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Welding Precipitation Hardenable Alloys

Most engineering metals are actually alloys – a combination of multiple elements. For example, carbon steels are primarily made of iron with small additions of secondary elements such as carbon and manganese. Stainless steels get more complicated with larger additions of chromium, nickel, and a few others. Alloys are stronger than the base metals but in annealed condition are still quite soft for most engineering applications. For structural applications, alloys can be made stronger by a mix of thermal and mechanical processing. Various means of strengthening include work hardening (mechanical: bending, extrusion, etc.), phase transformation (thermal: martensite formation in steels), and precipitation hardening (thermal: 17-4 PH, 6061, Inconel 718, etc.)

Precipitation hardening is a unique mechanism which, as the name implies, depends on formation of precipitates – second phase particles that form throughout the microstructure. Precipitation hardening is a three-step process. In the **first step**, the alloy is heated to a high enough temperature such that any precipitates that may have formed during prior processing steps are dissolved in the matrix resulting in a uniform microstructure free of any second phase particles; this step is called solutionizing treatment. The alloy may also be heated to above melting point for solutionizing; not typical in conventional hardening treatments but may happen in the fusion zone during welding.

In the **second step**, the alloy is quickly quenched down to room temperature such that the uniform microstructure is preserved. In the quenched state, the microstructure is unstable since the minor elements are not soluble in the matrix at the lower temperature, but do not have the energy to form precipitates. Quenching can also occur at the end of a weld cycle where the weld metal and HAZ can cool down very rapidly. In the **third and final step** the alloy is heated to a moderate temperature and held for a controlled period of time to allow precipitates to form. Size, shape, and number of precipitates are determined by the time-temperature heat-treatment program. Some aluminum alloys can be hardened even by holding the alloy at room temperature. With formation of precipitates, the alloy becomes stronger as the precipitates provide resistance to movement of dislocations, and consequently to any bulk deformation. Figure I is a schematic drawing depicting change in hardness with time and temperature. Higher temperatures in the hardening step can lead to faster increase in hardness but the maximum hardness produced may be lower. There is a limit to how strong the alloy can become, and in fact, there comes a point where the precipitates can become too big and loose the hardening effect. If the precipitates are allowed to keep growing, the alloy can actually become softer! So there is such a thing called precipitation softening!!

Since welding is a thermal event, the three steps of precipitation hardening can occur in the fusion and HAZ. In resistance welding, laser welding, and single-pass arc welding, the fusion nugget cooling rate is fast enough to mimic the first and second step of heating and quenching. Based on the heating rate and thermal conductivity, portions of HAZ may be exposed to temperatures that can result in hardening (or softening!) of the material in the HAZ. Precipitation hardening can also occur in multi-pass arc welds where the next weld pass can produce precipitation in prior passes.

Figure 2 shows a cross-section of TIG weld on 6061 sheet with 4043 filler; photo shows only one side of the symmetric section. With a two-pass TIG weld, the HAZ is exposed to a time and temperature combination that leads to change in hardness. Given that the parent metal is very soft, it was likely in the annealed state. Exposure of HAZ to higher temperatures led to hardening in the HAZ. Hardness of the fusion zone cannot be directly compared since it now an alloy of 6061 and 4043.

Figure 3 shows an example of resistance weld between two sheets of precipitation hardened Inconel 718; an autogenous weld with no filler or plating to change the weld chemistry. The fusion nugget is obvious in the center, but the HAZ is not so much and hence is marked with an oval with a dashed line. In this situation, the parent metal was already hard but that led to softening in the HAZ due to time/temperature exposure during welding. Since the fusion nugget reached a temperature above melting point, it lost all memory of prior processing and resulted in a soft nugget on rapid solidification.

These alternate hard and soft regions pose a challenge for the weld designer who surely wished for uniform mechanical properties across the weld. But now the engineer is stuck with three, and potentially five (when welding dissimilar alloys) regions with differing properties including base materials on either side, HAZ on either side, and the fusion zone which will make modelling such a welded connection a real challenge. Interpretation of weld test results will also have to be carefully analyzed with failure path evaluated to understand location of crack initiation and the crack path as it makes its way through the myriad regions of varying hardness. If not well understood, the engineer may find a weld that is much too compliant than anticipated or much too brittle; in either case, the weld may not meet the expected life.

