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# The Use of Induction Brazing in Casing Connections to Improve Well Integrity

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## Abstract

Today's wells are becoming increasingly complex. Casing connectors continue to be the weakest link, especially in complex wells that utilize premium connections or expandable liners.

Brazing technologies are used in the industry to join metallic and nonmetallic parts. It relies on a filler material that is melted to join the parts. The melted filler material creates a metallurgical bond between the substrate and filler. Brazing has traditionally been used to join non-weldable materials.

The technology here applies brazing to casing connectors for the first time to improve leak tightness of API or premium connectors, ensure leak tightness after severe plastic deformation and to increase torque capacity.

Starting with the deposition of filler material on the connection threads, it follows a process to make the final brazed joint. Briefly, the joint is stabbed, made up to a fraction of its optimum torque, filler is melted using heat and the joint is torqued to final make up torque, followed by cooling prior to running in hole. The process is termed Temperature-Torque-Time (TTT). Two TTT-processes are presented, one for quenched and tempered steel and one for expandable grade for sizes 5-1/2", 9-5/8" casing.

Results show that there are no microstructural changes to the substrate. Both processes produced leak tight casing connectors before and, when applicable, after expansion as shown by full-scale tests.

Preliminary successful results indicate that induction brazing could be a viable option to improve casing performance and could open opportunities to replace premium connections with API connections.

## Introduction

The need for this technology arose as a result of the application of expandable casing as part of the monodiameter well. During the expansion process of the casing, the casing as well as the connectors undergo severe plastic deformation. The connector is especially vulnerable to leak as a result of the loss of the metal-to-metal seal during and after expansion. A need was felt for maintaining and even improving the sealability after the expansion process and as a result several technologies such as welding and others were investigated.

The bond between the pin and box during a connection is a metal-to-metal seal that is in an elastic state. During and after expansion it is frequently a challenge to preserve this bond especially when regions of the threaded region undergo plastic deformation. Another approach that was tried out was through the utilization of various types of filler materials that were screened [2]. The ideal filler material was to be a highly ductile material that would soften and deform under the action of heat, yet provide a high shear strength to the pin-box bond when cooled, simultaneously ensuring that the base material did not degrade in the strength properties due to the heat applied during the brazing process. After exploring several technologies, the most viable method to develop a metallurgical bond with adequate sealability, strength and integrity was found to be in the brazing process.

There were several requirements that needed to be fulfilled for the creation of this bond. Firstly, the bond utilizing a filler material between pin and box needed to be created fast and safely in a drilling operations scenario. Secondly, the process should have none or very minimal effect on the mechanical properties of the base material. Thirdly, the filler material needed to be melted at adequately low temperatures and have sufficiently high shear strength as well as ductility in order to keep up with the plastic deformation of the expansion process and fill-up the voids and gaps between the threads thereby providing excellent leak tightness.

Based on all the above requirements, the brazing process was found to be the most viable one to be developed. The development was planned in such a way that after the prototype process was proven, it could easily be transferred on a drilling rig for brazing casing joints during the casing running operations as part of normal drilling. This paper discusses the development of the brazing technology, the challenges, and relates the processes and procedures that need to be followed for the implementation of the technology during casing operations.

## Brazing process and method with respect to casing

The brazing process involves several steps. Figure 1 shows a schematic representation of the steps in the brazing process.

Firstly, the braze material is pre-deposited on the pin and box portions of the casing separately through a flame spray process. The braze material used were both either in the form of powder or wire. The deposition is a very specialized and precise operation and was carried out for this project in specialty flame spray shops. After the deposition of the braze material, both the pin and box were protected using paper tape to limit contamination by dust etc. and stored.

During the preparation of the test joints, just before brazing, the protective tape was removed and the pin was stabbed into the box and partially made up as part of the normal casing make-up operation.

The braze material was then melted using an induction heater coil that was sized to take-in both the 8-5/8" and 9-5/8" casing joints considered in this project. The key part of the process was the simultaneous application of heat and make-up of the casing joint using casing-tongs as normal.

The brazed joint was then allowed to cool using forced air convection to a temperature that was deemed safe for handling. The casing joint should now be ready to be run into the hole as a normal part of the casing operations.

