The Effect of Cold Work and Fracture Surface Splitting on the Charpy Impact Toughness of Quenched and Tempered Steels

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Quenched and tempered (QT) steels are commonly used in the manufacture of transportable pressure vessels in Australia. During the weld fabrication process sections of the head and shell are cold formed (2–5% strain) prior to welding. The effect of this plastic strain on the impact toughness of the base (parent) plate is commonly overlooked because mandatory postweld heat treatment (PWHT) is likely to counteract any effects of cold work. However, since the PWHT of QT steels for transportable pressure vessels is currently under review in Australia, it is pertinent to consider the effect of cold work on impact toughness.

This paper specifically reports on the effect of 3.5% total strain (~3.2% plastic strain) on the impact energy values of 12 mm 700 grade QT steel. This steel, although not currently classified as a pressure vessel steel, is being considered as a potential steel for transportable pressure vessels based on its superior impact and fracture toughness to 700PV grade (currently used for transportable pressure vessels). It was found that a permanent strain of 3.2% significantly reduced the impact toughness of the 12 mm 700 grade steel, and that PWHT (545°C) resulted in recovery of the impact energy to a level similar to that for PWHT of non-cold worked steel.

This paper also reports on the role of splitting on the impact energy values of 700PV grade (11 and 20 mm) and 700 grade (12 mm) steels. Reports in the literature and the current work suggest that steels with a tendency to split record impact energy values significantly lower than similar steels that do not exhibit splitting. However, when other variables are kept constant, an increased incidence of splitting of the Charpy fracture surface was found to be associated with higher impact energy values. It is concluded that variable degrees of splitting is a major contributor to the well-known scatter in impact test results.

KEY WORDS: postweld heat treatment; quenched and tempered steel; impact toughness; cold work; transportable pressure vessels; plastic strain.

1. Introduction

Quenched and tempered (QT) steels are used in the weld fabrication of transportable pressure vessels because they satisfy requirements for tensile properties and toughness. Two types of QT steels were investigated in this project, 700PV grade (11 mm and 20 mm in thickness) and 700 grade (12 mm in thickness).

The 700PV grade is a pressure vessel grade steel designed to have a minimum impact energy of 40 J at −20°C, an ultimate tensile strength (UTS) of 720–790 MPa and a yield strength (YS) between 690 MPa and 93% of the UTS. On the other hand, the 700 grade steel is a structural steel with a lower alloy content and significantly higher impact energy than the 700PV grade. The 700 grade steel is considered to be a possible candidate for transportable pressure vessels because the critical properties of impact and fracture toughness properties are superior to those of existing pressure vessels.

All transportable pressure vessels, regardless of their plate thickness, require mandatory postweld heat treatment (PWHT) as specified in the Australian Standard for Pressure Vessel Manufacture.3) The main role of PWHT is to relieve vessels of elastic residual stresses by allowing plastic flow at the stress relieving temperature as a result of a decrease in yield strength.4) In addition, stored strain energy is dissipated by thermally activated re-arrangement and annihilation of dislocations. The need for PWHT in low thickness applications (<20 mm) is being scrutinised because the occurrence of hydrogen assisted cold cracking in the heat affected zone (HAZ) and weld metal (WM) is unlikely (due to slower cooling and improved ductility in thinner walled vessels).

Cold forming of the plate is an essential step in the fabrication process, since it is done to obtain the design shape of the vessel. Typically the cold forming process in the manufacture of pressure vessels can induce permanent plastic strain between 2–5% in the parent metal (PM). PWHT is believed to be necessary for mobilisation and annihilation of dislocations that increase in density as a result of the cold work.5)

Splitting or delamination of the Charpy fracture surface
is common in the PM of 11 and 20 mm 700PV grades and relatively uncommon in the PM of 12 mm 700 grade. This paper delves into the reasons for this difference and the effect of this phenomenon on impact energy values, using microscopy and hardness as analytical tools.

2. Procedure

2.1. Materials Selection

Quenched and tempered steel has widespread use in the transportable pressure vessel industry in Australia. Bisalloy Steels Pty Ltd supplies steel plate for this market and the company provided QT steel plate for the current project in thicknesses typically used for transportable pressure vessels (11, 12 and 20 mm).

The 11 and 20 mm plate are classified as 700PV grade (pressure vessel plate) in accordance with AS3597-1993.6) The 12 mm 700 grade plate is QT structural plate and considered a possible candidate for pressure vessels. The measured compositions of the plates are shown in Table 1.

