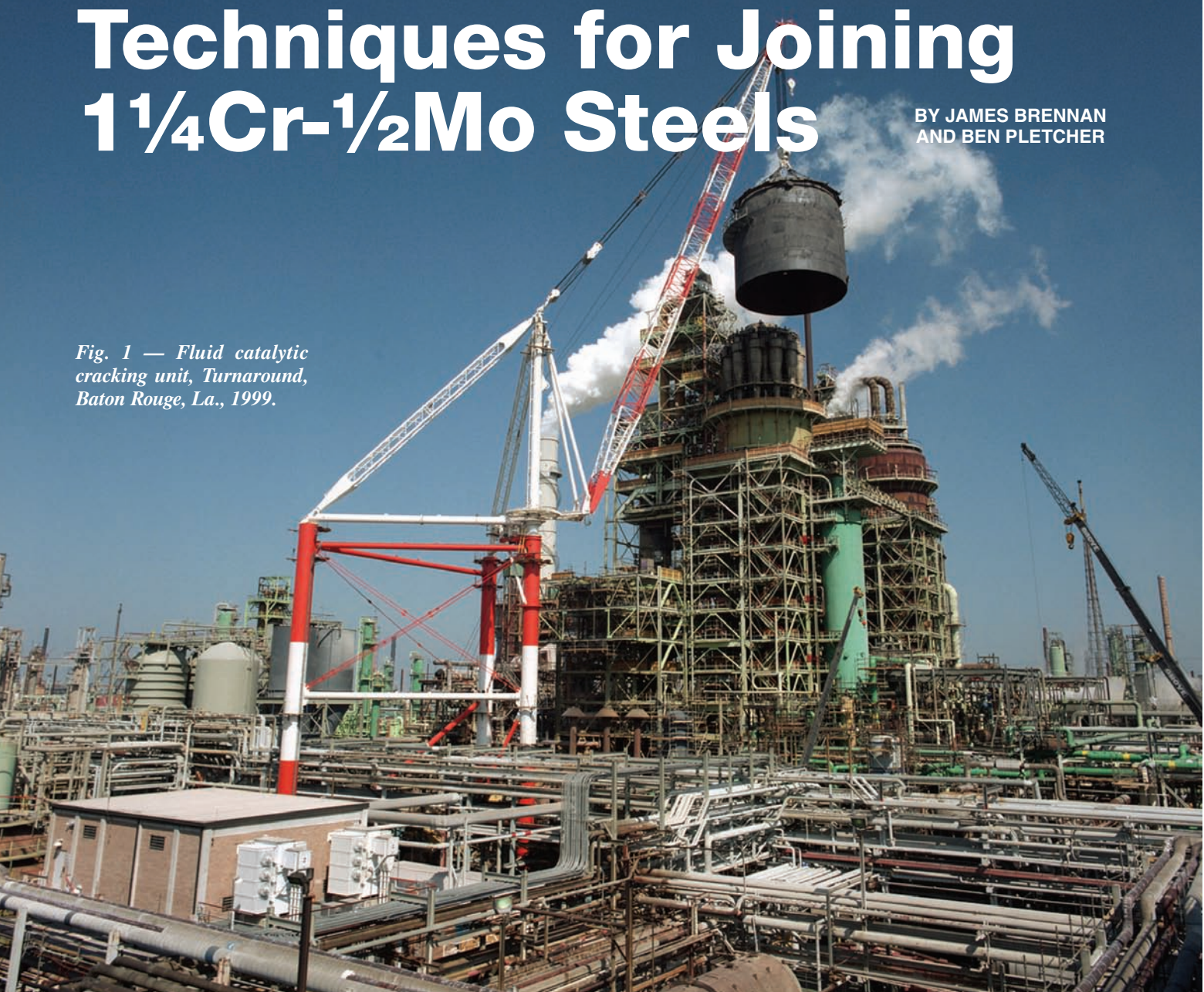


Techniques for Joining 1 $\frac{1}{4}$ Cr- $\frac{1}{2}$ Mo Steels

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Fig. 1 — Fluid catalytic cracking unit, Turnaround, Baton Rouge, La., 1999.



