental Procedure

2.1. Experimental setup

In this study a robotic laser aided additive manufacturing system with 6 kW fiber laser from IPG Photonics was adopted. The robot has six axes and an extra rotary. The laser is in continuous wave mode with wavelength of 1060-1070 nm. The inner-surface laser head integrated with optical head and powder feeding unit was mounted onto the robot arm. Argon gas was used to feed the powders and functioned as shielding gas to protect the melt pool from undergoing rapid oxidation at elevated temperature. A Twin 10-C powder feeder from Sulzer Metco was utilized to deliver the powders to the melt pool.

2.2. Materials

Gas atomized Inconel 625 powders were used in this study. The powders were in spherical shape with diameter in the range of 20-45 µm. Chemical composition of the powders in weight percentage is shown in table 1. Table 2 lists the chemical composition of the 4130 steel substrate from BGH Edelstahl Siegen GmbH. The material was normalized at 885 °C for 6 hours, then water quenched and tempered at 655 °C for 12 hours.

Table 1 Chemical composition of the Inconel 625 powders

Element	Ni	Cr	Co	Mo	Al	Ti	Fe	C	Si	CbTa
wt%	Bal	21.96	0.04	9.2	0.05	0.1	1.99	0.02	<0.1	3.75

Table 2 Chemical composition of the 4130 steel

Element	Fe	Ni	Cr	Mo	Al	Mn	P	C	Si	Cu	Cu	H (ppm)
wt%	Bal	0.2	1.06	0.21	0.041	0.56	0.004	0.314	0.28	0.074	0.074	0.074

2.3. Methodology

Preliminary study using flat samples were conducted for process development. Following the flat samples, mock samples with desired ID was used for the further development and benchmarking study. All the experiments were conducted without preheating of the 4130 substrate, which is necessary for arc cladding using the same materials. For process development, the clad quality needs to be considered. This includes low porosity, low dilution, crack-free, short post-clad heat treatment, acceptable hardness in HAZ and good tensile properties. Post-clad heat treatment was conducted to compare the material properties under different conditions. One batch of samples was heated to 635 °C and held for 8 hours and then cooled in furnace to room temperature. It is the same as the post-clad heat treatment specified for arc welding by American Petroleum Institute (API) standard. Another batch of samples was heated to the same temperature but held for 4 hours. Fig. 1 shows the schematic drawing of the clad sample for various tests and sectioning the coupons for the all-clad tensile test. Besides the all-clad tensile test, transverse tensile test was also conducted, as specified by the API and NACE standards for oil & gas applications. Fig. 2 shows the preparation of the test coupons schematically. A 60° v-groove was pre-machined in the 4130 substrate. Then Inconel 625 powders were deposited into the v-groove, as shown in Fig. 2a. The tensile test coupons were sectioned transverse the v-groove to include the base material and the deposited Inconel 625, as shown in Fig. 2b.

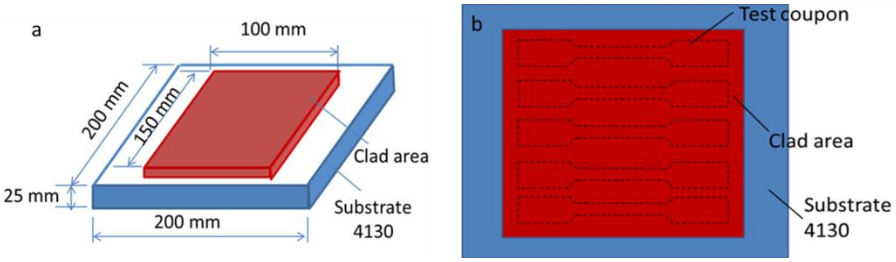

Fig. 1 Schematic drawing of (a) the clad sample and (b) top view of sectioning the all-clad tensile test coupon

