Enhanced Mechanical Properties of TMCP Clad Line Pipes by Explosion Welding

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ABSTRACT

The development of gas fields in harsh environments presents challenges to both designer and producers of clad pipe. The final product is often required to have a demanding combination of properties while remaining economically attractive. Some clad pipes can offer a beneficial combination of strength and excellent toughness of the thermo-mechanically controlled process (TMCP) carbon-manganese steel with the superior corrosion resistance of the internal clad layer. Toughness is a key issue when pipes are transporting compressed gas as fracture propagation is a major concern to high pressure lines. In this case, drop weight tear (DWT) tests are necessary to assess the transition temperature of the pipes while resistance against propagating fracture is verified by means of Charpy impact tests.

Explosion welding (EXW) is a method with which the clad material is bonded to the carbon-manganese steel utilizing the energy released by explosives. Due to the nature of the process, it is possible to sustain the favorable properties of the TMCP steel, especially the good toughness in terms of both DWT and Charpy impact characteristics. The decoupling of plate rolling and cladding process by explosion welding allows manufacture of clad TMCP line pipe steel plates that exceed the limitations set by roll-bonded clad steels.

This paper presents results of a dedicated study on toughness properties of TMCP pipe material that underwent the explosion welding process for cladding with Alloy 825 and 625. A range of material and wall thicknesses up to around 40 mm has been included to demonstrate the feasibility of this method. Toughness is characterized in terms of both Charpy impact and DWT transition curves to assess the properties before and after explosion welding.

Excellent low temperature toughness as is increasingly required in recent projects was found in the investigated pipe materials.

INTRODUCTION

Longitudinal welded pipes serve as part of pipelines, including subsea flowlines and risers, to transport fluids under high pressure. The most widely used material is thermo-mechanically controlled processed (TMCP) material that combines high strength and excellent toughness with good weldability. When transporting highly corrosive fluids or following a process design without inhibition, the TMCP carbon steels has its limit. In these cases, where the corrosive properties do not suffice for dedicated requirements, clad line pipes are frequently the first choice.

To date nearly the entire demand of metallurgical bonded clad line pipe steel plates are manufactured by roll-bonding. This is achieved by hot rolling a sandwich with a symmetric design, consisting out of two backer steel slabs on the outside and two corrosion resistant alloy plates in the inside; a separation agent between the two CRA plates ensures that the finished clad plates are easily separable. Due to thickness of the sandwich and the rolling parameters needed to achieve a sound bonding of the materials, a TMCP rolling optimized with regard to mechanical properties cannot always be applied. This in turn does not allow the final product to achieve the same toughness properties, especially drop weight tear test properties, in line pipes of the same strength level as compared to carbon-manganese steel pipes made from optimized TMCP steels.

