Stress Relief Cracking in Advanced Steel Material- Overview

S P Ghiya , D V Bhatt , R V Rao

Abstract— **This paper summarizes the quality problems of the weldability of advanced vanadium modified Cr, Mo alloy steel material, during fabrication of reactor, pressure vessel being used for Refinery, Petrochemical, Chemical plants. Authors have focused on stress relief cracking occurred in weld metal and HAZ after stress relieving heat treatment of the weld. From the literature review , it appears that till date significant amount of efforts are made to understand the stress relief cracking, occurring in alloy steel .However considerable work is still being done on this quality issue to understand root cause of stress relief cracking and remedy to prevent it.**

Key words: Cr, Mo, V alloy steel, Stress Relief Crack, Molybdenum carbide, Vanadium carbide

I. INTRODUCTION

In refinery, reactors and pressure vessels are required primarily either for desulpherisation of hydrocarbon or cracking heavier hydrocarbon to lighter molecules. This process is carried out at high design temperature (450 °C) and pressure (100 kg/cm2) under hydrogen environment in presence of catalyst. Alloy steels are being used to withstand against high temperature and pressure and improvements are made in alloy steels to meet requirements .5th generation steel in form of vanadium modified Cr, Mo alloy is used in 1995 for the first time. Looking at the present need in refinery and process criticality, equipment with large wall thickness either in plate or forging form are manufactured.

2.25 to 3.8 % Chrome molybdenum alloys used for the reactor, way back in 1920 in Germany[8] for the hydrogenation plant operating at pressure range of 28 to 70 MPa and was considered as first generation steel.

2nd generation steel: Mid 1960s to 1970s-Modern hydro processing reactors manufactured using modified 2.25Cr -1Mo alloy with improved toughness property of 54 J at 10 °C. No considerations were made for the temper embrittlement control.

3rd generation steel: 1970s to 1980s- Controls over impurities was emphasized and J factor was restricted to 180 to control temper embrittlement .Toughness was further improved to 54 J at -18 °C. Step cooling test was also introduced with hydrogen disbanding test over weld overlay.

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4th generation steel: 1980s to 1990s - Improved temper embrittlement characteristics by restricting J factor up to 100. Toughness property further improved to 54 J at -32 °C.

Presently 5th generation steel is in use. Mid 1990s onwards advanced 2.25% Chromium and 1% Molybdenum steel with improved toughness up to 54 J at -40 °C is developed. Additionally 2.25 Cr, 1Mo and 0.25V material with improved following properties were developed by leading steel suppliers.

- High tensile property at elevated temperature
- Toughness at 54J at -29 °C
- Increased hydrogen attack resistance
- Enhanced creep resistance property
- Lower susceptibility to hydrogen disbonding

Apart from welding, cracking during services due to reheat, or relaxation , cracking or failure during the shut down or repair welding due to service embrittlement of heat resistant materials remains great practical concern in the Power generation, Refinery and Petrochemical industry.[8]

II. REACTOR STEELS: CONVENTIONAL CR-MO AND V MODIFIED CR-MO:

Primarily three modified alloys 1) 2.25Cr-1Mo-0.25V, 2) 3Cr-1Mo-0.25V-Ti-B & 3) 3Cr-1Mo-0.25-Nb-Ca [14] utilize vanadium addition to enhance tensile strength at elevated temperature and creep rupture strength and to improve resistance to in-service degradation phenomena, such as temper embrittlement, high temperature hydrogen attack (HTHA) and hydrogen embrittlement.

Design properties of the conventional Cr-Mo steel and vanadium modified Cr-Mo steels are summarized in Table-1.Higher room temperature strength properties of the modified steels are presented. Increased mechanical properties allow for higher design stresses, leading to a decreased wall thickness and reduced weight of reactors.

According to API 941, 0.25 wt% of vanadium in 2.25% Cr-1Mo steel protects the material from HTHA under partial pressure less than or equal to 13.79 MPa up to 482 °C 454 °C for the conventional 2.25 %Cr-1 Mo alloy. However despite the vanadium addition, the maximum design temperature permitted by ASME SEC VIII-2 for modified 3Cr-1Mo steel is 454 °C at the present time. These steels can not meet design requirements of ASME SEC VIII-2 creep rupture requirements at 482 °C. It is seen from the Table-1 that application of the modified steels results in lower unit weight of the reactors.