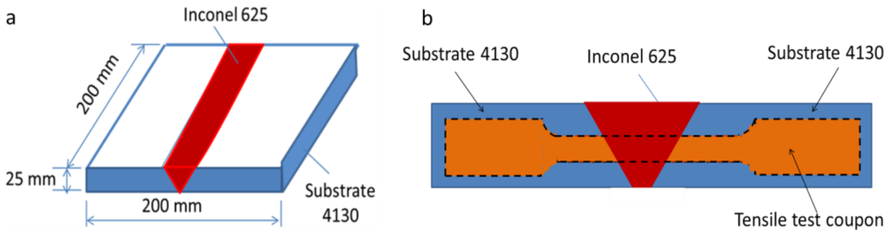

Fig. 2 Schematic drawing of (a) the clad sample and (b) front view of sectioning the transverse tensile test coupons

2.4. Material characterization

After experiments the samples were sectioned and polished down to 0.05 µm finish, and then etched using 5% Nital to study the micro-structure of steel 4130 in the HAZ and unaffected base material. Microstructures were examined by optical microscope (GX51, OLYMPUS) and SEM (EVO-50 & ULTRA plus, Carl Zeiss) with simultaneous elemental analysis using EDS (X-Max, Oxford Instruments). Micro-hardness was examined using Matsuzawa MMT-X3 Vicker's hardness tester with a testing load of 500 grams and holding time of 15 seconds. Tensile tests were conducted at room temperature using Instron 4505 tensile test machine.

3. Results and discussion

The LAAM process parameters were studied to achieve reasonable clad. The optimized process parameters are as follows: laser power 4 kW, powder feed rate 40 g/min, speed 600 mm/min. Average single layer thickness of 1.8 mm was achieved. No cracks can be observed in the base material as well as in the deposited Inconel 625. According to API and NACE standards for oil and gas applications, there are stringent requirements on dilution, heat affected zone (HAZ) hardness, tensile properties of all-clad and transverse clad for CRA clad components. In this section the results pertaining to the required material properties will be discussed in detail.

3.1. Dilution and HAZ hardness

Dilution is defined as the amount of intermixing of the deposited material and the base material. Dilution will degrade the properties of the deposited material. Hence, it should be controlled as low as possible. Due to the high heat input which will cause high dilution during arc cladding, it is a common practice to pre-machine minimum 3 mm of the base material and then deposit 6 mm Inconel 625, in order to fulfil the API required Fe content < 5 wt % measured at 3.2 mm from the fusion line. This causes long machining time and waste of expensive Inconel 625.

In this study, 3.5 mm Inconel 625 in two layers was deposited onto the substrate, without pre-machining of the substrate. The Fe content was measured using EDS line scan for the as-deposited, and heat treated samples. Fig. 3 shows the results of the Fe content measured from the fusion line to the deposited Inconel 625. It can be observed that the Fe content is 3.2 wt % for the as-deposited sample, 3.5wt% for the sample heat treated for 4 hours and 4.6 wt% for the sample heat treated for 8 hours, respectively. Longer heat treatment can cause more Fe diffused to the deposited Inconel 625. This can be verified by the increased percentage of Fe detected for the sample heat treated for 8 hours. The Fe-content for all the samples is below the API specified <5 wt%, even within 1 mm range, in comparison to 3.2 mm from fusion line. This is of significant importance for the cladding process. On top of the improvement of the dilution control, obvious machining time and cost saving can be realized using laser to deposit Inconel 625 onto AISI 4130 for oil & gas applications.

