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Microstructure characterization of fractured steel beam-to-column connections

C. P. OSTERTAG
Civil and Environmental Engineering Department, University of California,
Berkeley, CA 94720-1710
E-mail: ostertag@ce.berkeley.edu

The failure of steel beam-to-column connections during the Northridge earthquake of January 1994 was both surprising and alarming to the structural engineering community. These steel moment resisting frames (SMRFs) are intended to behave in a ductile manner. However, in many steel buildings inspected in the Los Angeles area after the Northridge earthquake the connections exhibited brittle fracture. Despite recent laboratory testing of numerous large and small scale structural connections reasons for brittle fracture are still not clearly understood. Therefore, rational design methods to prevent or control brittle fracture in building structures have not been established. This paper investigates the contribution of the microstructure of welded connections to brittle failure. The various microstructures present in a fractured welded connection were characterized and their influence on crack initiation examined. The predominantly brittle failure is preceded in this case by a ductile crack which initiates in a brittle microstructure in the vicinity of the weld root, adjacent to the unfused backing bar. *© 1999 Kluwer Academic Publishers*

1. Introduction

The brittle fracture of connections in steel moment-resisting frames during the Northridge, California, earthquake on January 17, 1994, was both surprising and alarming to the structural engineering community. Although SMRFs are designed to behave in a ductile manner during earthquakes, field inspections showed that the critical welded beam column connections (Fig. 1) in more than 100 steel buildings in the Los Angeles area exhibited brittle fractures. The most serious occurred at welded beam-to-column joints. Similar fractures were also observed following the 1995 Hyogoken Nanbu (Kobe) earthquake, in recently inspected SMRFs subjected to the 1989 Loma Prieta earthquake and in large-scale laboratory tests. Despite extensive laboratory testing of large-and small-scale structures in both the U.S. and Japan since these earthquakes, the numerous factors leading to brittle fractures have not yet been fully understood.

Brittle fracture in steel may be caused by factors related to connection configuration and joint detailing, microstructural and mechanical characteristics of the steel, weld and heat affected zones, the nature of applied and residual stresses, and presence of imperfections and discontinuities. The configuration and detailing factors are mainly controlled by the designer, or are imposed by the operating conditions and environment (i.e. strain rate, temperature, stress concentrations, notch effects, and triaxial tensile stress states).

Microstructural and mechanical characteristics, on the other hand, may be inherent in the materials used, whether as initially supplied or as changed by the fabricating processes and/or welding procedures. Residual stresses result principally from nonuniform cooling of hot-rolled shapes, from cold straightening of bent members, and from the welding process. Quality control is an important aspect in that construction defects can adversely affect behavior. To date, the focus of the investigations of brittle fracture in SMRFs has been mostly on the configuration and detailing of connections. There has been little research conducted on the influence of microstructural factors and/or residual stresses. Residual stresses can have a significant effect and measurements of these stresses in welded beam-to-column joints by acoustic microscopy are addressed by Ostertag and Drescher-Krasicka [1]. The current paper focuses on microstructural factors associated with welding that might also contribute to brittle fracture.

The ductile versus brittle behavior of a welded steel joint is strongly influenced by microstructure. Microstructure and other characteristics vary among the base materials in the column and beam, the weld, and the heat-affected zones. Microstructure within the weld is modified considerably by the multiple pass welding process typically employed wherein regions undergo multiple thermal cycles, resulting in inhomogeneous and complicated microstructures. The coarse grained region of the weld can be roughly categorized into four zones according to the reheating temperature: an unaltered coarse grained zone (the zone that is not reheated or reheated above the transformation temperature Ac_3), a supercritically reheated coarse grained zone (the zone reheated just above Ac_3), an intercritically reheated coarse grained zone (the zone reheated between Ac_1

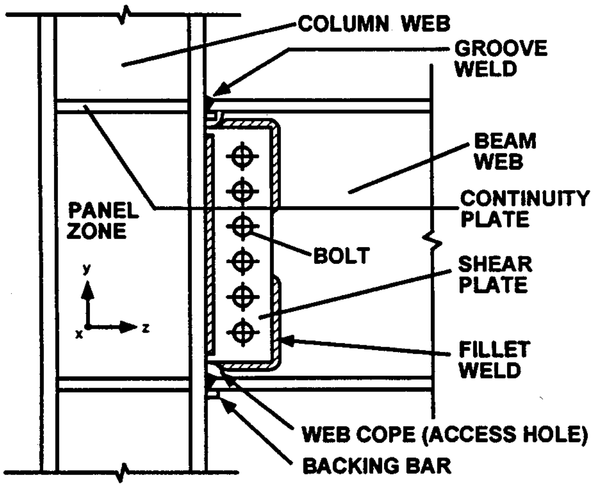

Figure 1 A typical welded beam-to-column connection [3].