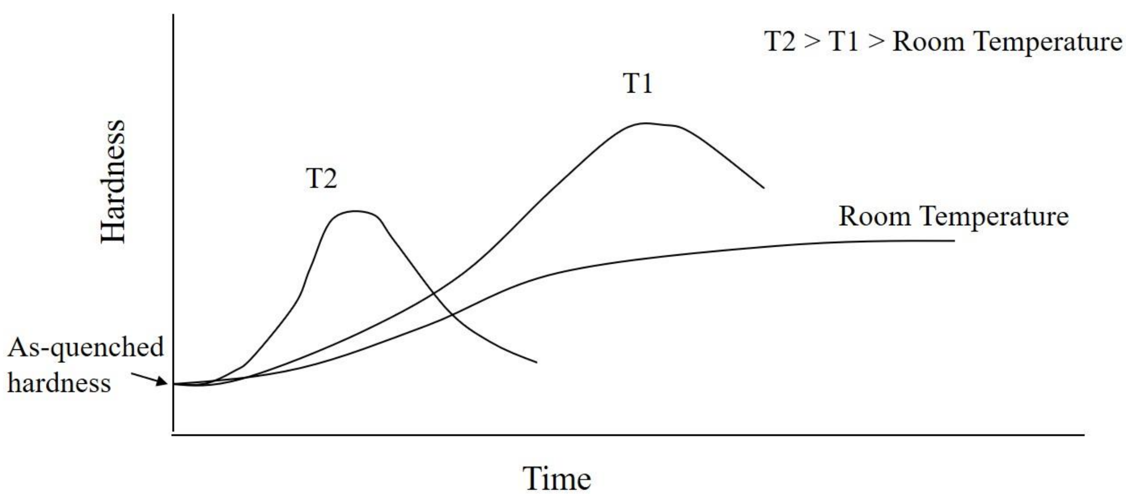

Figure 1. Schematic shows changes in hardness as function of temperature and time. Some alloys can undergo hardening even at room temperature.

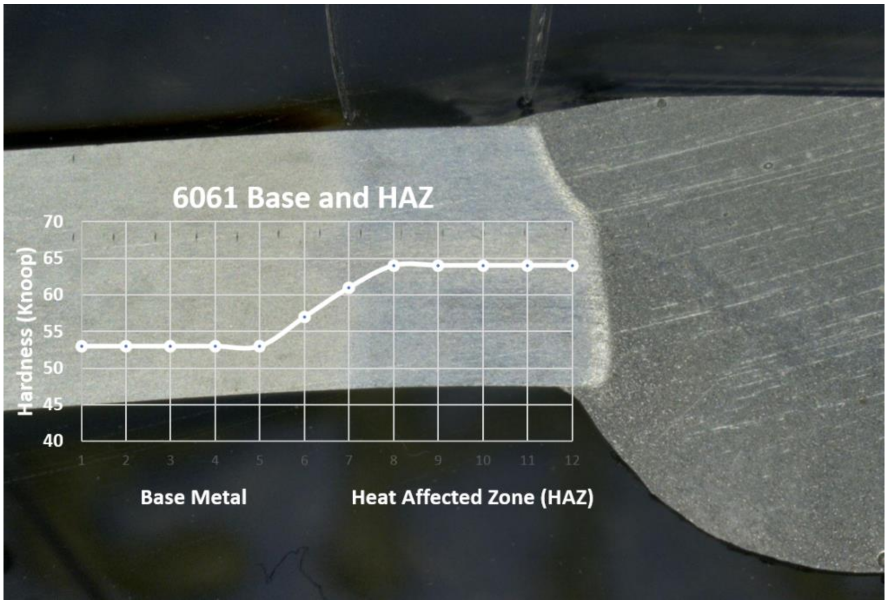

Figure 2. Hardness increase in the heat affected zone (HAZ) due to precipitate formation in annealed 6061 during two-pass TIG welding.

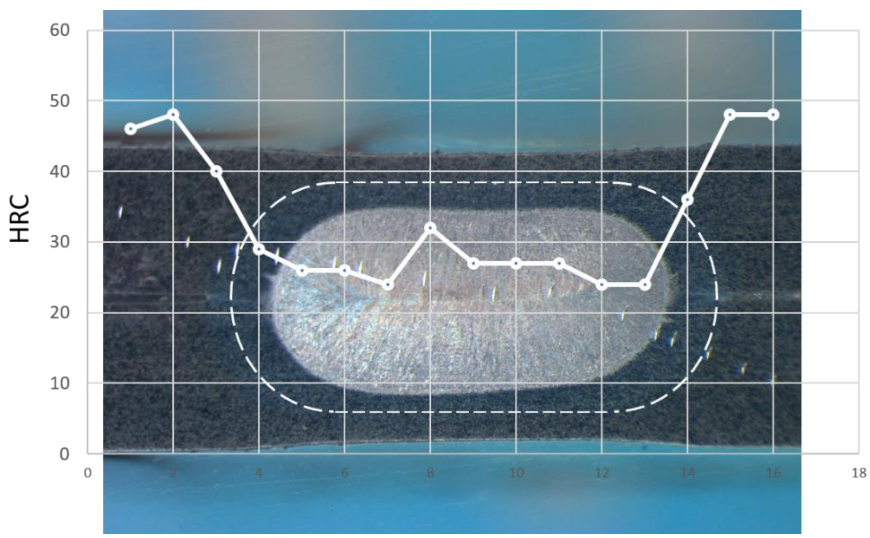

Figure 3. Hardness scan across an Inconel 718 resistance weld. Note the reduction in hardness in the HAZ (between fusion nugget and dashed-line oval) and further drop hardness in the fusion nugget where the Inconel undergoes a solutionizing treatment.

If you have any questions about the contents of this newsletter or any other question about welding, please contact us at [WJM Technologies].