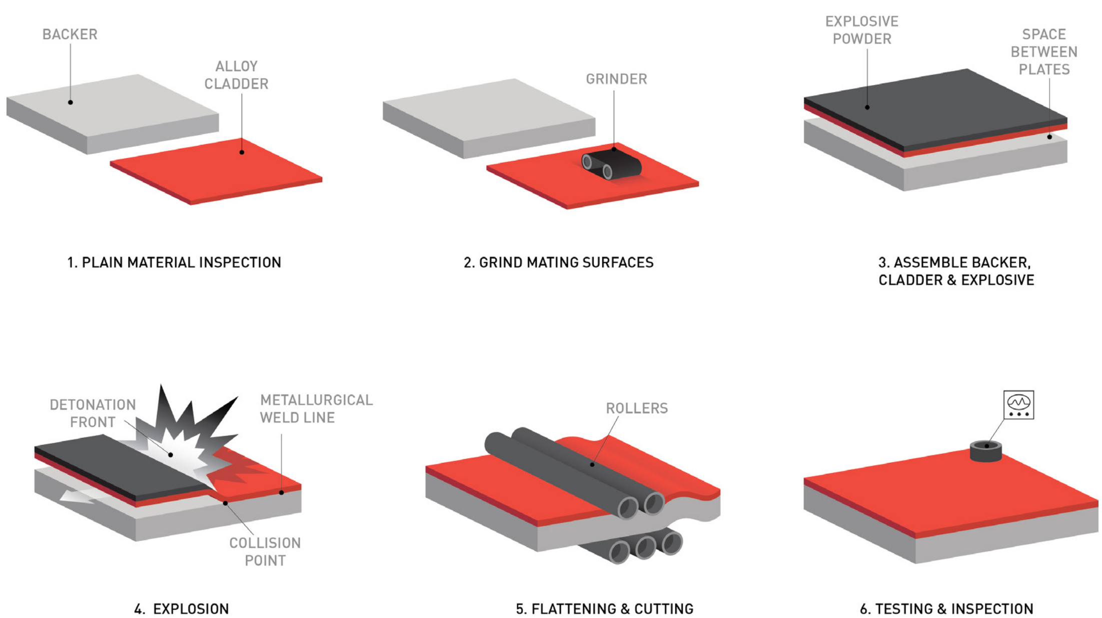
To take advantage of all properties provided by modern advanced TMCP line pipe steel in clad pipes, the process of plate rolling and metallurgical bonding of cladder and backer material can be decoupled by means of explosion welding. The backer steel plate and the CRA sheet are manufactured separately and subsequently welded onto each other in a dedicated production step. Due to the fact that the microstructure is not changed by the explosion welding process, the advanced TMCP steel properties are kept.

BACKGROUND

EXPLOSION WELDING PROCESS OF TMCP LINE PIPE STEELS

Explosion welding is a solid state welding technology specified in European and American standards which is used to manufacture large clad metal plates. The technology was developed and commercialized in the 1960's by DuPont; since 1962 this technology is a commercially viable solution. EXW is accomplished by creating a high-velocity collision between two metal plates. The explosive detonation causes shock loading of one of the metals, the flyer plate (cladder), accelerating it downward, causing

FIGURE 1: EXPLOSION WELDING PROCESS FLOW DIAGRAM



an oblique impact with the other metal, the backing plate (backer). It is necessary that this impact has sufficient energy to cause the colliding metal surfaces to flow hydrodynamically. Due to the angularity and the extremely high velocity of the collision a jet is created during the welding process. This jet, ejected outward from the collision point, removes oxides and impurities and activates the metal surfaces. The activated metal surfaces are then forced together under high pressure, resulting in an electron-sharing metallurgical bond between the two metal components.

These characteristics in turn allow the manufacture of clad line pipe steel plates that fully utilize modern TMCP line pipe steel production. The EXW cladding was performed by NobelClad. Figure 1 shows the flow diagram of the explosion welding process.

After incoming inspection, the plates are ground to remove any mill scale or contaminations of the mating surfaces before assembling the pack. Spacers are placed on the base steel plate, the corrosion resistant alloy sheet over that and then the explosive powder on top. In a shooting chamber, the explosive is detonated near the center of the plate and progresses concentrically over the entire plate. In about 2-3 ms, the clad plate is fully bonded. Flattening, grinding (if needed), and final inspections complete the production.

FRACTURE CONTROL - THE ROLE OF TOUGHNESS IN LINE PIPE APPLICATIONS

Fracture control is one of the prime requirements for any structure. Whereas most types of structures are designed to resist fracture initiation only, pipelines notionally are always exposed to the risk of a fracture initiating, even when meeting the requirements to prevent fracture initiation. The most common cause for pipeline failure is external interference, which can inevitably lead to initiation of a fracture. As compressible media have the characteristic feature of feeding the crack constantly with energy, it is mandatory to design against fracture propagation as well.

Designing against fracture initiation for pipes is comparable to that of most other structures. It is based on Charpy V-notch (CVN) impact toughness to ensure a minimum resistance to the initiation of a crack. Unlike typical structural design, the design to control the risk of propagating fractures in pipes is unique. The approach is two-fold, based on Drop Weight Tear Tests (DWTT) to control propagating brittle fractures and once again CVN toughness, but now on a much higher level than before, to arrest propagating ductile fractures.

