WELDING HEAVY STRUCTURAL STEEL—SUCCESSFULLY

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ABSTRACT

Welding heavy structural steel entails certain challenges. As steel plate becomes thicker, as shapes become heavier, and as assemblies become more restrained, construction problems are more likely. After reviewing the background and history of welding on thick, restrained steel, this paper explains that there are four categories of challenges that must be taken into account: high shrinkage strains; high restraint; cracks and/or crack-like stress raisers; and reduced material resistance to fracture. To maximize resistance to cracking, all four areas must be considered. Residual shrinkage stresses and restraint should be reduced, the number and size of cracks minimized, and the resistance to fracture increased. Practical, field-proven examples of how these objectives can be achieved are described in 38 principles. Whereas not all of them will have to be applied to each and every job, appropriately incorporating these principles into the design, detailing, fabrication, erection and inspection of welded projects involving heavy structural steel will lead to success.

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INTRODUCTION

Structural steel is fabricated and erected successfully every day, using a variety of cost effective and dependable arc welding processes. However, as steel plate becomes thicker, as shapes become heavier, and as assemblies become more restrained, the likelihood of problems in construction increase. Whereas distortion can be problematic when lightweight sections are welded, cracking and lamellar tearing are more likely to occur as members become heavier.

The use of heavy steel appears to be on the rise. Some of this increase is due to the movement to more blast-resistant design or seismic concerns. Column-free convention spaces and sports facilities with complex moving roofs require the use of heavier steel. Regardless of the reason, member sizes for these structures are larger, and connections are more complex. The inherent rigidity associated with such connections can pose fabrication and erection challenges.

Compounding the complexities of welding under such conditions is the reality that assemblies of highly restrained members typically serve critical functions. As redundancy decreases, for example, the remaining members usually are larger and thus more restrained, and simultaneously more critical in that fewer alternate load paths exist. Accordingly, it is essential that such connections be properly designed, detailed, fabricated, and inspected.

BACKGROUND AND HISTORY

Welding on thick, restrained steel is always a challenge, and successfully welding on “heavy sections” is no exception. AISC Specification A3.1c uses this term to describe rolled shapes with flange thicknesses exceeding 2 in., and built-up heavy shapes composed of components made from plate exceeding the same dimension. In the case of the rolled sections, these were formerly the Group 4 and 5 rolled shapes, typically called “jumbo sections.” Originally contemplated for use as column sections, these shapes found use as tension members in trusses and other tensile members. Problems due to material properties, detailing practices, workmanship, and perhaps other issues, combined and resulted in some cracking during fabrication and erection (Doty, 87; Fisher and Pense, 87; Blodgett and Miller, 93).

The typical cracking that had been experienced in the past was welding-related, with the cracks occurring in the base metal, driven by the residual tensile stresses on the thermally cut surface as well as the shrinkage stresses caused by welding, not by service loads. Cracking often initiated from workmanship-related notches associated with weld access holes. Investigation into the problems revealed that near the web-to-flange interface, material existed with low Charpy-V Notch (CVN) toughness, even though at that time, the material was not required to meet minimum CVN toughness levels, nor was this region the typical ASTM CVN testing location. Small notches, combined with the high residual stress of welding and the low localized fracture toughness, enabled cracks to initiate in this region and propagate elsewhere.

AISC responded by codifying a variety of new provisions. To ensure that the base metal had adequate toughness to resist fabrication stresses, a minimum CVN toughness of 20 ft-lb at +70°F was imposed. The CVN test specimen was required to be taken from a new location; not from the flange tip as is typically the case, but from a portion of the flange directly under the web—the location expected to have the lowest CVN values (AISC Specification A3.1c).

To control notches in the area, a maximum surface roughness value was imposed. When the radius portions of the access holes were to be thermally cut, a preheat of 150°F before thermal cutting was mandated to decrease the possibility of cracking on the cut surface. As an alternative to thermal cutting of the access holes, an alternative technique was promoted, namely drilling a hole to form the radius. Although not mandated in the AISC Specification, this practice had two beneficial effects. It eliminated the potential for harmful metallurgical structures developing due to thermal cutting, as well as reducing the residual stresses from cutting. All thermally cut surfaces were required to be ground to a bright finish, and inspected with magnetic particle or dye penetrant.

To help minimize the concentration of residual stresses from welding, the weld-access holes were modified and increased in size, not simply for welding access, but to minimize the interaction of multi-directional residual stress fields created by the weld shrinkage.

Time and experience have shown that the provisions for welding on heavy shapes were appropriate and that when they are followed, such materials can be welded—successfully.