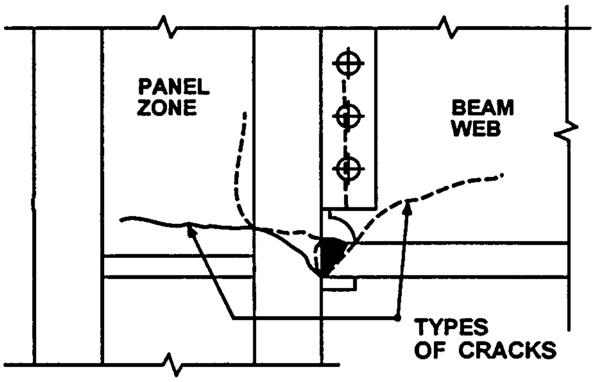

Figure 2 Common crack formations in welded beam-to-column connections [3].

and Ac_3) and a subcritically reheated coarse grained zone (the zone below Ac_1).

In order to assess the properties of these welded joints one needs to identify the various microstructures that are present due to welding processes, consumables and procedures, and determine the ability of the resulting joint to accommodate stress through plastic flow (i.e. their toughness). To explore this situation microstructure analysis were performed and mechanical properties determined near the fracture in large scale steel beam-column connection specimens tested at the University of California at Berkeley [2]. Macro and microscopic examinations of the fracture surfaces and a detailed mapping of the underlying microstructures was conducted. Crack initiation occurs at the weld root where a high strength, but low toughness, microstructure is prevalent.

2. MRFs connections and their failure modes

In welded beam to column moment resisting connections (Fig. 1), the top and bottom flanges of the beam are welded directly to the column by multiple pass, full penetration groove welds using self-shielded flux cored arc welding. The beam web is bolted or welded to a shear tab which is attached to the column by welding. Prior to the Northridge earthquake welds were typically executed using E70T4 weld consumables. These have no specified toughness properties. A backing bar is located at the bottom of the welded joints adjacent to the weld root. The backing bar was typically left in place following welding leaving an unfused interface between the column and the backing bar. This constitutes a stress concentration adjacent to the weld root.

To replicate the failure modes of Pre-Northridge SMRF connections, a number of specimens were fabricated according to the practices used before the 1994 Northridge earthquake and tested [2] at UC Berkeley as part of the SAC* Steel Program. Slowly varying cyclic loads were applied to the beam tip by an actuator. The beam column joint was 30.5 cm wide with beam and column flanges of 2.39 and 4.8 cm thickness, respectively. E70T4 was used as the weld metal. The dimensions, testing procedures, and complete test results of the steel beam column connections are reported elsewhere [2, 3].

The moment resisting frames under seismic loads are expected to form plastic hinges in the beam at the face of the column (or in the beam column panel zone). However, all of the tested connections failed prematurely due to brittle fractures initiating near the root pass of the bottom beam flange to column welded joint. Fractures in two of the three specimens propagated across the column flange and into the panel zone; one fractured across the weld. All fractures initiated in the center of the bottom beam flange in the joints. The failure of the bottom flange is linked in part to the difficulties associated with welding through the access hole. The access hole prevents the welder from continuously welding across the width of the bottom flange. The failure modes of the tested connections are shown in Fig. 2 and are typical of the failure observed in buildings after the Northridge earthquake. Fractographic, microstructure and microhardness analyses were performed on one of the failed specimens to investigate if microstructural changes and low toughness regions due to welding may have contributed to the brittle fracture of the steel beam-column connection.

3. Experimental

3.1. Specimen preparation procedures

In order to avoid excessive heat application to the fracture zone which would influence the microstructure, the area of interest (i.e. the joint) was removed from the connection by flame cutting far from the fracture surface. The large torched piece then was mechanically cut into a manageable size revealing the fracture surface for fractographic analysis. Metallographic and microhardness measurements were performed on samples sectioned perpendicular to the fracture surface at three different locations: at the fracture origin, 2 cm away from the fracture origin and 10 cm away from the fracture origin. Specimens from different locations were analyzed in order to study any variations in microstructure and

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* SAC is an acronym for Structural Engineers Association of California, Applied Technology Council, and California Universities for Research in Earthquake Engineering.

mechanical properties as a function of position along the weld. After sectioning, the specimens were surface ground and polished successively to a smooth finish with 240-, 320–400-, and 600-grit SiC abrasive paper, and 15, 6 and 1μm diamond paste. The polished samples were then ultrasonically cleaned with ethanol and acetone. A nital etchant, consisting of 2 ml of nicric acid and 98 ml of methanol was used to reveal the microstructure of the beam, column and weld material. Microstructural analyses were conducted by means of optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The fractographic examinations were preceded by careful cleaning of the fracture surfaces by repeated stripping of the fracture surface with cellulose acetate replicating tape.

Due to the microstructural changes occurring over small distances (on the order of 300 μm in some areas) both within the weld and in the heat affected zones of the parent metals, the hardness of the various microstructures was measured using microhardness indentations. The microindentations were performed with a Vickers Hardness tester using indentation loads of 100 and 140 N.

4. Experimental results

4.1. Fractographic analysis

Fig. 3 shows the fracture surface. The appearance of the fracture surface reveals the overall character of the brittle fracture. The crack initiated in the center of the bottom beam flange to column welded joint at the weld root and propagated across the column flange. The location of the fracture origin is clearly indicated marked by the Chevron pattern visible in Fig. 3b, which is an enlarged view of the fracture surface close to the fracture origin.