The Battelle Drop Weight Tear (BDWT) test as the common laboratory test method to determine fracture propagation characteristics of pipe line steels was developed in the 1960s at the Battelle Memorial Institute in order to establish, if pipe materials fail in a ductile manner at certain temperatures. By comparing shear area fractions of pipes in full scale burst tests with shear areas evaluated from BDWT specimen fracture surfaces, it was shown that 85% shear area in the BDWT test would be sufficient to avoid brittle fracture propagation in pipe.

DWT tests are dynamic three-point bend tests of notched specimens, somewhat similar to CVN tests but usually sampled from the full wall thickness in order to incorporate the thickness effect and reflect the ability of the pipe to resist fracture propagation. The test was developed when the common wall thickness of pipes was such that CVN and DWT tests were hardly different in their through-thickness dimensions. In these cases, the energy needed to fracture the specimens is not very large. In the meantime, with line pipes having wall thicknesses of more than 40 mm, the energy needed to break the specimens exceeds the limits of several existing testing machines. Therefore, in reaction to this development, the test standards for DWT testing allow for testing of sub-size specimens with a thickness of 19 mm. To compensate the effect of wall thickness on toughness, sub-size specimens have to be tested at reduced temperatures which are detailed in the test standard. To date, this temperature compensation takes into account a wall thickness of up to 39.7 mm, for which a reduction of the test temperature of 17 °C is required. Therefore, pipes with a wall thickness of more than 40 mm are currently not clearly covered by the test allowance for sub-size specimens.

While the DWT test is generally known to work for many years, recent research has been focused on a feature known as inverse fracture, which is linked to TMCP material to date. In this case, the requirement for brittle initiation under the notch of the DWTT specimen is violated in conjunction with formation of brittle fracture on the impact side of the specimen. Formally, such results are rated invalid. There is no further guidance in the test standard regarding further action to take in such cases. The discussion in the literature indicates that inverse fracture may be a test effect, making the test results questionable. There are some indications that the upper transition, in the range of the typically required 85 % shear area in DWT tests, is conservatively described by DWT tests when inverse fracture forms on the fracture surface.

While the requirements for CVN to arrest propagating fractures are in the range of 40 J to 150 J, in dependence of pipe geometry, strength and operating conditions (such as the mixture and pressure of the gas), there is only one unique requirement for shear area fraction of DWT specimens, typically 85 % as mean value. The only variable for DWT requirements is the test temperature, which is linked to the design temperature of the pipeline. A typical minimum design temperature is -10°C, which suffices for many operating pipelines. Recently, there has been a trend to specify lower test temperatures, which may be linked to arctic or other cold environments, or could be used to account for Joule-Thompson effects occurring in operation.

EXPERIMENTAL PROCEDURE

Three TMCP line pipe steels of two strength levels, X65 and X70, in thickness of 18 mm, 24 and 42 mm were investigated. Table 1 details the materials.

TABLE 1: TESTED MATERIAL

No.	Backer Steel	Backer Thickness	Cladder Alloy	Cladder Thickness	Pipe Diameter
1a	API 5L X65MS	24.1 mm	without EXW clad		plate only
1b			Alloy 625	3.8 mm	16 inch
2a	SAWL 485ME	18.3 mm	without EXW clad		plate only
2b			Alloy 825	4.0 mm	
3a	SAWL 485FD	42.0 mm	without EXW clad		46 inch
3b			Alloy 825	4.0 mm	

In trial #1 test samples were cut before and after explosion cladding. A clad plate 12 m long was formed and longitudinally welded to a pipe with an OD of 16 inch. Some of the subsequent tests were conducted on material in the stress relieved condition. Trial #2 included testing of the plate before and after explosion welding. In trial #3 two plates of the same heat and rolling campaign were investigated. 3a was formed to a 46 inch pipe and tested, 3b was explosion welded, formed to pipe and tested.