A fair question remains, however: if there are potential problems with welding, why not just bolt the sections together? The answer lies in economics. Various cost comparisons have been made (Miller, 93) which suggest welded connections may be up to 75% less expensive for comparable performance.

The AISC Specification Commentary C-J1.5 suggests a combination welded/bolted design might be a viable alternative to an all welded connection for splices of rolled shapes with flanges that exceed 2 in. However, a quick review of the connection sketch in Figure C-J1.1 and the associated details shows that the figure is intended as an illustration only. A detailed connection employing bolts on one of both sides of a tension connection would be much more complicated and expensive.

UNDERSTANDING THE BASICS

A review of some historical problems and the codified corrective measures highlights the factors involved, which can be summarized in the following four categories:

- High shrinkage strains
- High restraint
- Cracks and/or crack-like stress raisers
- Reduced material resistance to fracture

Shrinkage strains are created when localized portions of the base metal are heated and hot weld metal is deposited during welding operations. The hot, locally expanded metal must volumetrically shrink as it cools. If the whole weldment was all at the same temperature, it would globally expand and globally shrink. This, however, is not the case with structural steel weldments; only a small portion of the structure is heated.

The colder steel that surrounds the hot metal associated with a weld provides restraint. As the hot metal shrinks upon cooling, the surrounding steel resists the shrinkage. The combination of high shrinkage strains and high restraint lead to high residual stresses. It is essential to understand that both factors are involved. If metal didn't shrink when it cooled, there would be no residual stresses. Likewise, if the surrounding steel offered no resistance to shrinkage, there would be no residual stresses.

Traditionally, these stresses are viewed as "yield point" residual stresses. When triaxial shrinkage stresses are created, however, yielding of the material is restricted and even higher residual stresses result.

Restraint cannot be easily quantified, and thus terms like "heavily" and "highly" restrained can only be qualitatively described. Restraint is more likely to be identified by "feel" and experience. High restraint is typically associated with welds with the all of the following conditions: weld throat dimensions of 2 in. or greater, weld lengths of 1-1/2 ft. or more, and where steel members intersect from all three orthogonal directions. A concentration of complete joint penetration (CJP) groove welds in a localized area increase concerns about welding under highly restrained conditions. Therefore, highly restrained members would include splices of heavy sections, welded splices on transfer girders, various splices on trusses, and others.

The third factor that contributes to cracking are cracks and crack-like discontinuities. Discontinuities in the base metal, notches and cracks on cut surfaces, and cracks in the deposited weld metal are all stress raisers that magnify the effects of residual stresses. When welding on highly restrained members, surfaces of materials should b e smooth. Copes and weld-access holes, flame-cut and sheared edges, punched holes and other prepared surfaces that will be subject to the shrinkage stresses of welding should be carefully inspected before welding to ensure freedom from stress raisers. Grinding questionable areas is a simple way to eliminate potential crack initiation sites.

The final factor that contributes to fracture is reduced material toughness. Stated positively, higher material toughness resists fracture: therefore, using base metals and weld metals with defined notch toughness levels is helpful. However, specifying higher toughness in the absence of attention to other factors can be futile. The Specification Commentary A3.1c wisely notes:

“To minimize the potential for fracture, the notch toughness requirement of Section A3.1c must be used in conjunction with good design and fabrication procedures.”One method of increasing toughness is to specify steels and filler metals with defined toughness levels. However, this is not the only way: preheat can improve the fracture toughness of the material during fabrication since at higher temperatures, steel is tougher. For some steels where the fracture toughness transition temperature is very near room temperature, using preheat may shift the material’s behavior from lower shelf to upper shelf, providing significantly better resistance to fracture when at the elevated temperatures. Improved fracture toughness at elevated temperatures will assist in resisting welding-imposed residual stresses, but when the steel returns to room temperature, the fracture toughness will return to previous levels.

To maximize the resistance to cracking, all four elements need to be considered. Residual stresses and restraint should be reduced, the number and size of cracks minimized, and the resistance to fracture increased. Practical and field-proven examples of how these objectives can be achieved are discussed in the next four sections.

REDUCING SHRINKAGE STRAINS

Remember, it is the localized, hot expanded metal that shrinks. The shrinkage (straining) results in stresses. To reduce these strains and the associated stresses, three basic concepts can be employed: reduce the volume of heated metal, reduce the localized nature of the heated metal, and reduce the stresses associated with the strains.

Principle 1: Specify the smallest weld size possible, consistent with design requirements.

Larger welds naturally result in more expanded weld metal. Unfortunately, larger member sizes typically necessitate larger welds.

Principle 2: Select groove weld details that will require the least amount of weld metal.