The dominant brittle fracture was preceded by a ductile crack of 2 mm length. Fig. 4a is a SEM picture of the ductile fracture surface. The ductile fracture surface has a characteristic dimpled appearance in marked contrast to the faceted appearance of the cleavage fracture surface (Fig. 4b and c). Each dimple corresponds to a fracture nucleation site and these link up by microvoid coalescence. Fig. 4b is a SEM picture of the cleavage fracture surface corresponding to area *A* (fine-grained heat affected zone) of Fig. 3b. The cleavage fracture surface in Fig. 4c corresponds to area *B* (outside of the heat affected zone) of Fig. 3b.

The fracture surface contains spherical inclusions of various sizes ranging from 1 to 6 μm. *In situ* X-ray energy dispersive spectrometry (EDS) revealed that the inclusions contain traces of aluminum (Al), magnesium (Mg), sulfur (S), silicon (Si) and oxygen (O).

4.2. Microstructure analysis

4.2.1. Microstructure associated with crack initiation and crack propagation

The crack initiates at the weld root adjacent to the backup bar in the coarse grained region close to the fusion line. The microstructure associated with crack initiation is shown in Fig. 5. TEM analyses were required to identify each of the constituents due to its complex microstructure. The analysis revealed ferrite, martensite, retained austenite and carbides. The ferrite phase was present as grain boundary ferrite, small traces of a circular ferrite, and parallel aligned ferrite laths. Carbides were present in the form of Fe_3C. The morphology of martensite is dislocated lath type. The interlath boundaries of the ferrite laths contain martensite, austenite and carbides. This microstructure will be denoted as MAC microstructure in this paper. This MAC microstructure is associated with poor toughness as will be illustrated later. Optical micrographs taken from the weld root in sections 2 and 10 cm away from the center revealed the same coarse grained microstructure that was associated with the MAC in the center of the joint.

The change in fracture mode from ductile to cleavage did not coincide with a change in microstructure, but occurred within the same MAC microstructure. The brittle cleavage crack within the MAC structure is shown in Fig. 6. After reaching a length of 4 mm (2 mm ductile crack and 2 mm cleavage crack), the crack changed direction and propagated into the heat-affected zone of the column flange, encountering a refined microstructure (Fig. 7). This refined microstructure forms, when the column parent metal is heated above the transformation temperature (Ac_3) into the austenitic regime but low enough in temperature to suppress grain growth in the austenitic phase. The cleavage fracture surface associated with the refined microstructure is shown in Fig. 4b. Note the smaller cleavage facets associated with the fine grained microstructure compared with the coarse grained MAC structure (Fig. 6). When the fracture mode is cleavage fracture, the measured cleavage facet sizes in the coarse grained region correlate with the measured grain sizes of prior austenite [4]. The average cleavage facet size in the coarse grained region is 100 μm, which would correspond to prior austenite grains of that size range. In comparison, the average grain size of the ferrite grains in the column material is 70 μm. The prior austenite grain size of 100 μm indicates grain growth during the welding process, indicating that the peak temperature of the weld pass was far above the transformation temperature Ac_3.

4.2.2. Microstructural changes within weld region

The weld metal in the beam column connections is deposited in multiple paths, therefore, the microstructure (and hence the properties) of the early runs can be completely altered by the heat from subsequent weld passes. The variation in microstructures within the weld is revealed in Fig. 8. The optical micrograph in Fig. 8a was taken from the first weld pass. The microstructure is caused by a coarse prior austenite grain size indicating that the peak temperature of the first weld pass must have been far above Ac_3 to cause coarsening of the austenite grains. Coarse grained microstructures were observed besides the first weld bead at various locations within the weld region (Fig. 8b) and in the last weld pass (Fig. 8c). The coarse grained regions varied with