The aim was to investigate the effect of explosion cladding on toughness properties of TMCP line pipe steels. Therefore, both the un-clad and the explosion cladded state were investigated by means of toughness tests. Table 2 gives an overview of the tests conducted within this study.

TABLE 2: TESTS AND CONDITIONS

No.	Clad Condition	Product	Heat Treatment	Tests
1a	un-clad	plate	none	CVN-impact DWTT 19 mm specimen DWTT full thickness specimen
1b	EXW clad	plate	none	CVN-impact DWTT full thickness specimen
			stress relieved	CVN-impact
		pipe 16"	none	CVN-impact DWTT full thickness specimen
			stress relieved	DWTT full thickness specimen
2a	un-clad	plate	none	DWTT full thickness specimen
			stress relieved	
2b	EXW clad		none	
			stress relieved	
3a	un-clad	plate	none	DWTT full thickness specimen
	EXW clad			
3b	un-clad	pipe 46"		
	EXW clad			

The focus of the investigation was drop weight tear testing, as DWT is the more challenging test in terms of the requirements, especially for thick wall pipes.

The tests were conducted in accordance to API 5L3:2014. The specimens were extracted in transverse direction and fully flattened. The clad material was removed on a width of around 80 mm in the centre of the specimens, the location in which the fracture is expected to propagate. The specimens were tested with a standard press notch and assessed according to the prevailing standard. In case inverse fracture occurred, the rating remained the same, effectively counting any brittle fracture on the surface.

RESULTS AND DISCUSSION

The CVN-impact test results of #1 are given in Figure 2.

It can be seen that all values, CMn-steel plate as rolled, EXW clad plate with and without stress relieving and the clad pipe are at the same CVN-impact toughness level down to -40 °C on the upper shelf. At -60 °C the heat treatment shows a clear effect,

