



Corner cracking associated with the production of square tubing from low carbon ferritic stainless steel

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Synopsis

Low carbon 11.5% chromium stainless steels are finding increasing use in industry as square or rectangular tubing material for the construction of structures by welding. During processing, resistively welded circular pipes are bent into square or rectangular shapes. During this process longitudinal cracks can sometimes develop at one of the inner corners of the section. An investigation has shown that the processing of round into square tubing with very sharp corners can cause excessive cold working at the inner corners of the squared tube. This, together with the high tensile residual stresses and a susceptible microstructure due to the presence of grain boundary carbides, can result in brittle cleavage cracking. Measures that can be used to reduce the problem are described.

Introduction

Square or rectangular tubular sections are preferred in the construction of structures due to the ease with which such square sections can be joined at any angle by welding, as opposed to the joining of round pipes which requires complex profiling. The best fit between angled tubes can be attained when the corners are as sharp as possible. On the other hand, some material saving can be achieved by using a fairly large bend radius at the corners. By using less sharp corners, less ductile material can be squared without the danger of cracking. An industry norm is to use a bend radius of about 2.5 times the thickness of the material.

The most common way to achieve a square or a rectangular shape is to use a three-pass roll-forming mill. A square or rectangular shape is obtained by passing a round tube through three sets of grooved rollers. In order to produce a square tube, the material at the four corners has to be bent over a tight radius, whereas the section in between has to be straightened from the original round shape.

Bending can be produced by applying a bending moment to deform material around a curved surface, which is in contact with the material on the inside of the bend. In general,

the radius of curvature has to be smaller than the inner radius of curvature of the bend desired, as a result of elastic springback that occurs when the bending moment is released.

The springback¹ increases with an increase in the ratio of the radius of curvature to the material thickness. This is due to an increase in the flow stress and an increase in the elastic strain of the material. The amount of springback can be reduced considerably by applying a high tensile stress transverse to the direction of bending. This is particularly important when the accuracy of the final shape has to be maintained within a tight tolerance.

In the case of squaring round tubes, the bending is different in the sense that it is not practical to use dies that are in contact with the inner surface of the tube during the forming process. Instead, the external radius is governed by the radius of curvature of the grooved roll that is used to square the round pipe. Again in this case, especially if a tight bend is required, a compressive force transverse to the direction of bending is required to upset the material to make intimate contact with the grooved roll at the bend.

In the case of pure bending, where the neutral axis is at the centre of the section, the tensile and compressive strains on the outside and the inside of the bend, respectively, will be equal. Consequently, the external perimeter of the bent material will be greater than the original dimension.

Bending, together with the application of a high compressive stress transverse to the direction of bending, can be achieved by adjusting the roll gap so that the external perimeter of the squared profile is equal or even smaller than that of the original circular profile. A high transverse compressive force during bending will result in a shift of the neutral axis at the bend, from the centre of the section towards the outer corner of the bend.

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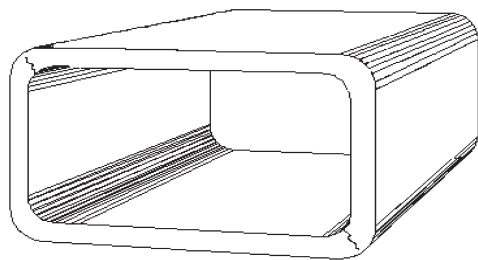


Figure 1—Schematic representation of cracks forming on the inner radii after bending

Table I

Typical chemical analysis of the material used

	C	Mn	S	P	Si	Ti	Cr	Ni
Typical comp.	0.03	1.5	0.03	0.04	1.0	0.6	11.0	1.5
	max	max	max	max	max	max	12.0	max