III. STRESS RELIEF CRACKING

Reheat cracking in welded structure has received considerable attention since mid 1950s primarily with austenitic steels used for power generating equipment for high temperature steam piping. In early 1960s similar cracking problem during stress relief heat treatments and high temperature service were again observed where ferritic creep resisting 2CrMo and CrMoV weldments in steam pipe work were found to exhibit occasional cracking. [1]

Reheat cracking may occur in low alloy steels containing additions of chromium and vanadium or chromium, molybdenum and vanadium when the welded component is being subjected to post weld heat treatment such as stress relief heat treatment. Reheat cracking is kind of intergranular cracking in the HAZ or weld metal occurs during the stress relief heat treatment or during service at high temperature. This phenomenon happens largely with alloy steel with Cr, Mo, V alloy.

An explanation, perhaps widely accepted, to reheat cracking is significant reduction in grain-boundary ductility during stress relief cycle or service due to either segregation of trace impurities or precipitation of carbides. The reduction in ductility, perhaps, to an extent that it is insufficient to accommodate the plastic deformation associated with stress relaxation. [5]

Stress relief crack may occur either on HAZ or within weld metal which will be detected either visually or by performing additional NDT testing like magnetic particle testing or ultrasonic testing methods.

IV. VISUAL APPEARANCE:

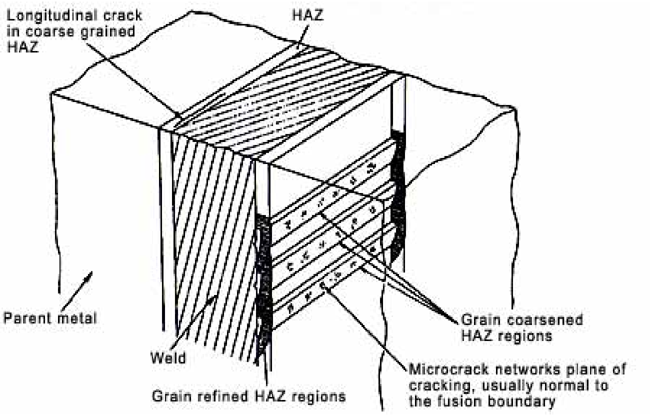

Fig: 1 `Location of reheat crack in reactor

As shown in Fig:-1 ,cracking is found primarily in the coarse grained regions of the heat affected zone, beneath the weld, or cladding, and in the coarse grained regions with in the weld metal. The cracks can often be seen visually, usually associated with areas of stress concentration such as weld toe.

A macro-crack will appear as a “rough” crack, often with branching, following the coarse grain region. Cracking is always intergranular along prior austenite grain boundaries as shown in Fig:-2. Macro cracks in the weld metal can be oriented either longitudinal or transverse direction of welding. Crack in the HAZ is always parallel to the direction of welding.

The characteristic features and principal causes of reheat cracking are described. General guidelines on best practice are developed so that welders can minimize the risk of reheat cracking in welded fabrications.

Table:1 Comparison of reactor steel conventional Cr - Mo and V modified Cr - Mo

Steel grade	**Conventional 2.25Cr-1Mo**	**2.25Cr-1Mo-0.25 V**	**Conventional 3Cr -1Mo**	**3Cr-1Mo-0.25V-Ti-B**	**3Cr-1Mo-0.25-Nb-Ca**
Max. allowed temperature ASME VIII-2	482ºC	482ºC	454ºC	454Cº	454ºC
Max. allowed temperature API 941	454ºC	510ºC	510ºC	510ºC	510ºC
Min. Tensile strength	517 MPa	586 MPa	517 MPa	586 MPa	586 MPa
Min. Yield strength	310 MPa	414 MPa	310 MPa	414 MPa	414 MPa
Design stress intensity value	at 454ºC 150 MPa	at 454ºC 169 MPa	at 454ºC 131 MPa	at 454ºC 164 MPa	at 454ºC 164 MPa
	at 482ºC 117MPa	at 482ºC 163 MPa	…	…	…
wall thickness [1]	at 454ºC 338 MPa	at 454ºC 298 MPa	at 454ºC 392 MPa	at 454ºC 307 MPa	at 454ºC 307 MPa
	at 482ºC 442Mpa	at 482ºC 310 MPa	…	…	…
454ºCdesign: reactor weight	1038 metric tons	916 metric tons	1203 metric tons	944 metric tons	944 metric tons
482ºC design : reactor weight typical	1359 metric tons	953 metric tons	…	…	…