FIGURE 2: CVN-IMPACT TEST RESULTS #1

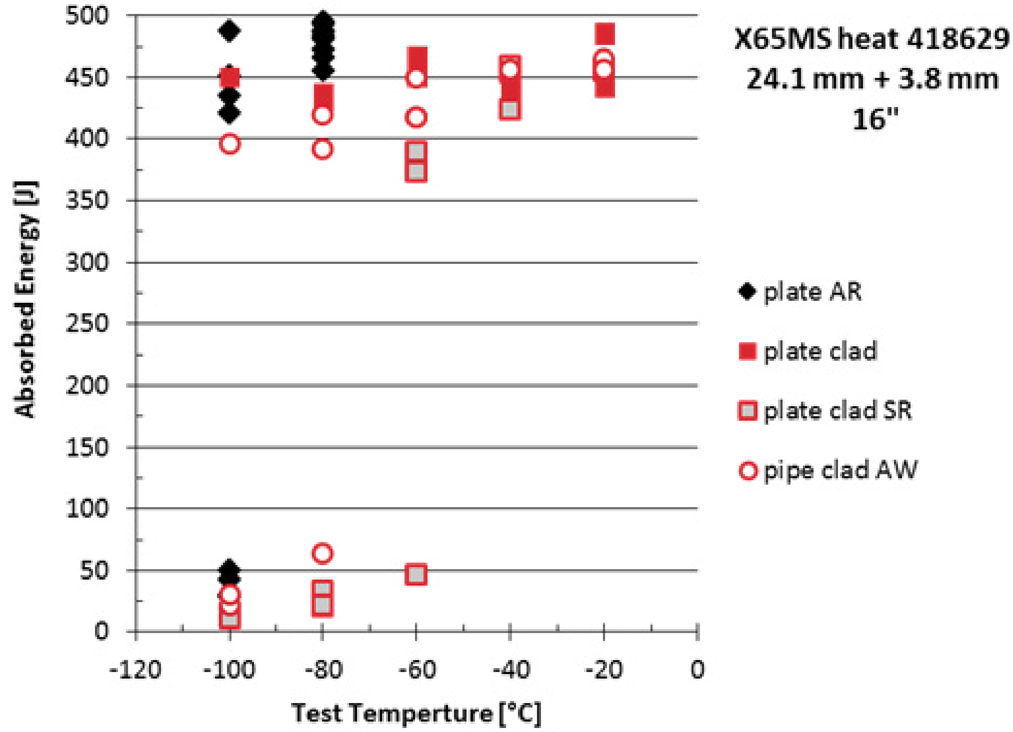
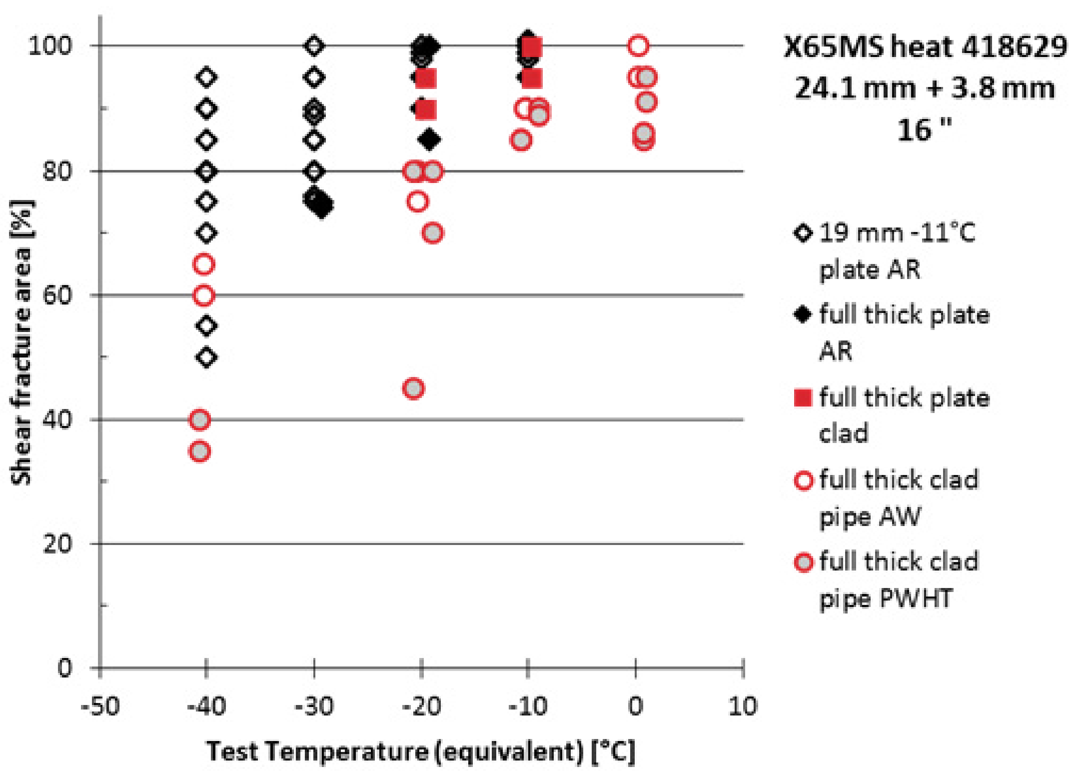


FIGURE 3: DWTT RESULTS #1



the values are in transition. At -80 °C the un-clad plate as well as the explosion welded clad remain on the upper shelf, stress relieved clad plate is in the lower shelf and the clad pipe in the transition area. At -100 °C, the un-clad and EXW clad plate are reaching the transition area.

No degrading of impact toughness, after explosion welding, could found. In contrast, a clear effect of heat treatment and cold deformation through pipe forming, forming degree 6.9%, was found to shift the transition temperature higher.

DWTT results of the material #1 are presented in Figure 3.

Shear fracture values are sufficient above 80% at temperatures to -10 °C. At a test temperature of -20 °C, the toughness values are degraded by pipe forming and post weld heat treatment. At 30 °C the values of the base material start to scatter, too. The values of the reduced thickness samples are tested according to API RP 5L3 table 1 with a temperature reduction of 11 °C, the coverage with the full thickness samples is sufficient.