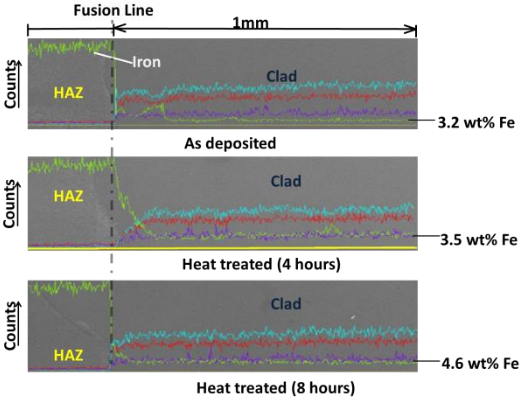

Fig. 3 EDS line scan for Fe content

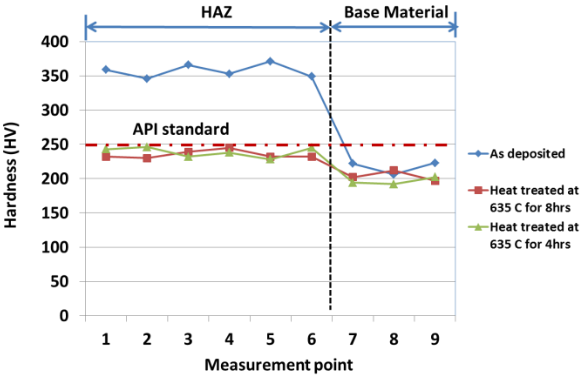

Fig. 4 Hardness measurement in HAZ and base material

Furthermore, hardness of HAZ is another key factor for cladding Inconel 625 onto AISI 4130 for oil & gas equipment. High hardness in HAZ will create potential cracking issues. As a result, the HAZ hardness needs to be maintained below 250 HV as specified by the industry standards. The measured hardness across the base material and HAZ is shown in Fig. 4. The hardness of the original base material is about 200 HV. The hardness in the HAZ of the as-deposited sample is obviously much higher than the base material, also severely exceeds the minimally required 250 Hv. After heat treatment, the HAZ hardness can be effectively reduced below 250 Hv to meet the requirements. Hardness of the samples heat treated for 8 hours and 4 hours is nearly the same. It is highly related to the micro-structure in different regions. It will be further analyzed in section 3.2. This result is quite promising for the industrial applications. If the post clad heat treatment can be shortened in half, a lot of energy and time can be saved. This will link to significant productivity improvement and cost saving.

3.2. Microstructure and interface

The microstructure determines the hardness, as well as the tensile properties of the material. Hence, the microstructure in HAZ and base material was intensively studied to further elaborate the obtained hardness shown in section 3.1.

Fig. 5 shows the optical micro-structures examined in original base material and HAZ, which was taken in the cross-section of the deposited samples. It can be clearly observed that in comparison to the base material, finer grains in HAZ were formed, even after post-clad heat treatment. Main microstructure of the original base material is austenite, as shown in Fig. 5a. During the deposition process, the resultant temperature in HAZ exceeded the phase transformation temperature. In combination with the fast cooling of the sample, martensitic microstructure was formed. When the austenite was cooled rapidly, the carbon diffusion was restricted. The face centered cubic crystal structure of austenite was transformed into the body centered tetragonal structure of martensite. This caused the significant increase of hardness in HAZ for the sample without post-clad heat treatment, as shown in Fig. 4.

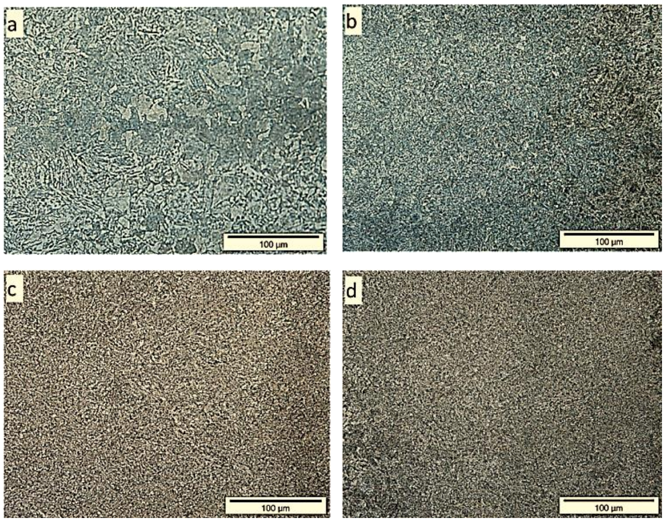

Fig. 5 Optical image of the (a) original base material, (b) HAZ of the as-deposited sample, (c) HAZ of the sample heat treated at 635 °C for 4 hours and (d) HAZ of the sample heat treated at 635 °C for 8 hours