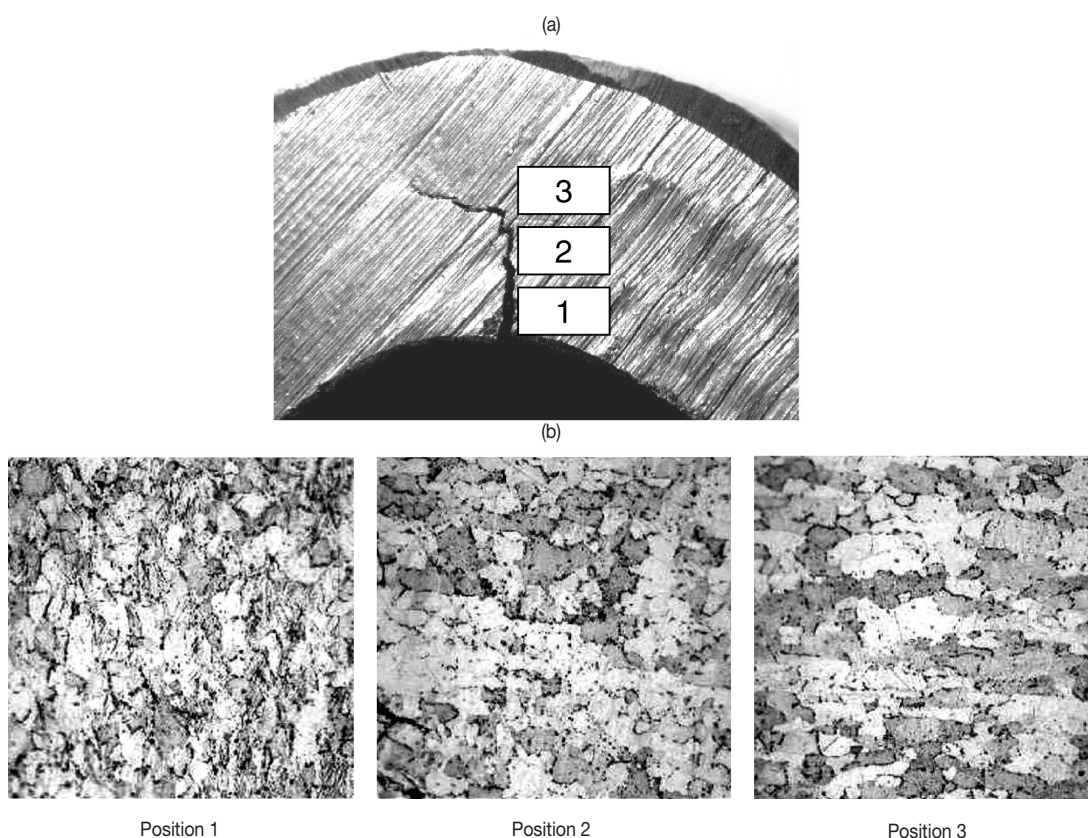


Figure 2—Microstructure at different positions within tube wall. (a) Cross-section through tube wall, showing the locations (numbers 1 to 3) where the microstructure was determined. (b) Microstructures at the three different positions. The orientation of the micrographs is as shown in (a).

Consequently, the bending strain and also the work hardening will be greater at the inner radius than at the outer radius.

Investigation

Cracking of square and rectangular sections, manufactured from 11.5% chromium low carbon ferritic stainless steel, occurred during sectioning when some of the tubes were sawn to length. Cracking occurred radially at the bend, originating from the inner corner as shown in Figure 1.

Cracking was frequently accompanied by an audible sound and occurred more frequently when the ambient temperature during sawing was low. Table I gives a typical chemical analysis of the material used.

The steel is a weldable, corrosion resistant steel and an alternative to carbon steel where corrosion is a problem. During the final stages of hot rolling, the material is usually deformed within the ferrite-austenite phase field. Consequently, the final grain structure has a distinctive 'pancake' shape. The mechanical properties are usually also anisotropic. Following hot rolling, some of the hot rolled coils are frequently cooled to room temperature by capping with a lightweight thermal insulated hood ('hood cooling'). This reduces the rate of cooling sufficiently to enable the austenite to transform to ferrite by nucleation and growth. On the other hand, the rate of cooling in air is usually so rapid that the austenite will transform to martensite, necessitating an additional annealing heat treatment cycle at 750°C to temper the martensite phase.

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Figure 2 shows a typical example of a cross-section at the corner of a tube with a radial crack, which originated at the inner corner of the tube. The external radius of curvature at the bend is smaller than at the inner radius, which is indicative of the high degree of compression that was applied during squaring. The thickness of the material at the bend was also about 15% larger than the original thickness, which is indicative of the upsetting that accompanied squaring. The external radius of curvature of the bend was about 1.5 times the thickness of the tube material, which represents a very sharp bend indeed. Figure 2 also shows the grain structure of the hood-cooled material at three different radial positions. From these photographs it is clear that the compressive strain at the corner radius was so high that the initial 'pancake' grain structure was re-oriented into a radial direction.