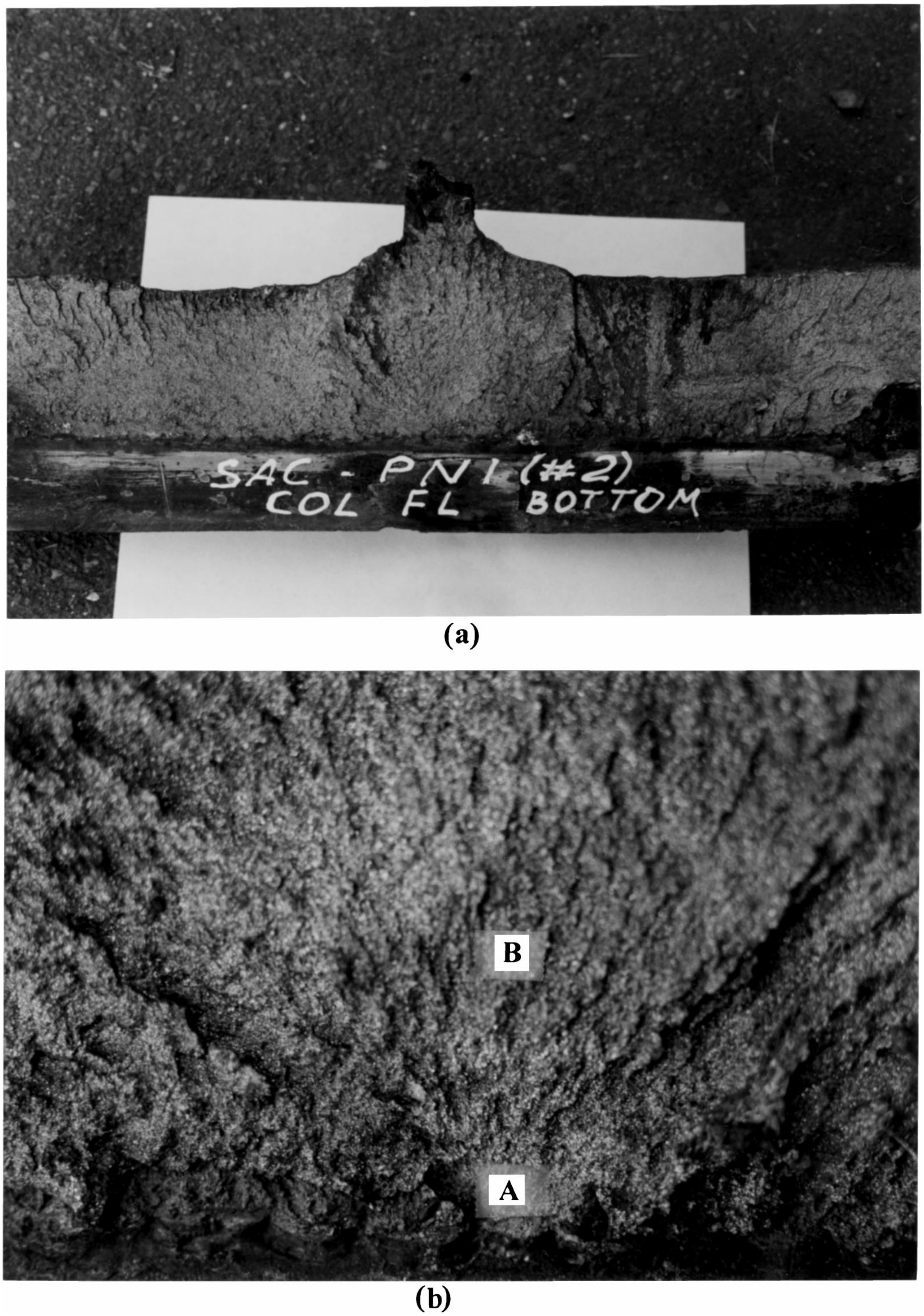
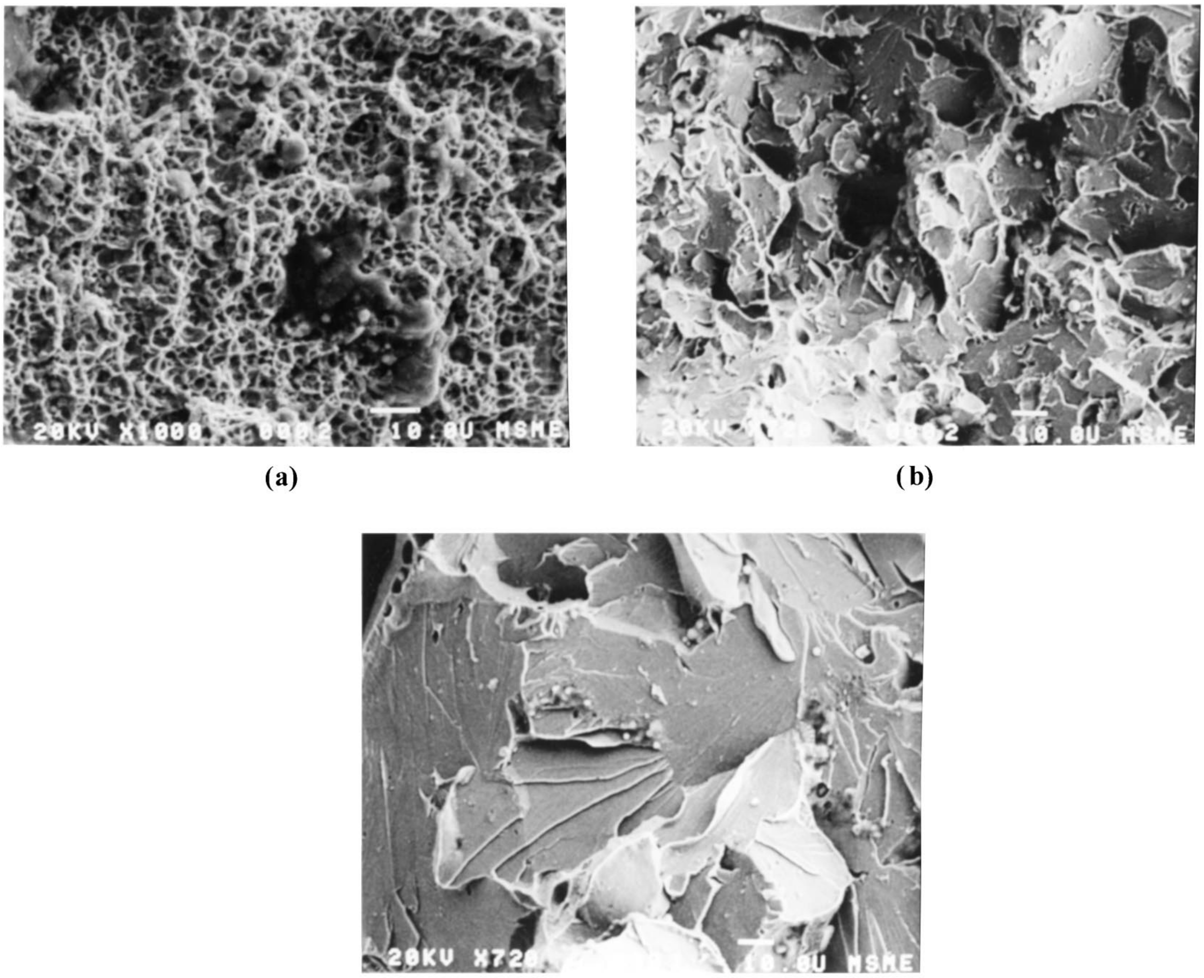