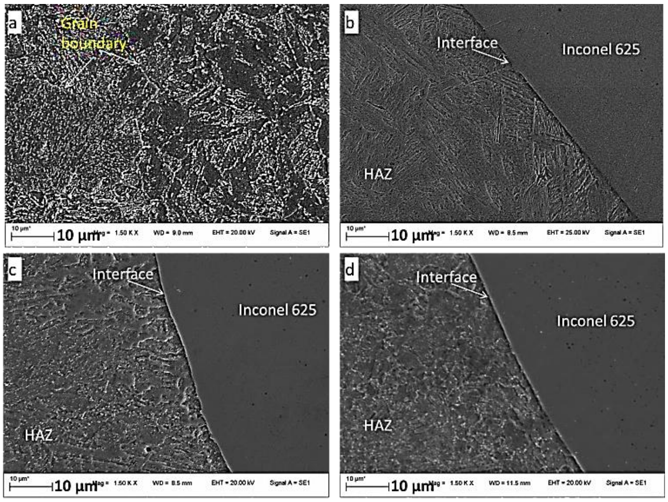

Fig. 6 SEM image of the (a) original base material, (b) HAZ of the as-deposited sample, (c) HAZ of the sample heat treated at 635 °C for 4 hours and (d) HAZ of the sample heat treated at 635 °C for 8 hours

To identify the effect of heat treatment on the microstructure and hardness in HAZ, SEM was adopted to further magnify the microstructure. As shown in Fig. 6a, austenite with carbides can be identified. Grain boundaries are also clearly seen. In Fig. 6b, fully martensitic microstructure is dominant. Very clear needle like martensites were formed. After heat treatment at 635 °C for 4 hours and 8 hours, the HAZ was tempered. The microstructure was transformed to tempered martensite with significantly reduced hardness than martensite. This is in accordance with the obtained hardness in the base material and HAZ for the as-deposited and heat treated samples. Heat treatment for 4 hours and 8 hours did not make any obvious difference in microstructure and resultant hardness in HAZ. It means that it is possible to shorten the post heat treatment for components clad with LAAM.

Furthermore, a very clear and clean interface between the base material and the deposited Inconel 625 can be observed. This phenomenon verified that the mixing between AISI 4130 and Inconel 625 during the deposition process was limited due to the fast melting and solidification. This can further explain the low Fe content detected in the deposited Inconel 625.

3.3. Tensile properties

Tensile properties of the clad samples need to fulfil the requirements for oil gas applications. As described in section 2. 3, both all-weld and transverse tensile tests were conducted in this study. The results are summarized in Fig. 7.

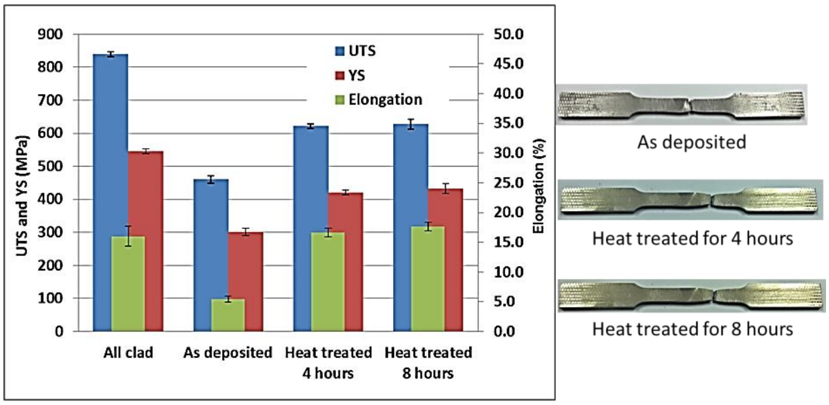

Fig. 7 Tensile properties of the all-clad Inconel 625, transverse tested samples of as-deposited, as well as heat treated for 4 hours and 8 hours