Hardness profiles (Figure 3) confirm this. The high hardness at the inner corner (approximately 250 HV, in comparison with an original hardness of approximately 180 HV) is indicative of the high degree of cold working, which occurred at the inner corner during squaring. The hardness at the outer corner was only slightly higher than the original hardness.

Scanning electron microscopy (Figure 4) of the slow cooled material showed the presence of a semi-continuous phase identified as $M_{23}C_6$ on the grain boundaries². Figure 5

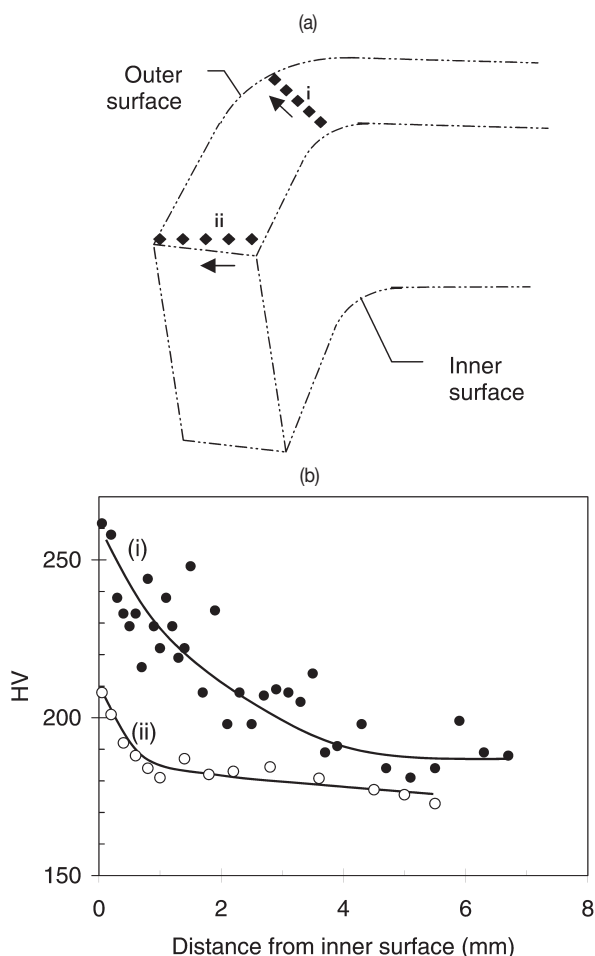


Figure 3—Hardness profile through the tube wall. (a) Schematic showing the positions of the hardness measurements. (b) Hardness profiles along lines (i) (at the corner) and (ii) (away from the corner)

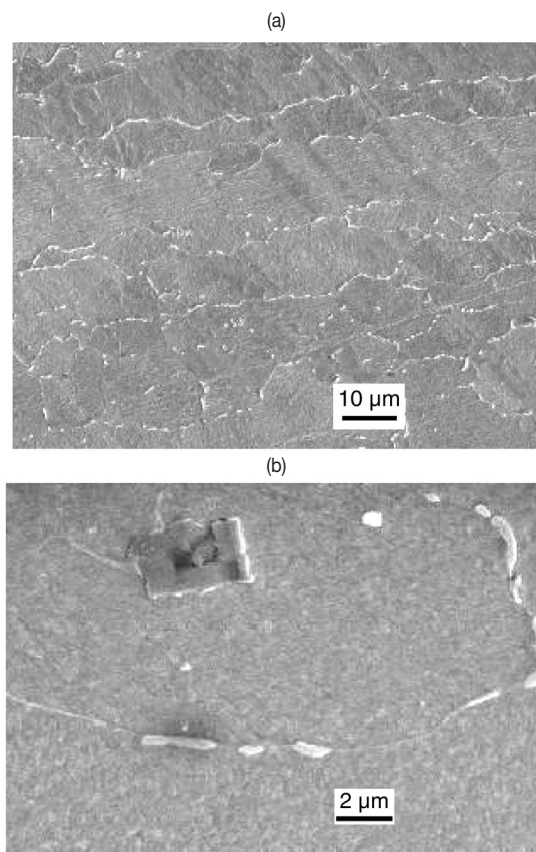


Figure 4—Scanning electron micrographs showing the semi-continuous carbide network on the grain boundaries, at (a) lower and (b) higher magnifications

shows the morphology of this phase as seen in a transmission electron microscope.