Figure 3 (a) Fracture surface of failed welded beam-to-column connection (b) Fracture surface close to the fracture origin at higher magnification.

respect to their hardness which may indicate that either the volume fraction of martensite or the carbon content in the martensite was different within the various coarse grained regions. Fine grained microstructures, an example of which is shown in Fig. 8d, were also observed at various locations within the weld region. Weld metal regions where the initial weld pass has been reheated just above Ac_3 into the austenitic regime by a subsequent weld pass reveal a very fine ferritic transformation structure. Such a microstructure is associated with good toughness. A fine grained microstructure was observed within the weld region at reoccuring distances



(a) (b)

(c)

Figure 4 Scanning electron microscope (SEM) picture of (a) ductile fracture surface, (b) cleavage fracture surface corresponding to area *A* of Fig. 3b, and (c) cleavage fracture surface corresponding to area *C* of Fig. 3b.

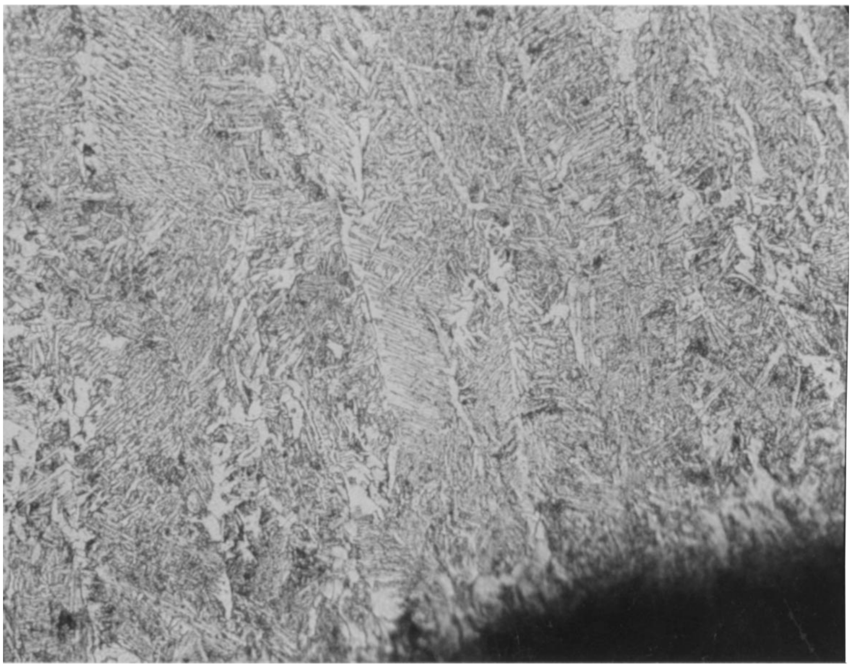


Figure 5 Optical micrograph of microstructure associated with crack initiation (magnification 200×).

of 4–5 mm between successive weld passes, except at the weld root in the center of the joint. The first refined microstructure was observed at a distance 10 mm away from the weld root.