AWS D1.1 contains many prequalified complete joint penetration (CJP) groove weld details. The capacity of each is the same, but the volume of weld metal required to fill the joint varies. Consider for example a splice of a W14x730, with 5 in. thick flanges. Viable options for submerged arc welding (SAW) include a B-U2-S single vee groove, a B-U3c-S double vee groove, a B-U7-S double U-groove, and a B-U3a-S double vee groove with a spacer bar. Utilizing joint details that are optimized for the 5 in. application (i.e., those that require the least amount of weld metal), the comparison of weld metal required is as follows:

Detail	Root Opening	Included angle	Other details	Required weld metal for 5 in. joint
B-U2-S	5/8”	20^o	--	26.2 lb/ft
B-U3c-S	0”	60^o	f = ¼”	26.9 lb/ft
B-U7-S	0”	20^o	r = ¼”	14.0 lb/ft
B-U3a-S	5/8”	20^o	1.4” x 5.8” spacer	18.1 lb/ft

Interestingly, the double vee groove detail (B-U3c-S) requires slightly more weld metal than the single vee groove option (B-U2-S). Preparation of the double U-groove detail (B-U7-S) is more complicated, but has the least amount of weld metal. A frequently overlooked option is the final one shown above, which utilizes a spacer bar, and the weld metal required for this detail is 30% less than that required for the single vee groove option.

Principle 3: For a given groove weld type, select details that will require the least amount of weld metal.

This principle provides an opportunity for significant reductions in shrinkage strains. Consider for example a B-U2a prequalified CJP groove weld detail. Three combinations of included angle (□) and root opening (R) are permitted, as follows:

Included angle (□)	Root opening (R)	Weight per foot for joint in 4 in. material
45^o	1/4”	27.2 lb/ft
30^o	3/8”	20.4 lb/ft
20^o	1/2”	16.9 lb/ft

The final column provides an estimate of the amount of weld metal that would be required to fill a joint in a 4 in. thick flange. Not only is fabrication cost reduced with the 20 degree, 1/2” root opening detail, but the quantity of shrinking weld metal is reduced by 38%, as compared to the 45 degree, 1/4” root opening alternative.

Principle 4: Control fit-up.

Excessive gaps increase the required weld metal and increasing shrinkage. Consider a TC-U4a single bevel groove weld. One combination of included angle and root opening is 45 degrees and 1/4”. The allowable variation in fit-up is -1/16”, +1/4”. While allowed, the 1/4” increase in root opening for a 1 in. thick member adds 30% to the required volume of weld metal, with a proportional increase in the shrinkage stress.

Principle 5: Control joint preparation angles.

The accuracy of the bevel for the groove weld preparation, typically prepared in the shop, can significantly affect the volume of weld metal required to fill the joint. Furthermore, estimating bevel angle with the naked eye is difficult at best.

Consider the same TC-U4a that was examined above. While the tolerance in AWS D1.1 permits an increase of 10 degrees, going from 45 degrees to 55 degrees increases the required weld metal volume by 30% for a 1 in. joint. As the joint thickness increases, the volume increase is disproportionately higher.

Principle 6: Don’t overweld.

Just as specifying larger than necessary welds increases the shrinkage strains, so does overwelding. A 3/8” fillet weld contains 44% more shrinking weld metal than does a 5/16” fillet.

Principle 7: Limit weld reinforcement.

The effect of weld reinforcement on shrinkage strains is no different from any other form of deposited weld metal: eventually, it must shrink. Excessive reinforcement is difficult to detect, particularly in T-joints, such as beam to column connections. Using the same TC-U4a detail previously considered, a 1 in. joint with “normal” reinforcement of 1/8” requires about 3.08 lb/ft of weld. Increasing the reinforcement by just 1/8” for a total of 1/4” will increase the required weld metal to 3.51 lb/ft, a 14% increase. If the reinforcement is increased to 3/8”, the amount of shrinking weld metal is increased by 28% over the “normal” value.

Principle 8: For a given weld size, make the weld in the fewest number of passes.

This principle may seem counterintuitive, but it is nevertheless true: less shrinkage stress is created if fewer weld passes are used for a given weld size. This means that larger weld beads are preferred if one desires reduced shrinkage stresses.

There are practical limits on the use of this principle: for example, larger weld passes require more heat input. Some steels, such as those that are quenched and tempered, may have limitations on permissible heat input. For applications where notch tough weld metal is required, welding procedures may have minimum and maximum heat input limitations. Similarly, other weld quality issues may impose practical limitations on the extent to which this principle can be applied.

This principle seems to conflict with Principle 1. However, the key issue is this: *for a given weld size*¸ make the weld in the fewest number of passes. In Principle 1, it is the weld size that is the variable. In Principle 8, the weld size is fixed; the variable is the number of passes.