2.2. Heat Treatment

Postweld heat treatment of all samples was carried out in a box furnace. Heat treatment conformed to AS4458-1997 Pressure Equipment Manufacture, and was conducted in an argon atmosphere.

The temperature of treatment was 570±5°C (validated by two thermocouples attached to each plate), and the holding time was 30 min. The ramp up rate was 200°C/h and samples were then cooled at 250°C/h to 400°C, followed by still air cooling. Cold worked samples were subjected to still air cooling only and a PWHT temperature of 545°C to minimise the effects of oxidation on samples, perilously close to 10 mm prior to final machining. All heat treatment procedures complied with AS4458-1997.3)

2.3. Impact Testing

Impact testing of the PM was carried out on 11, 12 and 20 mm plate in accordance with AS1544-1989. A striking energy of 325 J was used and the test temperature selected was 20°C as required by the Australian Pressure Vessel and QT Steel Standards (Australian Standard 3597, 1997). Impact energy was averaged from 5 test pieces in each group of tests.

Samples were standard size (Fig. 1(a)) and machined from the middle of the plate to assess impact energy where banding and segregation effects would be most severe. Impact test results are presented for the as-received and postweld heat treated plate for the orientation shown in Fig. 1(b). In this orientation (T-L) the length of the sample is transverse to the rolling direction and the notch propagates fracture in the direction of rolling.

Additionally, Charpy impact testing was carried out before and after PWHT on 3.2% plastically strained 12 mm 700 grade samples in the T-L orientation. These samples were uniaxially strained in tension transverse to the rolling direction and then machined into standard size Charpy samples prior to PWHT (Fig. 1(a)).

2.4. Hardness Testing

Microhardness traverses were taken across microstructural banding in a 20 mm 700PV grade sample. The load used was 25 g.

2.5. Microscopy—Low Magnification, Optical and SEM

Low magnification microscopy (~20×) was used to observe Charpy fracture surface features. Optical microscopy was used to evaluate the effect of microstructural banding and segregation on the occurrence of splitting. The fracture surfaces (splits) of Charpy samples were then investigated by SEM.
3. Results

3.1. Microscopy of As-received Material

Figure 2 shows the as-received quenched and tempered martensitic microstructure for the 11, 12 and 20 mm QT plates. Figure 3 reveals the banding present in QT steels through austenitising at 950°C and slow furnace cooling.

3.2. Impact Toughness—Effect of Cold Working

Figure 4 shows the effect of 3.2% permanent plastic strain on the impact toughness of 12 mm 700 grade at −20°C. This figure also shows the impact energy of the plastically strained materials after PWHT.

3.3. Impact Toughness—Effect of Splitting

Figure 5 shows the impact energy of all plates before and after PWHT in the T-L orientation at −20°C. This figure also shows the effect of splitting on impact energy when all other variables are kept constant (see Fig. 6).

Figure 7 shows that splitting occurs in the darkly etched region of the microstructure (shown by EDS analysis to be
richer in Mn by about 0.5 wt%). Splitting is also associated with brittle intergranular failure (Fig. 8).

Figure 9 shows a SEM fractograph of a large void formed by a large TiN particle ahead of the crack tip. These second phase particles (typically TiN or MnS) vary in size and hence voids of different sizes can form during fracture, depending on the distribution of particles ahead of the crack tip zone.

3.4. Hardness

Figure 10(b) shows the hardness values traversing microstructural banding below the split shown in Fig. 10(a). The bands that etched darkly (Mn-rich) showed a higher hardness than the bands that were lightly etched. The band relating to the split shown in Fig. 10(a) had a Vickers hardness value of 315 VHN. Fig. 10(a) also verifies that splitting is associated with thicker Mn-rich bands.

4. Discussion

Impact toughness is an important property of transportable pressure vessel steels. Australian QT Steel Standards specify for quenched and tempered pressure vessel steels that the impact energy based on an average of three Charpy samples in the T-L orientation should be no less than 40 J at -20°C. Orientation of the test piece is im-
important in quenched and tempered steels, even though the as-received martensitic microstructure in a standard Nital etch shows no sign of microstructural banding and segregation arising from the casting and rolling processes (Fig. 2). However, etching in Saturated Picral does reveal that centre-line segregation and microstructural banding can be significant in QT steels (Fig. 7). Moreover, austenitising and slow cooling provides clear evidence of the presence of bands enriched in Cr and Mn, through C partitioning during cooling from ferrite formed in alloy lean regions (higher Ar₃) into the alloy enriched regions (lower Ar₃) where pearlite bands subsequently develop (Fig. 3).