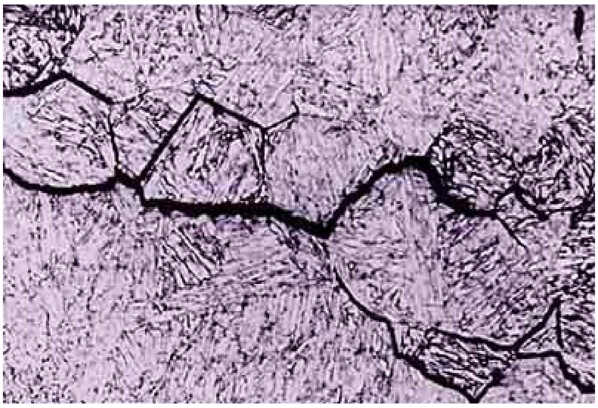

Fig: 2, Intergranular morphology of reheat cracks in weld

V. GENERATION OF STRESS RELIEF CRACKING:

Many papers are published on stress relief cracking in the past and most of these papers are related with HAZ and very few papers on weld metal. In fact, Cr, Mo, V material is highly susceptible to crack in the weld metal.

The principal cause is that when heat treating susceptible steels, the grain interior becomes strengthened by carbide precipitation, forcing the relaxation of residual stresses by creep deformation at the grain boundaries. The presence of impurities which segregate to grain boundaries and promote temper embrittlement, e.g. antimony, arsenic, tin, sulphur and phosphorous will increase the susceptibility to reheat cracking.

At lower temperature during stress relief heat treatment, interstitial elements carbon and nitrogen can produce strain aging embrittlement.

At higher temperature, thermally induced embrittlement such as secondary hardening and temper embrittlement, besides strain induced embrittlement or creep embrittlement can occur. These processes are enhanced by segregation of interstitial and substitutional impurity elements and by iron and alloy element carbide transformation.

Fig: 3(a) shows the hardness curves of a series of 0.6% Cr, 0.28% Mo-V steels tempered at each temperature. The secondary hardening does not occur in 0.06%V alloyed steels.

The temperature ranges of secondary hardening (SH) of those steels are 720 deg K to 850 deg K and 970 deg K to 850 deg K respectively. These are temperature range where the reheat cracking occurs. Graph shows that temperature between 770 deg K and 820 deg K causing stress relief cracking. It is concluded that vanadium suppresses the stress relaxation by causing secondary hardening in the temperature range where reheat cracking occurs. [4]

Vanadium carbide reduces the stress relaxation and in turn developing crack on grain boundaries.

Vanadium and chromium percentage play vital role forming carbides. Increasing chromium content increases the share of chromium carbides and decreases the share of vanadium carbides.

Carbides re-precipitation intragranularly during stress reliving and strengthen the grain matrix. This results in difference in strength between grain boundaries and the grain interiors. Due to weaker grain boundaries, cracking occurs intergranularly. Since Cr, Mo, V alloy steel contain reasonable amount of carbide forming elements like Cr, Mo and V. It is considered that all three materials may be susceptible to reheat cracking.[6]