Principle 9: For double-sided joints requiring backgouging, limit the backgouging to only that which is required.

The extra metal required to fill the joint will create more shrinkage stresses. While it is essential to fully gouge weld roots, wider and deeper gouges will require more shrinking weld metal to fill the resulting cavity.

Principle 10: Use filler metal with the lowest strength level possible, consistent with design requirements.

All steel weld metal will shrink the same amount. However, the shrinkage strains associated with higher strength weld metal will induce greater stresses.

Principle 11: In general, but not always, use higher levels of preheat, and heat a greater volume of weld metal.

Remember that it is the localized nature of the shrinking weld metal that causes the residual stresses. If the whole weldment was equally hot, and it cooled uniformly, no shrinkage stresses would be created. By heating more metal, the localized nature of the shrinkage is reduced. This benefit is independent of any reduction in cracking tendencies that might be experienced as well.

This principle does not always apply, however. Higher preheat temperatures and more extensive volumes of heated weld metal may result in heat shrinking (flame straightening) types of movement of the parts. Unfortunately, it is difficult or impossible to predict when such problems will be encountered.

Principle 12: Plan the welding to ensure the assembly will need to be welded only once.

When the first weld is place in a joint, the hot expanded metal causes the surrounding steel to yield to accommodate the shrinkage. If the original weld is defective and requires a repair, the steel is forced to endure yet another cycle of shrinkage. Of course, if the repair weld is defective, the cycle must be repeated again. Experience has shown that a repair or two can be made successfully on a routine basis. By the time steel has endured five or six repair cycles, the probability of eventual success is distinctly diminished.

Careful planning can help ensure to success on the first attempt. Practice on mockups, for examples, can identify and eliminate potential problems that might be encountered on the actual project. An old adage is appropriate here: if you fail to plan, you plan to fail.

Principle 13: Utilize post-weld thermal stress relief

Thermal stress relief can be used to reduce residual stresses. For most structural applications this is impractical, although it may be useful for subassemblies. However, in-situ thermal stress relief has been applied in the field to overcome ongoing cracking associated with residual stresses due to welding.

For carbon and low-alloy steels, this typically involves heating the welded assembly to 1100-1200°F, and holding the assembly at that temperature for an hour for each inch of thickness. Such treatment reduces, but does not totally eliminate, residual stresses.

Stress relief operations should not be approached casually. Both the steel and the weld metal must be suitable for stress relief. A form of cracking called reheat cracking can occur during stress relief, and steels alloyed with Cr, Mo, V and B are sensitive to this phenomenon. These alloys are found in many grades of structural steel. Weld metal properties may be negatively affected, although for some alloys, the properties improve significantly. Therefore, it is important to understand and be able to anticipate the behavior of the materials involved.

Principle 14: Peen deposited welds to reduce residual stress.

Peening can be used to reduce residual stresses. Normally, when this technique is employed, peening is applied to the intermittent layers of groove welds. Peening involves mechanically deforming the weld surface, inducing compressive residual stresses that offset the residual tensile stresses.

Peening is a powerful tool when used properly; unfortunately, it is often done improperly. To be effective, the weld metal must be warm (above 150°F) but not hot (less than 500°F). The peening must result in mechanical deformation of the surface, preferably with a rounded, blunted tool that doesn’t gouge the surface. AWS D1.1 contains a variety of restrictions on the use of peening in clause 5.27.

Principle 15: Control the placement of the final weld passes in a joint.

When a root pass is placed in a weld joint, the weld will contain residual tensile stresses. When a subsequent pass is deposited, the second pass will contain residual tensile stresses, and will reduce the residual stresses in the root pass. The reduction may even result in the introduction of compressive stresses in the root pass. The sequence continues: subsequent weld passes will have residual tensile stresses, and will reduce the tensile residual stresses in previous passes.

The last weld pass will always have residual tensile stresses (unless some post-weld operation is performed). Therefore, it is prudent to plan a welding sequence so that the last pass—the one with the highest residual stress—will be placed in a location where it will do the least amount of harm.

Consider a splice of a heavy rolled shape. Weld access holes are place in the web. Cracking from the access hole is a well established possibility. If double vee groove welds are applied to the flanges, some passes will be made on the inside of the flanges, near the access hole, while others will be made on the outside of the shape. Utilizing this principle, the final weld passes should be placed on the outside of the shape, away from the more sensitive weld access hole area.

REDUCING RESTRAINT

Since if hot expanded weld and base metal were free to shrink without restraint, there would be no residual stresses, reducing restraint is another option available to reduce cracking and lamellar tearing tendencies.