Discussion

The fracture surfaces, when examined by SEM, were typical of brittle transgranular cleavage. Charpy impact test specimens (substandard 5 × 10 × 50 mm Charpy specimens taken transversely to the rolling direction of rectangular tube



Figure 5—Transmission electron micrograph showing the typical location of the carbides on the grain boundaries (magnification 9000x)

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sections), fractured within the transition temperature range when examined in the vicinity of the fracture surface, frequently contained micro-cracks as shown in Figure 6. It was found that these micro-cracks invariably originated as a result of the cracking of the $M_{23}C_6$ carbides on the grain boundaries³.

Flattening tests on portions sectioned from the corners of the tube were also carried out. Prior to flattening, some of the specimens were heat treated at comparatively low temperatures. As shown in Table II, heat treatment at a temperature as low as 300°C was sufficient to allow flattening without cracking.

Conclusion

From the testing it is clear that there are at least four factors that contributed to the internal cracking of the tubes:

Carbide precipitation at the grain boundaries

It can be expected that a semi-continuous network of brittle carbides on the grain boundaries will result in an increase in the ductile to brittle transition temperature (DBTT), in spite of the small grain size of the material. This, together with the high degree of cold working at the inner corner, can result in brittle cleavage failures at ambient temperatures.

Continuous cooling transformation studies on the material have shown that during slow hood cooling, carbide

precipitation on the grain boundaries precedes the transformation of austenite to ferrite. Fast cooling of hot rolled strip material to a temperature of 700°C, before hot coiling and further hood cooling will reduce the precipitation of grain boundary carbides in comparison with hot coiling at a high temperature.

Alternatively, direct air-cooling of the material after hot rolling will completely eliminate the grain boundary precipitation. The austenite present will then transform to martensite, necessitating a subsequent temper heat treatment at 750°C. The temper heat treatment usually results in the random precipitation of carbides rather than a semi-continuous network of grain boundary carbides.

Sharp bending of the corners

The very sharp bend at the corners was associated with a high degree of cold working at the inner radius. It is well known that cold working increases the DBTT and the sharper than usual bend resulted in material that was more susceptible to cracking by cleavage⁴.

Orientation of the grain boundaries at the bend

The precipitation of carbides on pancake grain boundaries in material that is strained or stressed in the longitudinal direction of the grains is not nearly as detrimental to straining at right angles to the longitudinal direction of the grains⁵. It has been shown that the compressive upsetting at the inner corner resulted in a re-orientation of the longitudinal grain direction into a radial direction. Any tensile straining at right angles to the radial direction can cause premature brittle cracking by cleavage, as was experienced.

The presence of residual stress

Bending as a result of non-homogeneous deformation always results in a residual stress pattern after bending. The sign of the residual stress is usually opposite to the direction of the stress that had been applied during bending. At the inner corner, high tensile residual stress tangential to the bend can therefore be expected⁶. During sawing, the local force and moment equilibrium of the residual stress pattern is disturbed. It is undoubtedly the presence of high tensile residual stress that caused the cracking. Heat treatment at a comparatively low temperature was probably sufficient to relieve some of the high residual stresses and also sufficient to cause some recovery of the cold worked structure, eliminating the incidence of cracking during flattening of the bends.

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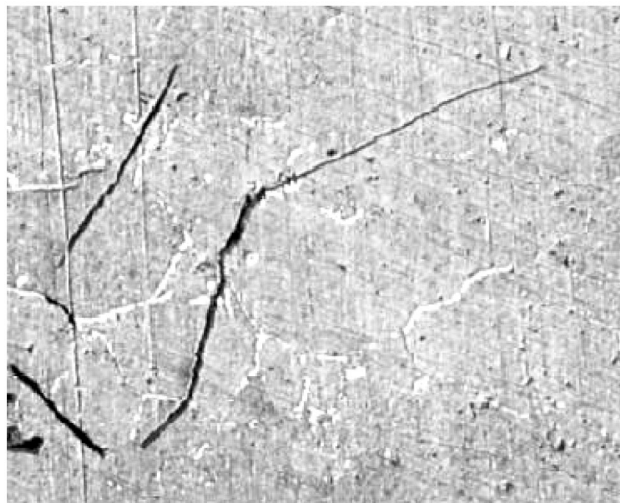


Figure 6—Typical location of crack initiation in Charpy test specimens

Table II

Effect of heat treatment on ductility of corner samples

Sample	Heat treatment (one hour)	Failure after flattening
1	As received	Yes
2	200°C	Yes
3	300°C	No
4	400°C	No
5	500°C	No