4.3. Microhardness characterization

Each microstructure that formed within the multiple pass weld revealed different microhardness values. The hardness within the weld ranged from 3.1 to 2.85 GPa

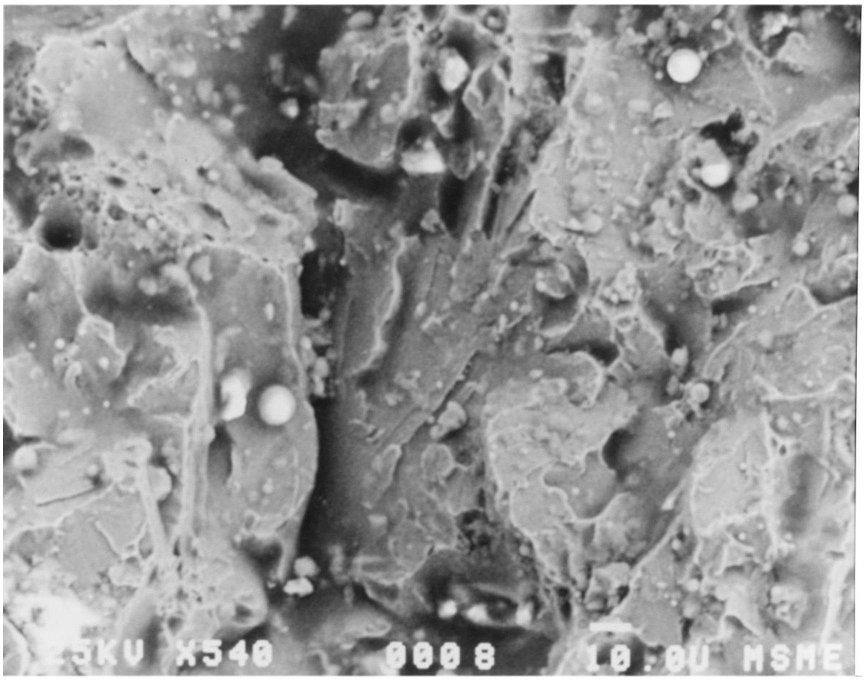


Figure 6 Cleavage fracture surface associated with brittle coarse grained MAC microstructure.

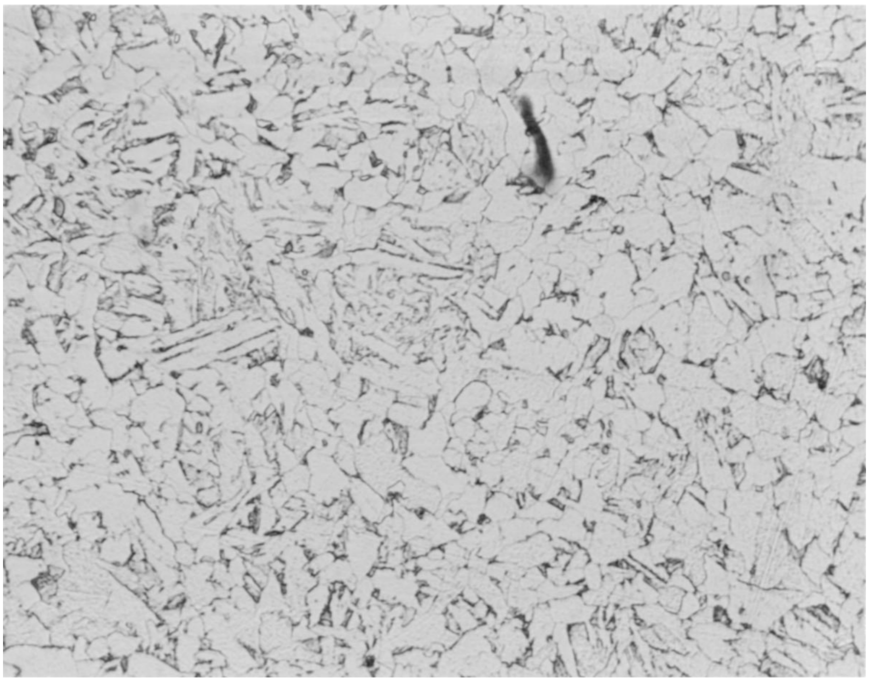


Figure 7 Optical micrograph of refined microstructure of heat affected zone in column flange (magnification 400×).

depending on the microstructure being indented. The highest hardness within the weld region occurred in the vicinity of the weld root (3.1 GPa) in the coarse grained region close to the fusion line in the center of the connection. The hardness of the weld within the coarse and fine grained microstructure decreased with increasing distance from the center of the connection. Specimens sectioned 2 and 10 cm away from the crack initiation site revealed a decrease in average hardness in the weld region of 7 and 18%, respectively. The same decrease in hardness with increasing distance from the center of the connection was also observed in the weld root.

5. Discussion

5.1. Microstructural aspects

In multipass welds, regions undergo multiple thermal cycles, resulting in inhomogeneous and complicated microstructures. The coarse grained regions have to be subdivided into zones according to the reheating temperature of successive weld passes. Therefore, even within the coarse grained regions different properties with respect to hardness, toughness and yield strength exist.