Principle 16: Fabricate small subassemblies, and then join subassemblies into the final assembly, when possible and practical.

The larger the weldment, the more rigid the assembly. Instead of fitting all the pieces together and welding the entire assembly as a unit, some structural assemblies lend themselves to subassemblies. Tree column construction is an example of this principle.

Principle 17: Weld components expected to have the greatest shrinkage first, then weld the members with less anticipated shrinkage.

Components with the greatest shrinkage are normally those with the largest welds. As these joints are completed, restraint increases. However, the shrinkage associated with the remaining members is less. Welding in the opposite sequence causes restraint to be increased when the large welds are made later.

This principle is so well established, it is codified in AWS D1.1 clause 5.21.5. Principle 17 is closely related to Principles 18 and 19, and indeed, these principles may conflict at times.

Principle 18: Weld the most rigid components first, saving the more flexible components for welding later.

As indicated above, Principles 18 and 19 are similar; the difference is this: the former focuses on the amount of shrinkage, while the latter deals with the flexibility of the member. Flexibility is not only a function of the thickness and width of the part (which will typically affect the amount of welding required) but also the length of the member. Sometimes it is better to make a small weld on a rigid assembly before making a larger weld on a flexible assembly.

Principle 19: Sequence the welding of various joints so that the shrinkage movement of the parts is all toward a relatively fixed central location.

Erectors typically utilize this concept when the overall erection direction is established. The same idea can be applied to individual joints. The greatest restraint is created when a weld is placed between two fixed members. However, if one member is fixed and the other is allowed to float or move, then the member can move to accommodate the shrinkage, resulting in less restraint. D1.1 encourages this practice in clause 5.21.4.

A commonly debated topic involves the welding of wide flange shapes, and the sequence of welding the web as compared to the flange. Assume that the application is a tension splice of a truss chord. At least three approaches could be used, as follows:

- Weld the flanges first, then the web
- Weld the web first, then the flanges
- Weld a portion of the flanges, then a portion of the web, returning to the flanges, and then to the web, etc.

The “flanges first” approach is supported by Principle 17: since the flanges are thicker and involve more welding, these welds should be made first. The second approach is usually a knee-jerk response that is taken when the flanges first method has not worked. The final option is based on Principle 19: move the flanges and the web together in a controlled manner. This is the preferred approach for the case of a chord splice.

Principle 20: For individual joints, balance shrinkage on opposite sides of the member, when possible.

This principle can be applied to a wide flange member in which case the balancing is between the welds on each flange, for example. It is better to do some welding on one flange, then some welding on the opposite flange, than to weld one flange completely. If the latter approach is used, the final weld will be made under conditions of much higher restraint.

The principle can also be stated in terms of a preference for double sided weld joint details as compared to single sided details for one joint. However, caution is needed: while not intuitively obvious, some single sided joints may require less welding than a double sided alternative. The table associated with Principle 2 illustrates this reality (even though the difference is minor in that particular case). This principle is codified in AWS D1.1, clause 5.21.2.

Principle 21: Create gaps between tightly fit parts.

Tightly fit joints, particularly between machined parts, are quite rigid and crack-sensitive. Slight gaps of 1/16” to 1/8” can help to accommodate shrinkage. Soft steel spacer wires in between members can assist in this regard; the spacer wire establishes a gap between the elements, and as the weld shrinks, the wire compresses, accommodating the volumetric shrinkage of the weld metal.

Some compression joints are milled to bear, eliminating the need to transfer the whole load through the welds. On one hand, this is good, since it eliminates the large volumes of shrinking weld metal required to transfer large loads. The members must be held in place for erection, and enough capacity must be developed in the connection to handle some secondary and miscellaneous welds. Thus, the detailer may want to apply a partial joint penetration (PJP) groove weld to mill to bear connections, and that’s where the other hand comes into play: welding into this tightly fitting joint can be problematic. These joints often crack when welded. To overcome cracking tendencies, the soft steel spacer wires mentioned in the previous paragraph may be used. When the weld shrinks, the wire compresses and in many cases, bearing will still be achieved. If the spacer wire solution is not acceptable, alternatives to the PJP groove weld should be sought. Lapped plates can be added, making certain that the weld is not placed over the interface of the splice.

Principle 22: Preset members before welding and allow them to move during welding.

Some members will be subject to angular distortion from welding. Locking the member in place may minimize distortion, but it will result in more residual stress. Overall restraint can be reduced by presetting the member in the opposite direction and allowing it to freely distort to the correct orientation.

Principle 23: Specify and make large weld access holes and snipes.