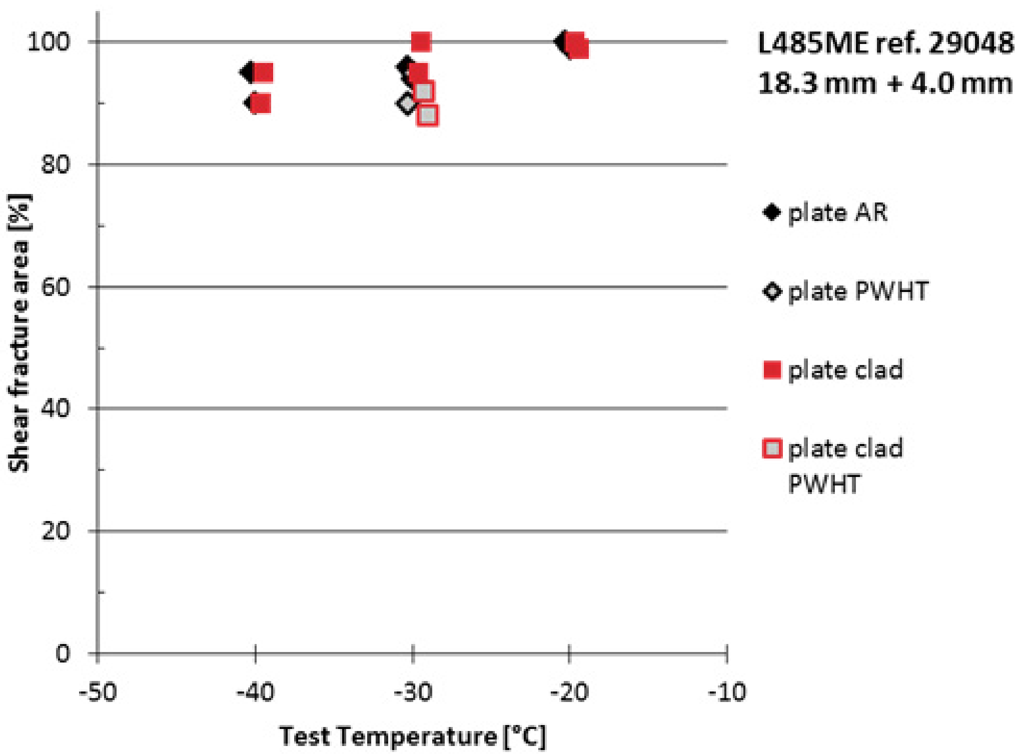


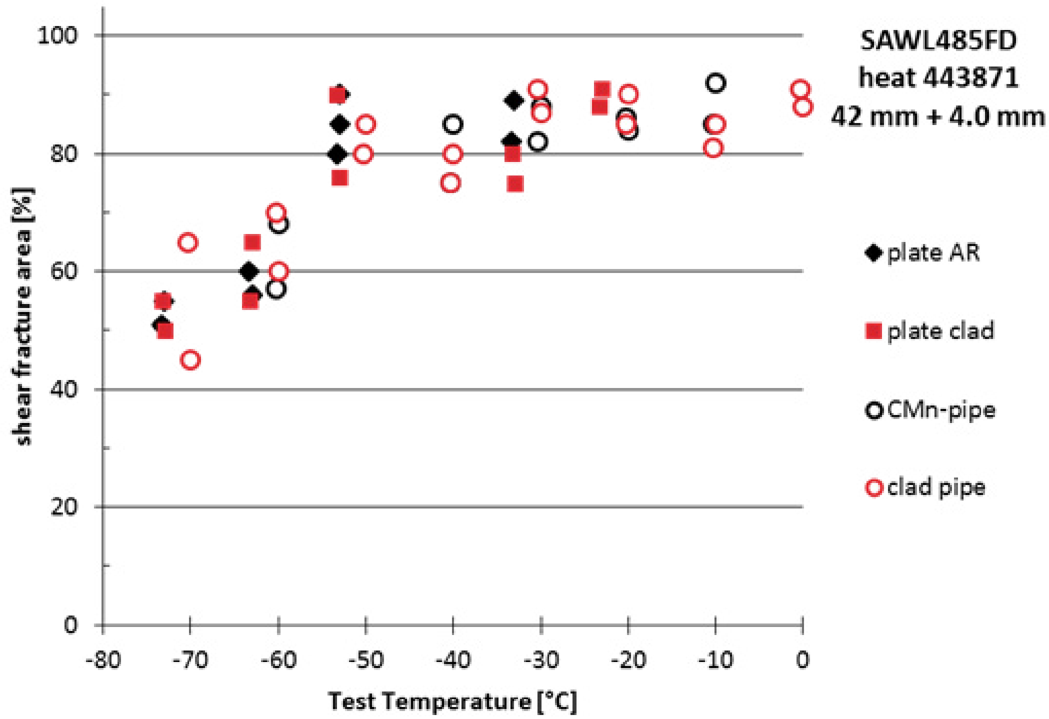
FIGURE 4: DWTT RESULTS #2

No effect on the drop weight tear test results by explosion cladding was found, but similar to the CVN-impact test results cold deformation by pipe forming and post weld heat treatments increases the brittle fracture areas.

In #2 DWT tests were made only on plate samples. See Figure 4.

The material of #2 is 25% (6 mm) thinner than the material #1, but with a higher strength level. It shows an overall better DWTT performance. Similar to the previous trials, no evidence was found that explosion cladding changed the DWTT behaviour.

FIGURE 5: DWTT RESULTS #3



Additionally, the effect of stress relief was not significant for this type of material.

In #3 complete transition curves over a wide temperature range from 0 °C down to -70 °C were made for plate and pipe in both conditions, CMn-steel and EXW clad (Figure 5).

It can be seen that from 0 °C down to -50 °C the DWTT values are relatively stable between 75-90% shear. Below -50 °C at -60 °C and -70 °C, the shear values are decreasing to around 60% and 50% respectively. The values of the pipe samples

FIGURE 6: DWTT SPECIMEN WITH INVERSE FRACTURE APPEARANCE

(forming degree 3.9%) seem to scatter a bit more than the plate values, but show, on average, no significant deviation to the plate values. Also similar to the trials #1 and #2 no evidence was found that the explosion welding process alters the brittle fracture control. It is worth noting that the specimens, even at relatively high testing temperatures, show inverse or abnormal fracture appearance. Figure 6 gives an example.