A major concern of this project was to investigate the effect of PWHT on the Charpy V-notch impact properties of the PM region of QT steels. The parent region is of paramount concern to the pressure vessel industry because this is the zone where reported failures in traffic collisions have generally occurred. Figure 5 shows a column graph of impact energy before and after PWHT of unstrained parent plate. It is evident from this figure, irrespective of PWHT, that the impact toughness of 12 mm 700 grade is superior to 11 mm and 20 mm 700PV grade. This figure also shows that PWHT is detrimental to the ‘strain free’ QT parent plate, due to structural coarsening, particularly of carbide precipitates. It is evident from Figs. 3 and 4 that after PWHT, strained (3.2%) and unstrained plate exhibited similar impact toughness values, which were significantly lower than that of the as-received plate (by approximately 25 J). Therefore, although PWHT is effective in normalising differences in impact properties of differentially strained regions of the plate, it also significantly degrades the impact properties.

A uniaxial plastic strain of 3.2% decreased the impact energy of 12 mm 700 grade (T-L) at −20°C by approximately 30 J (Fig. 4). This decrease in impact energy is due to the significant increase in dislocation density as a result of cold working, which in turn increases strength and decreases ductility. PWHT at 545°C for 30 min increased the impact energy of plastically strained 12 mm 700 grade (T-L) by approximately 5 J. This slight increase is due to the recovery process. Recovery by dislocation annihilation and redistribution into subgrain boundaries is much more pronounced at higher treatment temperatures, but the PWHT of the QT steel was conducted well below the plate manufacturer’s tempering temperature to preserve the mechanical properties of the QT steel.

Figure 6 shows low magnification images of Charpy fracture surfaces of the parent plate of 11 mm 700PV grade, 12 mm 700 grade and 20 mm 700PV grade (various PWHT status). Significant splitting is evident in most of these macrographs, except the 12 mm samples. It has been suggested that steels with a tendency to split or delaminate generally have lower impact energies than those that do not. The 700PV grade plate (11 mm and 20 mm) has lower impact energy values than the 700 grade plate (12 mm) due to the higher contents of alloying elements such as Cr and Mn, which are known to segregate and promote splitting. For example, in the T-L orientation the 12 mm PM plate has an average impact energy value of 104 J and the more highly alloyed 20 mm PM plate has an average impact energy value of 60 J, and shows more pronounced splitting (compare Figs. 6(b) and 6(c)). DeArdo stated that splitting of the fracture surface of mechanical test specimens (tensile and impact) was found to occur when the levels of Cr in HSLA steels were ≥0.5%. However, the present results indicate that levels of less than 0.5% Cr can have an effect on splitting (Table 1).

Although banding was identified in the 12 mm 700 grade steel (Fig. 3(b)) the lower contents of Mn and Cr, and the relative absence of splitting in Charpy test pieces, indicate that the more heavily banded segregation in the 11 mm and 20 mm steels (Fig. 3) is significantly more prone to splitting. The prominence of splitting in the more highly alloyed 11 mm and 20 mm steels indicates embrittlement along alloy enriched bands (Fig. 10). Therefore variations in Charpy behaviour is directly related to the compositional and structural differences between the 700 and 700V grades.
of steel.

It is demonstrated in Fig. 6, that splitting or delamination in the Charpy fracture surface is the main reason for a significant scatter in impact energy values. Splitting exerts a strong effect on the impact energy required to cause failure in high strain rate tests. It is a phenomenon that occurs in some steels and not others. Factors that have been reported to influence the initiation of splitting in Charpy V-notch samples are chemical composition (in particular, the presence of Mn), microstructural banding and centre-line segregation. Regardless of the notch orientation, splitting results in scatter of impact energy values. Samples with identical notch orientation and exposed to the same conditions can show different impact energies depending on their ability to initiate splits. Results from work carried out on 11, 12 and 20 mm samples show that increased splitting results in an increased value of impact energy when all other variables are kept constant (Fig. 6). It is proposed that this trend is a result of the increased fracture surface area, due to branch cracks propagating normal to the general crack plane, as well as the mechanism by which these splits initiate.