Hot expanded weld metal shrinks volumetrically—through the weld’s length, width and height. When welds intersect from different orthogonal directions—particularly when interesting from all three—the resultant weld shrinkage creates tri-axial stresses that limit the ability of the steel to behave in a ductile manner. A generously sized snipe or weld access hole can limit the interaction of stresses from various welds.

The sizes of the weld access holes prescribed in AISC Specification J1.5 go beyond what is required merely for welding. If that were the only purpose, the sizes of the holes would not need to change with the foot-weight of the beam. While a minimum hole size is prescribed, proportionality is maintained for larger members since the height and width is a function of the thickness of the member in which the hole is made.

These dimensions, according to AISC Specification J1.5 “…are required to provide increased relief from concentrated weld shrinkage strains, to avoid close juncture of welds in orthogonal directions and to provide adequate clearance for the exercise of high quality workmanship in hole preparation, welding and for ease of inspection.” Further, the commentary for J1.6 discusses the length of the access hole as follows: “This minimum length is expected to accommodate and relieve a significant amount of the weld shrinkage strains at the weld-to-flange intersection.”

It is noteworthy that some connections for seismic applications also require carefully detailed and produced weld access holes, in order to provide necessary ductility (AISC, 2005 b). It is not surprising, therefore, that the type of detailing necessary for resisting fracture during fabrication and erection would be similar to that required for seismic ductility.

Principle 24: Spread the joints out.

When multiple large members intersect at one point, and when the various members are welded together, the weld shrinkage must overcome the restraint associated with the intersecting members. Relief can be provided in such conditions by spreading the joints out. For example, several members may be joined to one large connection plate, reducing the number of complex intersections. The restraint at the connection is reduced, and the corresponding welds will have reduced interaction one with the other.

ELIMINATING CRACKS AND CRACK-LIKE CONDITIONS

The best way to preclude major cracking while fabricating heavy steel is to eliminate the stress raiser that amplifies the localized stress. Of course, a true crack represents the worst possible condition: the radius at the edge of a crack is zero, and the theoretical stress concentration factor is infinite. Planar discontinuities such as lack of fusion planes behave in a crack-line manner. Notches, gouges and sharp corners can also create stress concentrations that and may be the initiation point for cracking during fabrication.

The overall importance of eliminating stress raisers, and the advantageous effect on fracture resistance is captured in the AISC Specification Commentary A3.1a as follows:

> "Good workmanship and good design details incorporating joint geometry that avoids severe stress concentrations are generally the most effective means of providing fracture-resistant construction."

To the fracture mechanics practitioner, all planar discontinuities are considered "cracks" since in terms of the mathematical relationships used in that science how the planar discontinuity was created is irrelevant. A plane of incomplete fusion in the root of a CJP groove weld, for example, is modeled in the same manner as would be a crack in the root of the same weld.

To the welding engineer, however, incomplete fusion is not a crack at all: it is a fusion problem. This is a completely separate issue from a crack in the root of a groove weld in that other phenomena cause the planar discontinuities, and the solutions to overcome the problem will be entirely different. Regardless of the source, however, stress concentrations should be minimized before fabrication begins.

Principle 25: Carefully inspect incoming steel.

Incoming steel members should be carefully inspected for fins, laps, tears, laminations and other discontinuities before fabrication begins. Portions of the steel where welds will be placed deserve special attention. AWS D1.1 clause 5.15 addresses this topic. For laminations, inspection must be performed using ultrasonic testing.

When discontinuities are discovered, corrective action should be taken before further fabrication is performed. In many cases, the easiest way to correct for an imperfection is by grinding the defective material away, leaving a smooth, gradual depression on the surface. In other situations, the member can be rotated, placing the problematic steel into a part of the structure where the discontinuity will have no effect on the structure.

Principle 26: Visually inspect cut surfaces.

Cutting operations, particularly those involving thermal cutting, can reveal internal discontinuities in the steel. Severely laminated plate, for example, is very difficult to cut. Inclusions in the steel may cause the cut to become irregular. Repairing such discontinuities before welding will eliminate the stress concentration that would otherwise result. Clause 5.15.1 of AWS D1.1 deals with such discontinuities, providing some acceptance criteria as well.

Principle 27: Preheat steel before thermal cutting.

The oxidation reaction associated with thermal cutting results in a rapid heating and cooling of the cut surface. Complex chemical and metallurgical changes occur during the cutting process. The rapid cooling of the cut surface may result in small cracks on the surface. For this reason, AISC Specification M2.2 requires a preheat of not less than 150^{o}F prior to the thermal cutting that is used to create weld access holes and beam copes in heavy sections.