The crack in the welded joint initiates at the weld root adjacent to the backing bar. The microstructure at the crack initiation site contains brittle microstructural

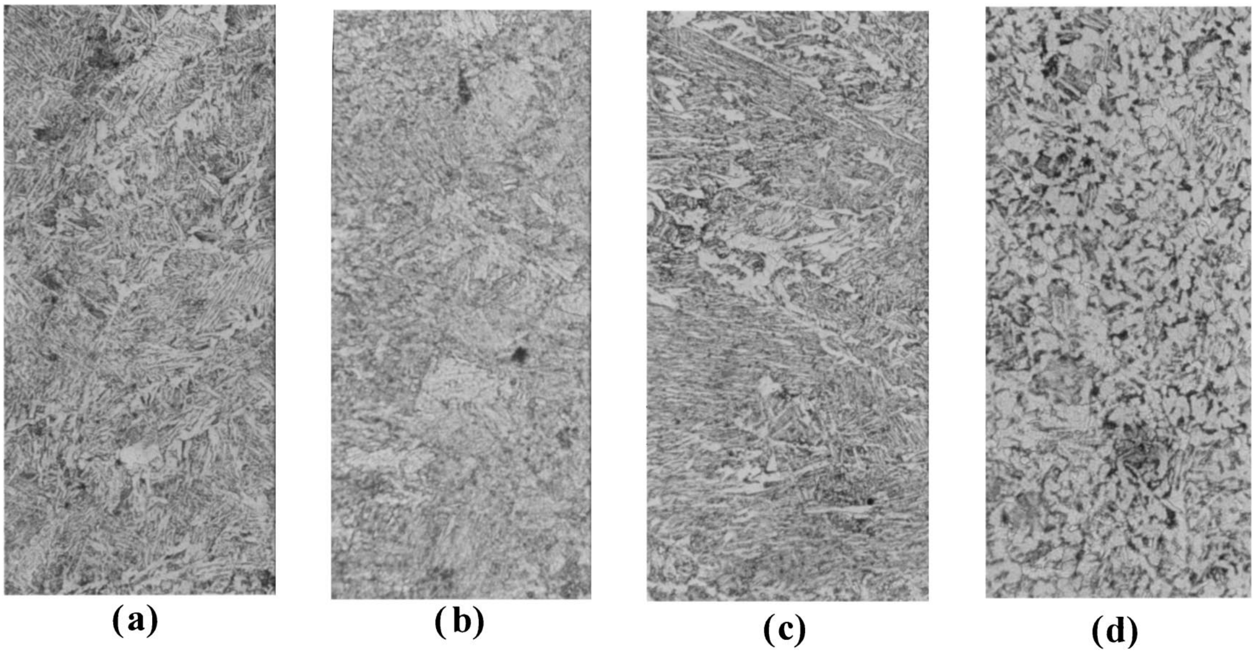


Figure 8 Optical micrographs of microstructural variation in weld due to multiple pass welding (magnification 200×); (a–c) coarse grained regions within the weld, (d) refined microstructure between weld passes.

constituents such as martensite and carbides. The microstructure, denoted as MAC microstructure, exhibits high hardness. The MAC structure is associated with the coarse grained regions which form when the peak temperature due to the welding process exceeds the temperature associated with Ac_3.

Microstructural analysis of the weld root in sections cut 2 and 10 cm away from center all revealed the same coarse grained microstructure as in the center of the connection. However, different hardness values were obtained. The hardness in the vicinity of the weld root decreased with increasing distance from the center of the joint. The difference in hardness within the different sections may indicate a difference in the volume fraction of the martensitic islands or a difference in the carbon content of the martensitic phase. The volume fraction of the martensitic islands depends on the peak temperature of the weld passes. The higher the peak temperature (i.e. $\gg Ac_3$), the higher the volume fraction of the martensitic islands [5]. Furthermore, once a weld pass is deposited at a high peak temperature, the successive weld pass may increase the volume fraction of martensitic islands even further depending on its effect on peak temperature. For example, if the first weld pass is deposited at high peak temperature ($> Ac_3$), and the second weld pass reheats the first weld pass between Ac_3 and Ac_1 (i.e. in the intercritical regime), a higher volume fraction of martensitic regions will result. The martensitic phase has a higher carbon content, further increasing brittleness. Therefore, coarse grained regions in multipass welds may differ substantially with respect to hardness, strength and toughness, depending on the thermal cycles of the weld depositions. The lack of a refined microstructure in the vicinity of the weld root in the center of the joint may also indicate that the peak temperature for the first and second weld pass where too high (i.e., above Ac_3). A refined microstructure requires the peak temperature of the first weld pass not to exceed Ac_3. The high peak temperature of the weld passes in the center of the joint may be associated with the difficulty of welding through the access hole.

5.2. Properties of crack initiation site

The weld metal (E70T4) tensile strength and toughness are assumed to be 483 MPa and 66 MPa $m^{1/2}$ [6], respectively. The toughness is based on Charpy V-notch toughness measurements. However, these properties change considerably depending on the welding procedures and conditions, the cooling rates and the resulting microstructures. The tensile strength of the microstructure in the weld root in the center of the joint (based on the hardness results) is 998 MPa, far exceeding the assumed tensile strength of the E70T4 weld metal. Since the tensile strength of this microstructure far exceeds the assumed weld tensile strength of 483 MPa, the weld metal toughness might be far below 66 MPa $m^{1/2}$ in that region.