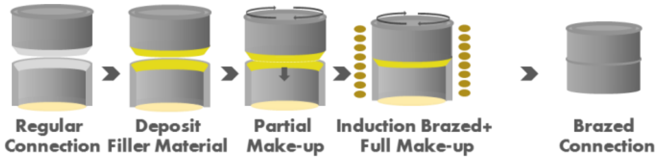

*Figure 1 Schematic representation of the brazing process*

### Pipe material grade and filler materials

The filler material used depends on the casing material grade [1]. This is because, the brazing process itself could inadvertently cause unwanted heat treatment of the casing material grade. High strength quenched and tempered material grades such as L80, P110 and Q125 are sensitive to this heat treatment resulting in a yield strength reduction. Lower strength grades of casing such as VM50 are on the other hand, not susceptible to this exposure. Therefore, two types of fillers were selected very carefully during the development of the technology.

For the ductile material grade used for expandable liners (VM50) a high melting temperature (1220°F) alloy, a silver based filler, BAg-24 was chosen. This gave high bonding strength combined with the ductility to survive the expansion process.

For the high strength grades of casing the lower melting temperature (718°F) alloy, ZnAl15 was used. This material provided enough bond strength to withstand the pressure differential while not affecting the base material microstructure.

### The brazing process (T-T-T)

The brazing process has been termed the Temperature-Torque-Time (TTT) process [2]. As mentioned earlier, the brazing process is defined based on the casing material type and properties. The brazing process temperature is then determined based on the filler material melting temperature.

Given sufficient power for the heating apparatus, the duration of the process is determined by the wall thickness and thermal conductivity of the casing material. The brazing process is shown in Figure 2, and the steps are described as follows:

1. Stab the pin into the box connection and make-up to 20% of the prescribed torque.
2. Start heating using the induction heater with full power.
3. Dwell at 85% of filler material melting temperature to allow the box to heat up through thermal conduction.
4. Increase temperature to 105% of filler melting temperature.
5. Make-up to 100% prescribed torque.
6. Dwell at 105% of filler melting temperature for full heat through to ensure proper bonding.
7. Stop heat.
8. Cool brazed joint using forced air convective cooling.

The dwell time in step 3 can be determined by the following empirical formula [2]:

$$\Delta t = \frac{6.4\cdot 10^{-5}\pi}{4} h(d_2^2 - d_1^2)\ [s] \qquad (1)$$

Where $\Delta t$ is the dwell time, $h$ is the connection height, $d_1$ is the pipe inner diameter and $d_2$ the pipe outer diameter.

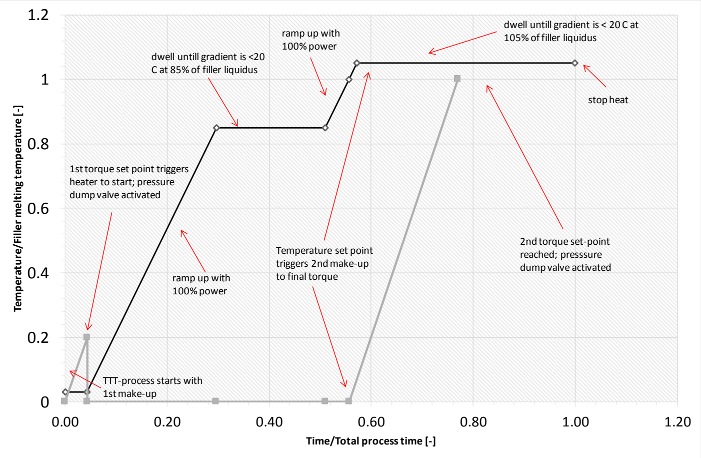

*Figure 2 Temperature-Time-Torque (TTT) process as determined relative to the liquidus temperature of the filler material.*

### The heating process

The heat needed for the brazing process is generated using the induction heating principle. Alternating current is applied to a high conductivity copper coil. The current induces a magnetic field which in turn induces an opposing current in the pipe body. Resistive heating then causes the pipe body to heat up.