Principle 28: Mechanically cut surfaces.

The surest way to avoid any cracking from thermal cutting is to avoid it all together. While it is more expensive, groove weld preparations can be machined. Saws, drills and mills can be used to prepare other cuts. Mechanical cutting eliminates the potential of cracking from flame cutting.

For copes and weld access holes, a combination of mechanical and thermal cutting can be used: the radius portion is made by first drilling a hole. Straight cuts into the drilled hole are made next with flame cutting. The straight flame cut surfaces can easily be ground to remove any potential cracks.

Principle 29: Grind and nondestructively inspect thermally cut surfaces.

Shallow grinding of flame cut surfaces will typically remove any cracks. Nondestructively inspecting the ground surface with magnetic particle inspection will verify that all cracks have been removed. This is required for weld access holes and copes in heavy sections, per AISC Specification M2.2. Preparing other regions that might be subject to high shrinkage stresses may be prudent in other situations.

Cracks have developed in flame cut copes and weld access holds of steel shapes during galvanizing. For this reason, regardless of foot weight, AISC Specification M2.2 requires these surfaces to be ground.

Principle 30: Drill versus punch holes, or ream punched holes.

Punched holes may contain tears on the surface. Replacing punching with drilling or reaming punched holes will eliminate these potential stress raisers.

Principle 31: Take measures to eliminate all forms of weld cracking.

Weld metal and the heat affected zone (HAZ) next to the weld are subject to different types of cracking. Cracking in the weld metal may be “hot” cracking; cracking in the weld metal or in the HAZ may be “cold” cracking. Depending on the type of cracking involved, different measures must be undertaken to eliminate the cracking.

A discussion of all the various types of weld cracks and remedies is beyond the scope of this paper. However, Principle 31 simply encourages the use of good welding practices, including but not limited to:

- Selection of base metals with good weldability
- Proper preheat (temperature and volume of heated metal)
- Proper selection of filler metal (with an emphasis on the use of electrodes with controlled hydrogen levels)
- Proper storage and controlled exposure of filler metals
- Adherence to appropriate WPS parameters
- Welding on dry, clean steel

Principle 32: Complete highly restrained weldments without interruption.

Ideally, heavily restrained projects would be completed with interruption. This may require around-the-clock welding in some situations. When around-the-clock welding is impossible, it is desirable to maintain around-the-clock interpass temperature control, keeping the partially welded assembly at welding temperatures at all times until the welding is complete.

As was discussed under Principle 31, one form of cracking is “cold” cracking. Simply put, cold cracking cannot occur when the steel is still hot. When welding is completed without interruption and when the interpass temperature is maintained, cold cracking tendencies are minimized because the steel never cools into the region where such cracking occurs. Further, when steel is maintained at elevated temperatures, hydrogen diffuses more quickly. As hydrogen is released, the probability of cracking is minimized. This principle is codified in AWS D1.1, clause 5.21.7.

ENSURING MINIMUM LEVELS OF FRACTURE TOUGHNESS

The material property that resists the propagation of a crack (or crack-like discontinuity) under tensile load is fracture toughness. This property may be measured many ways, but the most common test is the Charpy Vee Notch (CVN) specimen. The CVN test has a variety of shortcomings, but it is fairly simple to perform and can be done at a relatively low cost.

Many ASTM designations have no requirements for CVN properties as part of the basic material classification. Supplemental tests may be ordered that mandate certain CVN requirements. For welding filler metals, some classifications have mandatory CVN requirements while others do not.

In addition to the fracture toughness of the base metal and the weld metal, the heat affected zone (HAZ) is another region of interest. Depending on the base metal chemistry and metallurgical structure, the heat input of welding and other factors, the HAZ fracture toughness may be higher than that of the virgin steel, or it may be lower.

Principle 33: Specify minimum fracture toughness levels for base metals.

AISC Specifications for building structures do not, in general, mandate that steels have certain minimum fracture toughness requirements. One notable exception, however, applies to heavy sections. AISC Specification A3.1c requires a minimum CVN toughness of 20 ft-lbs at +70^{o}F for rolled shapes with flanges that exceed 2 in. when such members are to be joined with CJP groove welds. A3.1d extends the same requirements to plates exceeding a thickness of 2 in.

It is noteworthy that the early examples of fracture associated with heavy rolled shapes often came from integrated mills that used ingot-based production. Such methods likely permitted greater segregation during solidification than would be associated with the electric furnace melted and continuously cast steel that is popular in the US today.

Principle 34: Specify minimum fracture toughness levels for filler metals.