Examples are presented that simplify the complex welding of Cr-Mo steels

Successful welding of Cr-Mo steels requires proper design, material selection, and quality control throughout all phases of engineering and construction. Early welding of Cr-Mo materials, pre-1950s, varied little in technique from low-carbon steel welding. Producing high-quality

welds was difficult and quickly generated research into the effects of hydrogen, material chemistry, vessel design, and post-weld heat treatment (PWHT). The past half-century yielded significant advancements in consumables and methods to reduce hydrogen effects in welding. Mod-

ern welding techniques, including pre-heat, postheat, and PWHT, provide a repeatable methodology producing high-quality welds in both the shop and field construction. The lessons learned throughout the industry provide the base knowledge for construction codes and

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standard practices such as API 934-C, *Materials and Fabrication of 1/4 Cr-1/2 Mo Steel Heavy Wall Pressure Vessels for High-Pressure Hydrogen Service Operating at or below 825°F (441°C)*.

Applications

ASTM SA-387, Grade 11 defines the 1/4 Cr-1/2 Mo steels. Minor additions of the elements Cr and Mo, to standard carbon steels, provide creep resistance at elevated service temperatures. Typical plate structures, utilizing SA-387, Grade 11 material, include reactor vessels and coke drums for refinery operations (Fig. 1), and basic oxygen furnaces for steel mills. These large structures have wall thicknesses from 1 to 3 in. (25 to 75 mm), are 22–36 ft (6.7–11 m) in diameter, and between 80 and 120 ft (24 and 36 m) high. Coke drums endure the most severe cyclical thermal service with temperatures reaching as high as 1000°F (538°C) followed by a water quench. Typical service allows for two thermal cycles per day and an estimated vessel lifespan of 3000 cycles. Figure 2 shows an extreme example of a coke drum replaced after seven years in service. Bulging of the vessel was caused by thermal fatigue exacerbated by the differential yield strength between the base metal and weld. Higher-strength weld metal has a stiffening effect, resulting in stress concentrations, and ultimately leads to distortion and later cracking (Ref. 1). The lifespan can be prolonged, without changing the base material, by lowering the quench rate, matching the weld metal yield strength to the base material, and minimizing residual stresses. Current standards for vessel design, fabrication, and construction have developed from more than 60 years of experience.

Early Welding

Early Cr-Mo vessels, including stainless steel clad vessels, were welded and placed into service beginning in the mid-1940s. Plate material was not standardized, but was typically designated as SA-301 material, which later evolved into the SA-387 grade. Low-hydrogen shielded metal arc welding (SMAW) electrodes were not manufactured at that time; therefore, cellulose-covered electrodes such as E7010, E8010, and E9011 containing additions of Cr and Mo were used. Clearly, weldability was poor compared with modern standards, but quality welds were still possible with highly trained welders. Radiography, still in its infancy, was used extensively on Cr-Mo vessels. Some of the first vessels with 100% radiography were coke drums and reactors. Notable vessels from CB&I history include a large Houdriflow Reactor built in



Fig. 2 — Extreme example of a coke drum shell bulging. Originally built in 1954, it was replaced in 1961.

El Segundo, Calif., in 1950. The plates were SA301 Grade B and welded using E8010 with additions of 1%Cr-0.5%Mo. Historical construction documents show that obtaining uniform preheat was difficult, but an important factor in producing acceptable welds. Repairs were especially prone to cracking, due to the localized heating and the relatively high hydrogen content of the cellulose-coated electrodes. By 1954, low-hydrogen electrodes were introduced that vastly improved the weldability and crack resistance of these materials. After the first decade of Cr-Mo welding, three major considerations were identified:

- Hydrogen contamination
- Temper embrittlement
- Stress concentrations

Recognition of these common factors, which often led to cracking during

construction and a shorter, usable vessel lifespan, prompted research to improve the welding processes.

Limiting Hydrogen Contamination

Hydrogen control begins with the consumable manufacturer. The SMAW consumables are supplied in hermetically sealed containers with tested hydrogen levels. Once opened, proper electrode storage must be followed per the manufacturer's guidelines. Uncontrolled exposure to the atmosphere can lead to hydrogen absorption by the flux that could be introduced into the weld. The now common E8018-B2 electrodes, used in conjunction with ovens, introduce minimal hydrogen into a weld. By 1960, field construction organizations were using elec-



Fig. 3 — A vertical plate coke drum in fabrication.



Fig. 4 — Preheat applied by electric resistance heaters formed to fit the vessel shell.

tric resistance heaters to maintain a continuous preheat of 300°F (149°C). The low-hydrogen electrodes coupled with preheat techniques vastly improved the weldability, while lowering the risk of delayed (hydrogen-induced) cracking. Preheat eliminates hydrogen sources, such as condensate, from the material surface and slows the cooling rates giving entrapped hydrogen time to diffuse from the weld. Postheat, that is holding the weldment at

interpass temperatures after welding is completed, provides additional diffusion time for hydrogen to escape. The PWHT, standardized at 1250°F (677°C) for 1 h/in. (1 h/25 mm) of plate thickness, provides stress relief of the vessel, lowers the weld metal hardness, and allows more time for the hydrogen to diffuse from the weld metal. Caution must be taken to ensure that the PWHT does not exceed the tempering temperature applied by the steel

mill. Exceeding the tempering temperature may degrade the mechanical properties of the base material.