The process of converting electrical current into heat is most efficient for magnetic and high electrical resistance materials with a minimal gap between pipe body and induction coil. The heat is induced only in a portion of the pipe body because of the "skin effect" [3]. The penetration depth of the induced current can be computed as shown in (2).

$$\delta = \sqrt{\frac{\rho}{\pi\mu_0\mu_r f}}\ [m] \qquad (2)$$

Where $\delta$ is the skin depth, $\rho$ is the resistivity of the pipe material, $\mu_0$ is the magnetic permeability of vacuum, $\mu_r$ is the relative permeability of the pipe material and $f$ the resonance frequency of the current. Choosing typical numbers in the consistent set of units for common casing materials yields a graph showing the variation of the skin depth as a function of frequency in Figure 3. To heat the pipe completely by induction is only possible with very low resonant frequencies. The electronics needed for this can often become bulky and therefore unsuitable for rig use. For the present project a higher frequency of 2 kHz was chosen because of this primary reason.

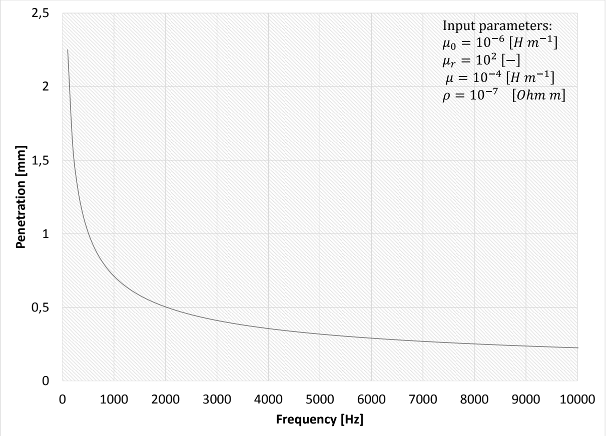

*Figure 3 Penetration depth as function of resonance frequency. Note that it is asymptotic for high frequencies.*

From Figure 3 it is important to note that the heating is confined to the 'skin' depth of the casing specimen and hence the remainder of the pipe heating is governed by thermal conduction of heat from the induction zone in the radial direction. This determines the duration of the brazing process to obtain uniform heating across the wall of the pipe.

### *The connection testing*

A reduced load envelope testing (with respect to connection strength ellipse envelope) was carried out on the brazed connection specimen to test the quality of brazing process [4]. Moderate loads were applied in quadrant 1 and 2 of the connection strength envelope according to the load paths shown in Figure 4.

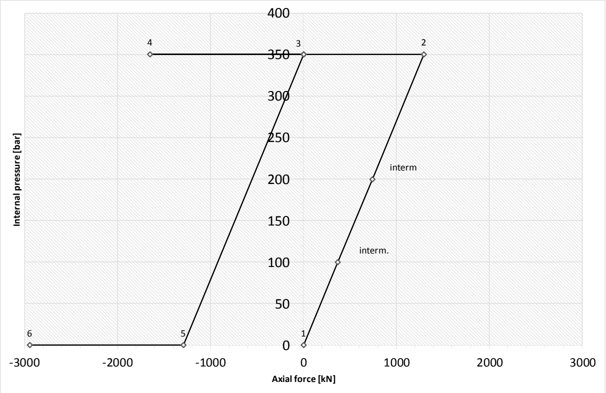

*Figure 4 Connection integrity testing*

Connection testing was carried out in an Amsler (make) press capable of ~661,400 lbf (~300 mT) compressive force. Internal pressure was regulated by a Resato (make) 14,500 psi hydraulic pressure unit with fine adjustment of the pressure. The measurement of leakage was carried out using a Quizixx (make) pump.

With reference to Figure 4, the load path was defined by load points 1 – 6 and was followed in the counter clock-wise direction and clock-wise direction twice. At each load point, 5 minutes of stabilization time was allowed before measuring displacement. The displacement was then monitored for 15 minutes using the Quizixx pump. If the displacement was under the API limit [4] of 1.2 ml/15 minutes the testing was moved to the next load point, otherwise the test was terminated.

The expandable grade connections were tested with the ends capped (load point 1 - 2) in unexpanded condition and subsequently expanded prior to strength envelope testing. Expansion was carried out under the Amsler press with a 10.2" cone.