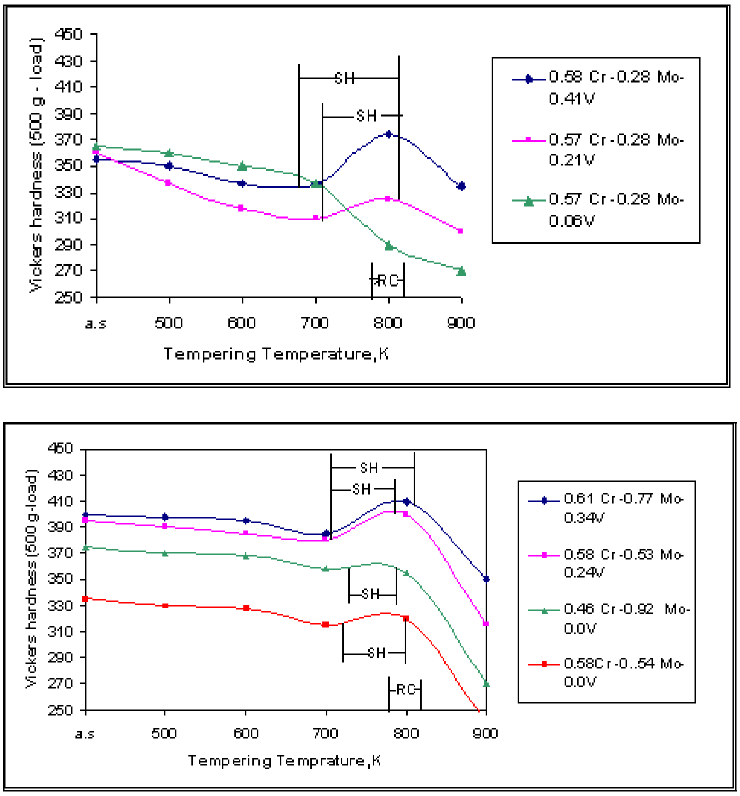

Fig.3 Examples of hardness of tempered Cr-Mo steel with and without vanadium.
Note: " SH" & "RC"; temperature ranges in which the secondary hardening & the reheat cracking occur ,respectively

VI. CHARACTERIZATION BY PHYSICAL SIMULATION:

Thermo mechanical simulation can be a useful development tool if capabilities and limitations are known to users. Gleeble is the most well-known physical simulator.

Virtual simulators, like video game, interactive education program, flight and driving are best known for the computer simulations.

However physical simulators are real and use computers only for process monitoring and data acquisition.[2] Safety of operators becomes utmost importance as electric shock , large load and other physical hazards are managed in a safe working environment. Gleeble test provides the facility to simulate physical condition on the test piece and testing can be performed on the basis of the various data is fed into the computer. Typical simulations use small specimens of the actual metal to be tested, typically uniform diameter of 9.5mm * 127mm in length but can be made smaller as well. The specimens are resistively heated at rates up to 10,000 ^{0}C/s [2] for specimens of 6.4mm diameter, typical to thermal cycles experienced by arc weld HAZs. Tensile or compressive static loading of up to eight metric tons can be superimposed on this temperature cycle as well as strain rates up to 50.8mm/mm/s. With these capabilities, the Gleeble is a dynamic physical simulator. Gleeble is based on a computer controller that reliability sends and adjusts control signals and acquire 200 samples per second. Under normal circumstances, it operates with great accuracy and reproducibility.

Merits:

- Accurate and reproducible simulation of physical process
- Feasible and flexible, useful in design, manufacturing and service.
- Small size samples required low material costs.
- Simulated microstructures are homogeneous and can be reliably tested.
- Can apply a wide variety of thermal and mechanical loads at high rates. It can separate thermal from mechanical effects during processing.

Demerits:

- The specimen must be electrically conductive.
- The simulated parameters must be well known.
- Extrapolating Gleeble results to full scale applications can be difficult.
- Equipment, maintenance and training can be costly.
- Simulating high cooling rate can be difficult.
- Helium or water jets can be necessary.

When merits and demerits are well understood and proper methodology is established, the Gleeble remains excellent tool for HAZ characterization.

VII. DISCUSSION:

Factors responsible for reheat cracking could be:

1. Rate of heating can be faster between 500 to 700 °C during stress relieving heat treatment to provide less chance to form vanadium carbide and rate of cooling. It is not only stress relief temperature and soaking time.[10]
2. Welding parameters including interpass temperature control while welding.
3. Chromium and vanadium content ratio which form the carbide susceptible to reheat cracking. Vanadium carbide is stronger than the chromium carbide.
4. Welding diameter, probably less diameter electrode would provide less heat input while welding leading to less inter pass temperature.

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