Even though the increased incidence of splitting increases the impact energy of a Charpy sample exposed to the same conditions, it is associated with intergranular failure (Fig. 8), which normally results in lower impact energies. Therefore, the impact energy values are expected to be lower than for steels that do not show splitting. It is evident in Fig. 8(b) that splitting initiates by microvoid formation and linkage at prior austenite grain boundaries in regions containing the Mn and Cr rich bands. Since the elements Cr and Mn are concentrated in these regions, their stronger carbide forming propensity than Fe, should ensure more pronounced carbide precipitation during tempering, particularly at prior austenite grain boundaries. It is proposed that these particles can nucleate voids that link to produce intergranular fracture. The microplasticity associated with the fracture process is expected to contribute to the required energy of fracture.

Figure 10(b) shows the hardness profile below the split shown in Fig. 10(a). The bands that etched dark (Mn rich) recorded a higher hardness than the bands that did not etch dark. The band where the split is shown in Fig. 10(a) had a Vickers hardness of 315 VHN and is a thicker band. Thicker bands and an increase in the localised hardenability in the Mn-rich bands due to the segregation of key alloying elements are therefore associated with the splitting phenomenon.

The incidence of splitting was also reported by Ryall and Williams to decrease in the lower portion of the DBTT curve. The superior toughness of 12 mm 700 grade is evident in Fig. 5. After PWHT, the 12 mm 700 grade plate has an impact energy of approximately 85 J and the 11 mm and 20 mm 700PV grade plates respectively have impact energies of approximately 38 J and 50 J. The higher impact energy of 12 mm plate is due to relatively less microstructural banding (Fig. 3); a lower alloy content that reduces the susceptibility to splitting; and lower carbon and alloy contents (Table 1) that significantly lower the DBTT. The 11 mm BIS80PV plate contains approximately 40% more sulphur than the 20 mm BIS80PV plate, and therefore has a lower impact energy than the 20 mm plate. Sulphur is a tramp element that combines with Mn to form MnS inclusions, which have a deleterious effect on impact toughness.

The 11 mm and 12 mm plates contain bands of pearlite that are thinner than those in the 20 mm plate (compare Figs. 3(a)–3(b) and Fig. 3(c)). Thicker banding, mainly in the plate mid-section, is evident in the 20 mm plate because the plate thickness reduction ratio (RR) as a result of hot rolling determines the thickness of the segregated layers, and the resulting thickness of the pearlite bands and their elongation in the rolling direction. Assuming a 200 mm thick cast strand, the RR is 10 : 1 (90% total rolling reduction) for 20 mm plate but 18 : 1 (94.5% total rolling reduction) for 11 mm plate.

Apart from splitting, there are other factors that contribute to the scatter of impact toughness values, namely:

- Size and distribution of MnS and TiN particles, which play an influential role on the final impact energy value by creating fracture acceleration sites (see Fig. 9).
- Fracture acceleration sites lower the impact energy by promoting formation of large voids or regions of easy (cleavage) fracture.
- Test completion time. The Australian Standard for impact testing states that the non-room temperature tests must be completed within 6 s of being removed from the temperature bath. A ‘fast’ test would result in a lower impact energy value than a ‘slow’ test performed within the 6 s time limit.
- Variations in machining can influence impact energy. The most critical dimension is the radius of the notch, with sharper notches leading to lower impact energies than more well-rounded notches. Verification of sample dimensions and tolerances is imperative for statistically valid data.

5. Conclusions

The following conclusions are drawn:

1. Plastic strain resulted in a significant reduction in impact energy by subsequen PWHT “normalised” the Charpy impact energies of both strained and strain-free samples of 12 mm 700 grade QT steel.

2. The impact toughness of the 20 mm 700PV grade plate was greater than the impact toughness of the 11 mm 700PV grade plate, because of a more favourable chemical composition. The impact toughness of the 12 mm 700 grade plate was higher than that of the 11 mm and 20 mm 700PV grade plate because of a leaner chemistry and more favourable as-rolled structure.

3. The variations in impact energy for the Charpy tests performed are attributed mainly to the amount of splitting or delamination and the number of fracture acceleration sites that result in large voids or cleavage cracks ahead of the crack tip. For the same steel and test conditions higher impact energies were found to be associated with more pronounced splitting. This effect is attributed mainly to the increased creation of crack surface area.
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