## The rig ready prototype brazing system

In order to produce full-size brazed joints using actual threaded casings, a brazing system was designed and fabricated for the prototype testing such that after the completion of all the tests, this unit could be packaged and trialed on a drilling rig. Figure 5 shows the laboratory prototype machine assembled and ready to braze.

The brazing system consists of a circular induction heater into which the casing is positioned concentrically. The heater is envisaged to be packaged into an environmental chamber designed such that it would be possible to transfer to an oil rig location and operated on the rig-floor.

As part of the development, standard casing tongs were modified and tested to enable the use of regular make-up procedures while heat was being applied to the casing joint.

The entire brazing process was controlled (almost) automatically utilizing a PID control system protocol for regulating the heating rate and temperature on the casing joint. The temperature was measured and recorded using infrared thermometers (pyrometers) aimed at the OD of the casing specimen. The components of the induction heating system are discussed briefly below. The final set-up on a simulated rig-floor for the casing brazing operation is shown as well.

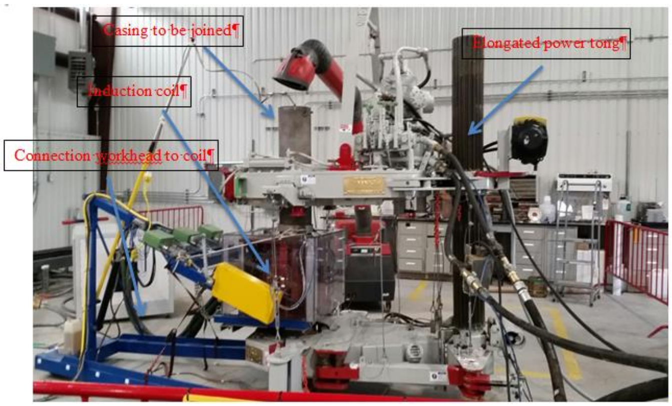

*Figure 2 Laboratory prototype brazing machine showing induction heater and modified casing power tongs.*

### *Induction Heater*

For the present application, a 225 KW induction heating system was selected. The induction heating unit consisted of (i) heating coil (ii) workhead (iii) power supply (iv) cooling system.

(i) The heating coil for this application was 10.625 in OD that could easily accommodate up to 9-5/8" casing with a 0.5 in radial gap. The coil itself consisted of fourteen (14) windings of copper strips of unequal length that was specially designed so that it provided a uniform and homogeneous circumferential heating. The cooling of the coil was with de-ionized water. For the test application of the prototype brazing system, the cooling system was rented for cost control reasons. In the unit itself, there is a provision for a suitable cooling unit to be integrated as part of the heater system.

(ii) The work head consisted of a means to modulate and power the coil excitation to produce an oscillating magnetic field that heated the workpiece (casing) due to induction heating. For this application the work head was positioned away from the coil and connected using three (3) flexible power lines. This application was slightly different from the normal where the coil was in close proximity to the work head. Such a design was undertaken to remove the work head from the well-center.

(iii) Power supply was standard 400VAC to the work head that was compatible with induction heater power supply.

(iv) The cooling system for the induction heater system circulated deionized water to all the power supply units, the work head as well as the heating coil windings as per manufacturers specification.

### The brazing trials

All the brazing trials with the prototype equipment were carried out at the Shell Gasmer Prototype Facility in Houston, TX. Table 1 shows the complete test program. The trials were run during 2015 in batches of 5 to 6 joints per run session. Two different pipe sizes (8-5/8", 9-5/8") were considered. Two different braze materials alloys (ZnAl15, BAg-24) were considered. Other information about the type of casing joints considered and the type of threads are all shown in Table 1

The details and break-up of the thirty four (34) joints that were brazed are shown in the table. Note that thirty one (31) of the connection joints were premium connections with three (3) API BTC connections that were also brazed.