The inverse or abnormal fracture behavior of advanced TMCP line pipe steels with extreme toughness is known and well observed. The test standard does not give guidance on how to deal with this issue, therefore the brittle fracture has to be counted when assessing the surface of a specimen.

The above discussed findings and results suggest new DWTT design temperatures for clad line pipes when using advanced EXW clad TMCP line pipe steels. Table 3 gives achievable DWTT design temperatures for clad pipes of various steel grades (tested by full thickness specimens).

Steel grade thickness 20-45 mm	X65M/L450 sweet	X65M/L450 sour	X70M/L485	X80/L550
Test temperature	-35 °C	-25 °C	-25 °C	-5 °C

TABLE 3: NEW TEST AND DESIGN TEMPERATURES FOR DWTT SPECIMENS (FULL SIZE) FOR CLAD PIPES WITH FORMING DEGREE < 7%

CONCLUSION

The explosion welding process is well-suited for the production of TMCP clad plates for line pipes.

Evidence was introduced that cladding by explosion welding allows the user to retain the toughness and fracture control properties of TMCP line pipe steels.

The concept of decoupling plate rolling and cladding by explosion welding allows the use of advanced TMCP line pipe steels for manufacturing metallurgical clad pipes that provide enhanced mechanical properties.

By means of explosion cladding of TMCP plates, the exceptional properties of carbon-manganese steel pipes is now also available for clad line pipes.

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