As is the case for base metals, AISC Specifications do not, in general, mandate that filler metals have certain minimum fracture toughness requirements. One exception is for heavy sections, and other is for seismic applications. A variety of filler metals for all the commonly used arc welding processes are available to meet these requirements.

Interestingly, when the initial requirements for heavy section welding were first implemented, there was no toughness requirement for filler metals. This was reasonable, given that the observed fractures had typically occurred in the base metal, not in the weld metal. With time, however, mandatory toughness requirements were extended to filler metals, and are addressed in AISC Specifications J2.6, where a minimum CVN toughness of 20 ft-lbs at +40^{o}F is mandated.

Principle 35: Consider heat affected zone toughness.

When evaluating base metal, heat affected zone or weld metal, theoretically, any one of the three may have the lowest fracture toughness. However, for typical rolled shapes produced today in accordance with ASTM A992, and with the typical heat input levels associated with the commonly used welding processes, it is unlikely that any special requirements are justified (Johnson and Ramirez, 00).

Two important caveats apply to the above conclusion: modern production of shapes to A992 requirements, and heat input levels associated with commonly used arc welding processes (such as SMAW, FCAW, GMAW and SAW). The conclusion cannot be extended to all steels, or to all welding processes.

Principle 36: Realize that steel is not purely isotropic.

Steel is not purely isotropic. Depending on the particular property of interest, considerable directionality may exist. For most applications, the primary material properties are in the direction of rolling, and this is also the orientation of many material tests. The AISC Specification Commentary A3.1a contains this summary:

> "One such case is the design of highly restrained welded connections. Rolled steel is anisotropic, especially insofar as ductility is concerned; therefore, weld contraction strain in the region of highly restrained welded connections may exceed the strength of the material if special attention is not given to material selection, details, workmanship and inspection."

As connections are detailed, it is important to consider anisotropic ductility since some weld details are more suitable than others. The rolling direction of plate, for example, should be identified and the plate oriented to maximize ductility where large shrinkages will be experienced.

Principle 37: Recognize areas of potential low toughness in steel members.

Steel members from one heat of steel will have varying properties: variations between pieces, variations end to end within one piece, and variations across the cross section of the member. Such variations are normally minor and inconsequential. There are some well established variations, however, that should be considered, particularly when welding heavy steel.

1. The core region in heavy rolled shapes

   The center of the web to flange interface of heavy shapes with flanges greater than 2 in. thick may have an enriched chemistry. This core region will naturally cool more slowly than will the thinner web, or the tips of the flanges. This may lead to a coarser grain structure. Finally, the core region may undergo less mechanical working during the rolling process. These factors combine to create conditions wherein the notch toughness at the web-to-flange region of the shape is reduced. This characteristic is discussed in detail in the AISC Specification Commentary A3.1c.

2. The k-area

   Rolled shapes are often subject to a straightening operation in the mill. Called "rotary straightening", it involves cold working of the rolled shape. The cold working is concentrated in a small region of the web of the shape, approximately 1- 1.5 in. away from the k-detailing dimension. As a result of the localized cold working, the yield and tensile strength are increased, while the ductility and notch toughness are decreased. This characteristic is discussed in detail in the AISC Commentary A3.1c. Briefly, welding in the k-area should be avoided since cracking can result after welds cool and subsequently strain this area. Some detailing suggestions are illustrated in AISC Specification Figure C-J10.7.

3. Corners of cold-formed tubes

   The corners of HSS are cold-formed, that is, the bending takes place when the steel is cold. Cold forming causes the steel in the radius region to develop higher yield and tensile strengths, while the ductility and notch toughness are decreased. Welding on these corners can be problematic under some conditions. However, experience has shown that cracking rarely occurs in this region, likely due to the limited restraint afforded by these (typically) lighter weight members.

Principle 38: Recognize the limitations of standard ASTM tests.

ASTM specifies standardized tests for classification purposes. Such tests may not, however, reveal the material property of interest. For example, before the “alternate core test” was proposed by AISC, the low toughness zone in core region of rolled shapes was not typically measured. Now, it is part of ASTM A6, and known as Supplemental Requirement S30.

No standardized ASTM test exists to measure toughness of the k-area and toughness tests in the radius of A500 tubular members are not part of that specification. Principle 37 alerts those involved with highly restrained applications that the relevant toughness to resist fabrication-related cracking may not be measured by standardized tests. Moreover, the actual properties of interest may be significantly less than those measured in the standardized test.

CONCLUSION

These 38 principles can help mitigate cracking tendencies when welding heavy structural steel. Whereas not all will need to be applied to each and every job, the success of each has been documented on various projects. By incorporating these principles into the design, detailing, fabrication, erection and inspection of projects involving heavy structural steel, welding can be performed—successfully!

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