*Table 1 Overview of used pipe grades, joint types and filler types.*

| **Variables** | | | | |
|---|---|---|---|---|
| **Casing sizes (in)** | 8-5/8" | 9-5/8" | 9-5/8" | 9-5/8" |
| **Grades (lb/ft)** | L-80 | VM-50 | P-110 | P-110 |
| **Weight (lb/ft)** | 40 | 43.5 | 53.5 | 53.5 |
| **Thread types** | BTC | SLIJ II | TH-513 | SLIJ II |
| **Braze alloys** | ZnAl15 | BAg-24 | ZnAl15 | ZnAl15 |
| | | | | |
| **# of samples** | 3 | 10 | 8 | 13 |

The brazing process itself involved the application of the Time-Torque-Temperature (TTT) sequence that was utilized through a suitable PID-type control system that was developed for the tests.as mentioned earlier.

Figure 3 below shows the TTT brazing process for a 9-5/8" P-110 53.5 # casing that used ZnAl15 as the braze material. Note that utilizing the TTT sequence, the joint was pre-torqued to 10,000 ft-lb and then heated using the induction heater to 425°C (797°F).

The temperatures on the surface of the casing were monitored using both pyrometers (infrared thermal sensors) as well as thermocouples for comparison. The temperatures measured by both the pyrometers and the thermocouples were found to match closely.

The final torque of ~22,000 ft-lb was applied for final make-up of the joint. The brazing time was about 3-4 minutes which depended on the time for the temperatures to become uniform across the thickness of the casing. It was considered important to have uniform temperature across the thickness of the casing specimen for the production of a good brazed casing joint.

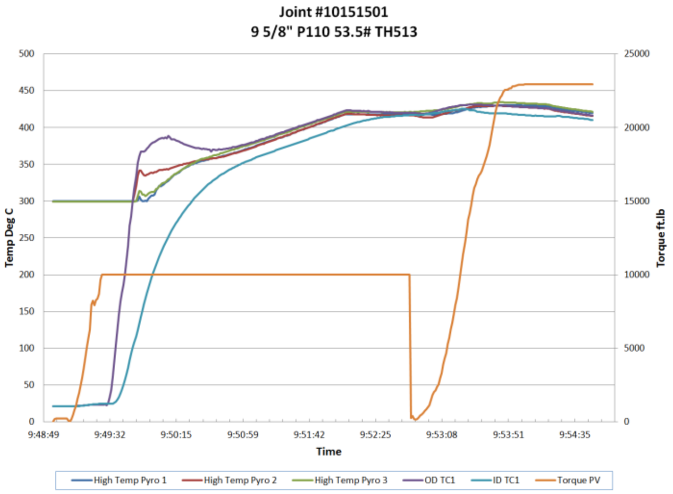

*Figure 3 Typical TTT process for the 9-5/8" P110, 53.5# casing with thread type TH-513. The braze material is alloy ZnAl15 that has a melting point ~425 $^{0}$C.*

Brazing trials were also conducted on expandable grade casing VM-50. Figure 4 shows the TTT process during the brazing operation for a VM50 casing specimen. Temperatures both on OD and ID of the casing at selected points were tracked while inside the heater coil. Figure 7 clearly shows that the ID temperatures took a longer time to catch-up to the temperatures on the OD. This was due to the induction heating being localized to the small 'skin' at the outer surface of the casing specimen. The pre-torque used for this joint was also 10,000 ft-lb. When the temperature at the joint area was reasonably uniform around 1292$^{o}$F, the joint was made up to the final torque of ~15,000 ft-lb. The total time taken for brazing this joint was ~7 minutes (more than the time for brazing a P-110 type casing joint). Understandably this was due to the time taken to rise to the higher temperature of 1292$^{o}$F.