The area that is of most interest to us is the toughness of the MAC microstructure associated with the crack initiation site (i.e. in the center of the beam column joint). However, due to the small size of the first weld bead, conventional toughness testing techniques cannot be employed. One effective way to estimate the toughness in small regions is by utilizing the indentation fracture toughness technique [7]. The crack lengths measured as a function of various indentation loads are correlated with the toughness through:

$$T = \xi (E/H)^{1/2} P/c^{3/2} \quad \text{for} \quad c \gg a \qquad (1)$$

where ξ is an indenter constant, H the hardness ($H = P/2a^2$), "a" being the distance from the center of the indentation to the corner of the indent and c the crack length.

At an indentation load of 140 N, cracks predominantly initiate from the indents when the corner of the indent is placed perpendicular to the aligned ferrite laths. This orientation of the indent corners causes a tensile stress field parallel to the martensitic phase. No cracks initiated at the indent corners in the MAC structure in sections 2 and 10 cm away from the center, confirming the more brittle, high carbon martensitic phase within the center of the joint. Toughness values using Equation 1 could not be obtained, because the observed cracks emanating from the indents did not satisfy the requirement of $c \gg a$. Nevertheless, the fact that cracks initiate from the corners of the indentations at a load of 140 N reveal a rather low toughness associated with the MAC structure at the crack initiation site.

5.3. Ductile crack preceding brittle fracture

Brittle fracture was preceded by a ductile crack of 2 mm in crack length. The change in fracture mode from ductile to brittle was not associated with a change in microstructure but occurred within the same MAC microstructure. Ductile crack initiation is most likely associated with local stress concentrations. The rapid change in cross-section in these welded joints results in local concentrations of stress and strain. Any such change results in a notch effect. It may, however, range in severity from a mild concentration, caused by a gradual change, to a very severe concentration at the root of a sharp notch. The most severe concentration occurs at the root of a natural crack. As any such concentration favors the initiation of a crack, the first concern should be to avoid, as far as possible, any severe form of discontinuity or notch, whether as a design feature or accidental. For example, the unfused interface between the backing bar and the column flange may be considered as a design related notch leading to a local stress concentration.

The change in cross section in general or the unfused back up bar in particular can be considered as a notch in steel beam column connections. Because of the large size of the column relative to the beam, the column provides considerable constraint to deformations in the joint in both the width and thickness directions. This leads to the development of triaxial tensile stresses ahead of the notch. The triaxial stress state reaches a maximum ahead of the notch tip with its magnitude dependent on the severity of the stress concentration (i.e. apex of the notch tip).

Ductile fracture in the presence of a notch occurs by microscopic fracture in front of the notch tip. The fracture is accomplished by the sequential processes of void nucleation, growth and coalescence. In the MAC structure, microstructural features such as the brittle martensite constitute potential microcrack origins. Microvoids are initially nucleated at the interface between the martensite and ferrite phase. The initial microvoids become larger along the interface as the surrounding ferrite undergoes plastic deformation. Eventually the martensite fractures in the later stage of void growth [5]. Finally, these growing voids link up to form the dimple patterns in the ductile fracture.

The stress that causes decohesion/fracture of the martensite arises from the externally imposed stress altered by the presence of the notch. Stresses are expected to be most favorable for decohesion/fracture nucleation at the elastic-plastic zone interface for small plastic zone sizes associated with a brittle microstructure such as MAC. In case of a brittle microstructure even a small stress concentration will be sufficient to cause a crack to initiate at the plastic-elastic boundary and linkage occurs directly across the plastic zone by fibrous, ductile fracture of the matrix grains.

Once a ductile crack forms it may become unstable (i.e. turn into a brittle crack) or blunt due to plastic flow ahead of the crack tip. In case of a brittle microstructure, crack tip blunting is the less likely process.

A brittle microstructure within the weld root ahead of a stress concentration such as the unfused backing bar undoubtedly contributes to brittle fracture of steel beam column connections. At this stage, however, it is not known if the formation of a ductile microstructure in the weld root adjacent to the notch associated with triaxial stress conditions could have prevented brittle fracture. The effect of a ductile microstructure in the weld root on connection behavior is currently being investigated using solid steel T-sections with various stress concentrations simulating beam column joints.

6. Summary

The microstructural and microhardness variations in failed steel-beam-column connections were investigated and the results are summarized below:

- The crack initiation occurred in the weld root in the center of the beam column joint adjacent to the unfused backing bar.
- The microstructure associated with crack initiation is a coarse grained MAC microstructure.
- Ductile crack initiation preceded brittle fracture.
- A change from brittle to ductile failure occured within the same MAC microstructure.
- The highest hardness was observed within the weld root in the center of the beam column joint and decreased with increasing distance from the center.

The brittle microstructure in the vicinity of the weld root adjacent to the unfused backup bar undoubtedly contributes to brittle fracture. In order to reduce the probability of brittle failure of welded steel beam column connections the brittle microstructure needs to be avoided specifically in the vicinity of the weld root adjacent to the local stress concentration present in beam-column joints. However, at this stage, it is not known if the formation of a ductile microstructure could have prevented brittle failure. The large change in cross section of the beam column joint which acts like a notch (with or without unfused backing bar) may cause sufficiently high triaxial stresses to develop, that even a ductile microstructure in its vicinity may not be sufficient in preventing brittle fracture in these connections, unless the notch effect in steel beam column connections is being reduced considerably.

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