Controlling Temper Embrittlement

Base material and electrode chemistry play a major role in both vessel constructibility and its service application. Temper embrittlement is defined as a decrease in toughness when the material is heated or cooled through the 570°–1110°F (300°–600°C) temperature range (Ref. 2). This temperature range coincides with the thermal cycling that a coke drum experiences in service. In addition, the unintentional additions of silicon, phosphorus, tin, antimony, and arsenic can increase the susceptibility to temper embrittlement.

In the late 1960s, CB&I researcher Robert Bruscatto examined Cr-Mo weld deposits and quantified the relationship between these trace impurities and their effects on temper embrittlement. The now common Bruscatto temper embrittlement factor, \bar{X} , can be calculated using the following formula, where elements are given in parts per million (ppm) (Ref. 3).

$$\bar{X} = \frac{10 \cdot P + 5 \cdot Sb + 4 \cdot Sn + As}{100}$$

The accepted limits are $\bar{X} \leq 15$ for coke drums; however, critical applications of higher-alloyed Cr-Mo materials may require $\bar{X} \leq 12$. Modern material processing facilitates the production of base materials and consumables with low levels of these undesirable “tramp” elements. Fabricators and end-users must be vigilant in defining material limits for proper procurement of high-quality products.

Minimizing Stress Concentrations

Stress concentrations are responsible for a variety of crack-related failures and must be minimized by design. Elimination of circumferential or girth seams in the vessel shell of the coke drum eliminates the strength mismatch between weld and base metal, thereby lessening the effects of thermal fatigue. Vertical Plate Coke Drum™ technology, a proprietary design from CB&I, allows for shell sections up to 46 ft (14 m) in height — Fig. 3. Vertical plate design, whether applied to vessel replacement or a new process unit, will outlast conventional “can section” designs due to the elimination of stress concentrations at the girth seams.

A weld profile can also affect local stress concentrations. All welds must be profiled to eliminate sharp transitions and excessive reinforcement. Grinding inte-

rior weld joints, especially girth joints, to a flush, smooth and blended finish is common practice in coke drum fabrication.

1¼ Cr-½ Mo Welding Challenges

Advancements in the processes used for manufacturing welding consumables, driven by the need to limit trace elements and lower diffusible hydrogen, have given the industry many good options for welding Cr-Mo materials. Most SMAW consumables can easily meet the $\bar{X} \leq 15$ requirements, while providing excellent weldability. Modern submerged arc welding (SAW) electrodes also have excellent chemical makeup. When used in conjunction with significantly improved SAW fluxes, these consumables result in minimal cracking, smooth weld beads, and good operator appeal. The AC waveform control used in SAW is a recent modification to the process. This AC waveform technology allows greater control of the depth of penetration and deposition rates, while using the same consumable/flux combination. These techniques are easily applied to shop-built vessels decreasing production time. While significant improvements have already created good

consumables for SMAW and SAW, flux cored arc welding (FCAW) remains a new product to the market. History shows that careful material evaluations are required to ensure that all design requirements are met by any new product.

Preheat and postheat methods are always being pushed for faster application while providing improved energy efficiency. Heating rates and temperature control can be improved with modern gas burners and electric resistance heaters formed to fit the vessel shell — Fig. 4. As previously noted, PWHT must consider the temper of the plate material, as surpassing this temperature may have detrimental effects on the mechanical properties. Owners and end users often require multiple thermal cycles, allowing for subsequent repairs followed by PWHT, thereby increasing the life of the vessel. Retaining mechanical properties after several PWHT operations is difficult for both the base materials and the welds. Ultimately, the vessel is limited by the material to which it was designed and the conditions of its operation.

Summary

Significant advancements over the past half-century have made 1¼ Cr-½Mo

steels readily weldable. Ongoing research is pushing to increase productivity by enhancing the deposition in AC waveform-controlled SAW and new FCAW consumables. Material and design improvements are continually pushed by the desire for steel plate structures with longer lifespans. Innovative designs, such as the vertical plate coke drum, provide fundamental engineering improvements, while quality consumables limit the introduction of detrimental elements. Whatever the future holds, three basic factors must be controlled to produce quality products: hydrogen contamination, temper embrittlement, and stress concentrations. ♦

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