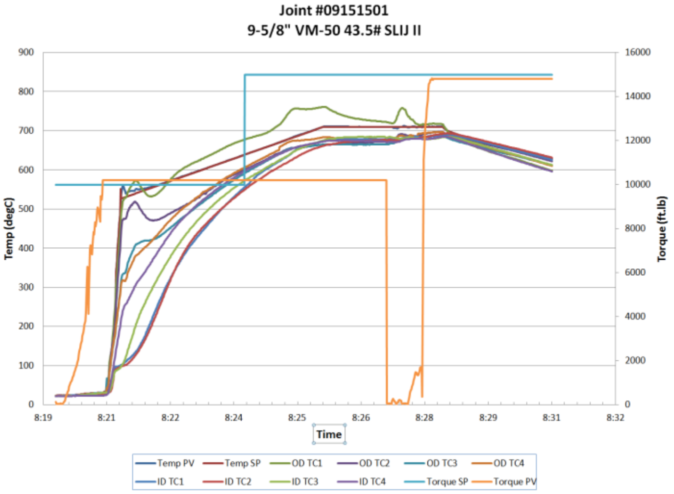

*Figure 4 Typical TTT process for 9-5/8" VM-50 43.5# casing with thread-type SLIJ II. The braze material is alloy BAg-24 that has a melting point ~1292$^{o}$C.*

In the case of expandable connections the primary requirement is joint integrity after the expansion process [1]. During and after expansion, the possibilities for some of the threads of the joint to 'jump' and separate existed. This was due to the rigorous plastic deformation that accompanies the expansion process. Based on the studies related to this project, the best possible method to prevent this from happening appeared to be through the formation of a metallographic bond box/pin substrate and the brazing filler material. This is possible through brazing as demonstrated in Figure 8 below. The upper picture (Figure 8a) shows a cross section of the threaded connection with no brazing that failed after expansion. The bottom picture (Figure 8b) shows the same connection after brazing and then expansion.

The key to the success of this process has been to use a highly ductile low melting point material to serve as a filler material and one that would form a metallurgical bond between the box and pin thereby preventing separation even under load.

*8a*

*8b*

*Figure 5 The upper cross section (8a) shows a threaded connection that failed after expansion and the lower cross-section (8b) shoes the same connection after expansion but with the braze material that formed a metallurgical bond.*

## Results

For the VM50 grade casing material used in the expandable application it was observed that at high temperatures its microstructure was not affected. This was also validated by expanding the brazed joints. The filler material selected for the VM50 casing was BAg-24 as stated earlier. The brazed connection expanded without any issues. This material provided the required ductility and shear strength.

The microstructure of VM50 material before and after brazing is shown in **Error! Reference source not found.**. The 'as-received' material, 9a, has a ferrite microstructure. The heat treated material at two locations on the box side in 9b and 9c show essentially the same microstructure. There are some perlite bands visible (9b), which may in some cases be detrimental for the formability of the material (expansion) due to differences in local hardness, which can induce local cracking on the grain boundaries. However, for the joint material in this study that was expanded, none of these issues were observed.

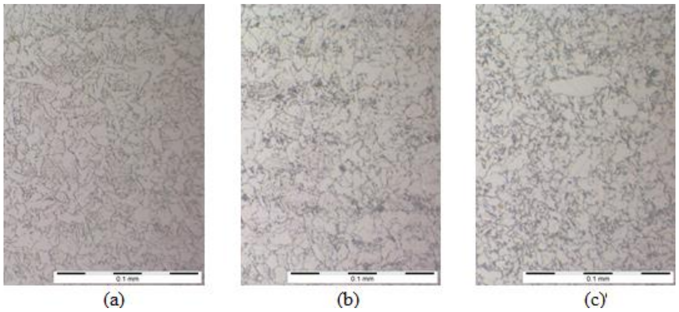

*Figure 9 Microstructures for VM50 pipe material. Figure 9a shows the as received material. Figure 9b and 9c shows the microstructures after brazing in the middle of the box section and the tip of the box respectively.*

For the standard casing connection application (i.e. no expansion), the objective was to braze L80 through the Q125 grade range without affecting the microstructure.

**Error! Reference source not found.** shows the results of the brazing trials on P110 material. From the chart it can be seen that the material begins to soften around 550° C (1022°F). This value coincides with the tempering temperature of quenched and tempered material grades (such as P-110). Therefore, a low melting temperature alloy, such as ZnAl15, (melting point ~425°C (797°F)) was selected for brazing this type of quenched and tempered material.