The ultimate tensile strength, yield strength and elongation of the deposited Inconel 625 are 840 MPa, 545 MPa and 16%, respectively. The tensile properties are within the API specifications. The results of the transverse tensile test show that the as-deposited sample has the much worse tensile properties compared to the heat treated samples. The test coupon was broken in the HAZ region, whereas the heat treated coupons broke in the unaffected base material, as shown in Fig. 7. This can be linked to the micro-structures analyzed in section 3.2. As fine martensites were formed in the HAZ of the as deposited sample, the HAZ became very brittle with reduced ductility. As a result, the tensile properties showed low strength and elongation. After heat treated at 635 °C for 4 hours and 8 hours, the fine martensites in HAZ were transformed to tempered martensites. This kind of microstructure exhibits better strength compared to the original AISI 4130. Hence, the failure happened in the base material outside the HAZ. The results also show that no obvious difference of the tensile properties can be seen for the heat treated samples for 4 hours and 8 hours.

4. Trials on AISI 4130 pipe

Based on the results obtained, the material properties are in the range specified by API. The process parameters are adoptable to deposit Inconel 625 to the inner-surface of AISI 4130 pipe. Fig. 8a shows the

LAAM process. The bore diameter is 125 mm. Wall thickness is 25 mm. With the developed process parameters, a stable deposition process was achieved. Very smooth clad surface can be observed.

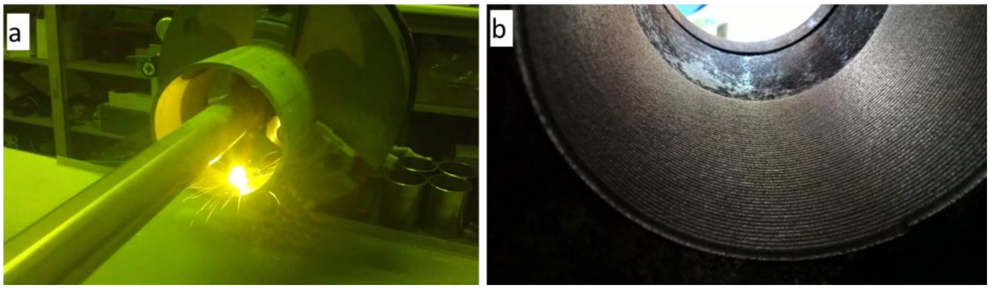

Fig. 8 (a) Photo of LAAM process for deposition of Inconel 625 to AISI 4130 inner-surface and
(b) Top-view of the surface of the deposited Inconel 625

5. Conclusions

Deposition of Inconel 625 onto AISI 4130 alloyed steel using LAAM was studied for oil & gas applications. Material properties were examined to benchmark with API standard. Based on the results and analyses, the conclusions can be summarized as follows:

- Due to the much lower heat input of LAAM than TIG cladding, HAZ cracking can be eliminated without pre-heating of the substrate.
- Phase transformation occurred in the HAZ. Needle like martensites formed in the HAZ of the as-clad sample. This hard phase significantly affected the micro-hardness and tensile properties of the material.
- Post-clad heat treatment is necessary to reform the microstructure, so that both the HAZ hardness and tensile properties can be modified to meet the requirements. However, it is possible to shorten the holding time.
- Tensile properties of the deposited Inconel 625, the HAZ hardness and tensile properties of the heat treated samples can meet the specifications for oil & gas applications.
- LAAM is proven promising for cladding CRA to alloyed steel for oil & gas applications.

6. Future work

Further study is necessary to develop customized tools for different size and geometry of the bores. Deposition process needs to be investigated for more material combinations. New industry standards needs to be set up, as current standards are only applicable to arc cladding.

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