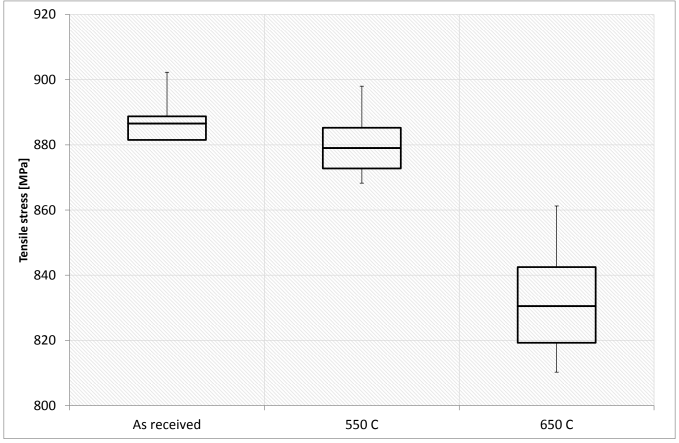

*Figure 10. The loss in tensile strength as a function of temperature (550°C (1022°F), 650°C (1202°F)) is shown for P-110. The pronounced decrease at 650°C can be clearly noticed. (Note sample size N =4 at each temperature)*

The microstructural changes due to this softening of the P-110 at 650°C (1202°F) are shown in **Error! Reference source not found.**. In Figure 11b, the originally precipitated large carbides present in the 'as is' received sample are observed to be completely dissolved back into the metal matrix due to the heating process thereby softening the material as observed in the tensile tests shown in Figure 10.

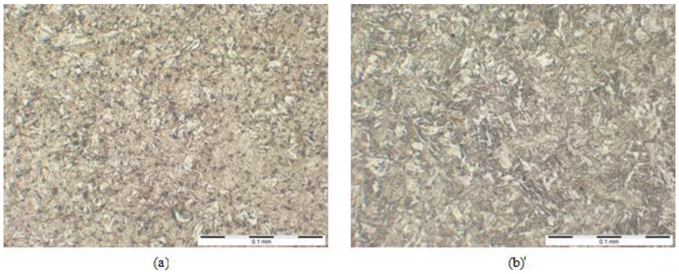

*Figure 11 Microstructures of P110 pipe material. Figure 11a shows the 'as received' microstructure and 11b shows the microstructure after heating to ~650°C (1202°F) and softened.*

## Conclusions

A comprehensive test program was undertaken towards the development of a brazing prototyping technology and system to prove the feasibility and applicability of brazing on expandable type material (VM-50) as well as regular casing connections material grades (L-80, P-110). These called for two different types of brazing material alloys.

The results indicated that (for both types of casing steel grades), there was no microstructural changes to the substrate material detected. The pin and box were found to be strongly joined with a metallurgical bond by the filler material.

As a result of the above, both the processes produced leak tight casing connectors before and (when applicable), after expansion as shown by full scale tests. Based on the above the following conclusions could be listed as:

1. A laboratory brazing process has been developed and was proven for producing brazed connections by (i) spraying braze material on casing threads, (ii) made-up with induction heating, and (iii) utilizing conventional casing make-up and torqueing procedure
2. The brazing process was proven in the laboratory with the prototype brazing system utilizing field-type but modified casing-tongs for the sizes of 8-5/8" and 9-5/8" casing.
3. A rig-ready prototype brazing machine with packaging elements to render it field rig- ready have been designed.
4. Limited pressure testing conducted on the produced brazed joints using the prototype brazing machine has demonstrated that it is possible to produce leak tight brazed connections (for both conventional and expandable casing joints) for the pressures tested (5,070 psi).
5. Post-mortem and microscopy of tested brazed joints clearly indicate the presence of a metallurgical bond that provides the seal tightedness.
6. The brazing process holds promise to enhance the sealing capability compared to existing casing pressure ratings.

## Recommendation and path forward

Based on the results obtained so far in this project the following future work has been suggested:

1. There is a need to include pressure testing in all the quadrants of the casing connection envelope.
2. Further refinement and optimization of the brazing process may be needed to consistently produce high quality leak-tight brazed joints. This could be accomplished with

streamlining the spray process as well as fine tuning the control protocol for maintenance of a uniform temperature across the wall of the casing specimen

3. The method of making-up casing joints with the brazing process could also potentially provide an enhanced torque capability with possible applications in Casing while Drilling (CwD) operations.

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