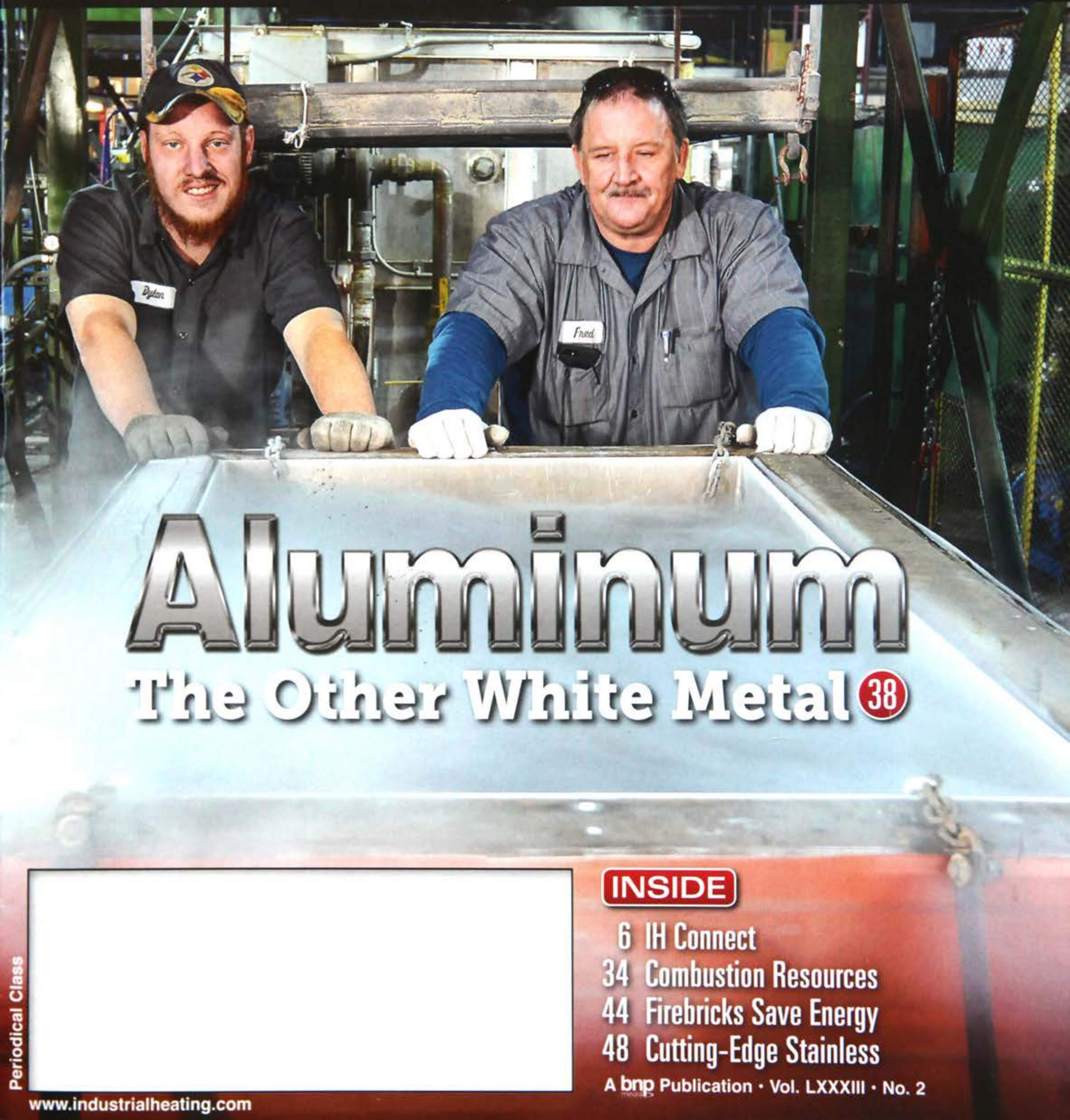
INDUSTRIAL HEATING

The International Journal of Thermal Processing

FEBRUARY 2015



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Periodical Class

INSIDE

A bnp Publication • Vol. LXXXIII • No. 2

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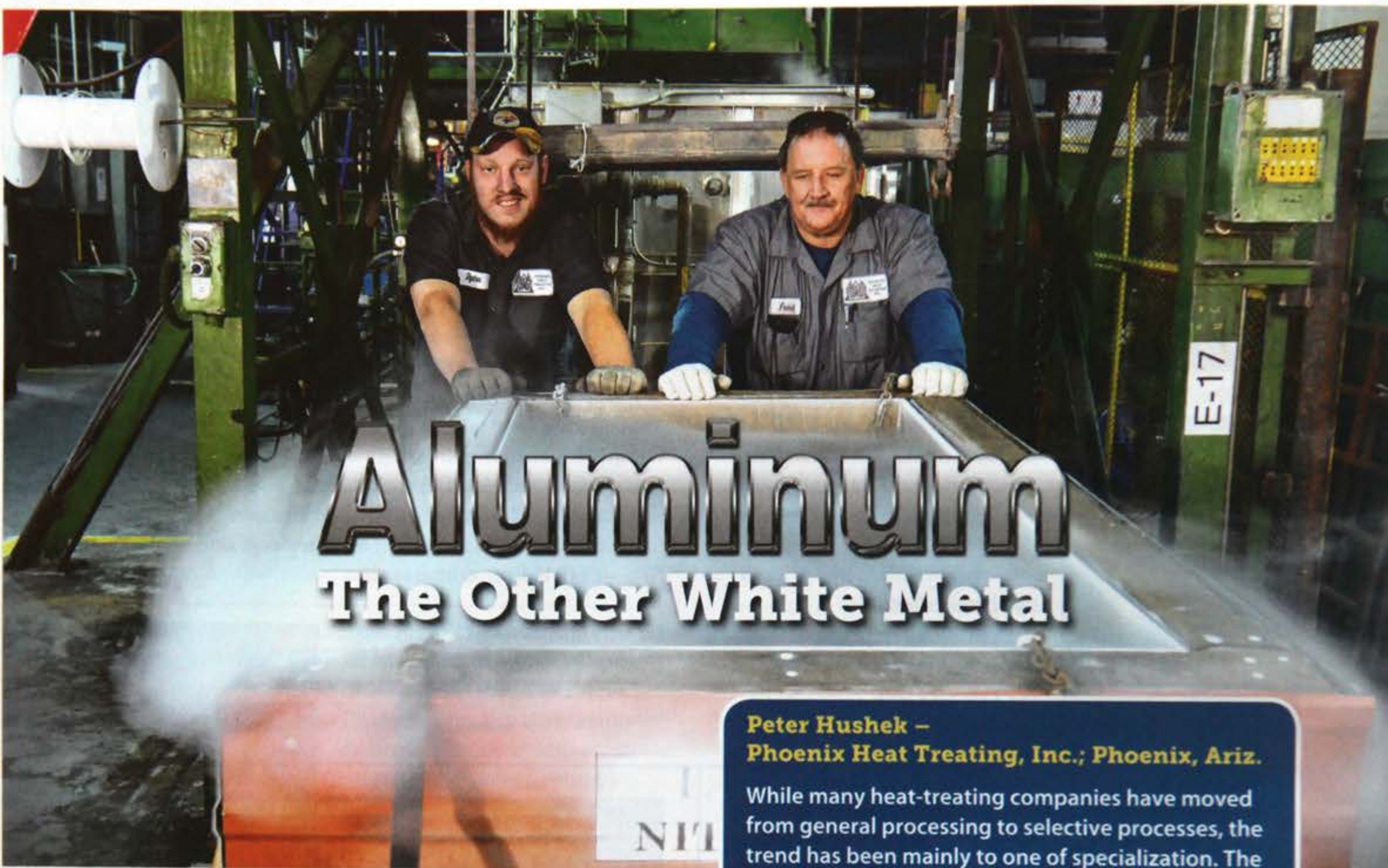

Aluminum
The Other White Metal

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While many heat-treating companies have moved from general processing to selective processes, the trend has been mainly to one of specialization. The thinking is that specializing will simplify focus on process improvement, enhance productivity and increase profitability.

The downside, however, is that plant specialization can lead to a false sense of security based on a single market focus and tentativeness to broaden the company's capabilities and services. While specialty houses will separate ferrous heat treaters from those of the nonferrous variety, broadening processing services can protect the company from the loss of key clients and business that occurs in changing markets. This is most evident in the steel versus aluminum processing arena.

Aluminum is a completely different animal than steel. A simple comparison is that when steel is quenched, it becomes hard and brittle, whereas aluminum becomes soft and ductile. Hopefully, this article will demystify aluminum processing to a degree and encourage you to consider adding aluminum to spread your economic risks across different industrial markets. Why is this important? As I see it, the heat-treating industry is entering a theater of change. Adapting to this change could require adding new services and client types to position the company as more diversified and capable to meet future demands.

To know aluminum, you first must be able to decode the way different aluminum conditions are defined. There is no basic qualification statement such as "harden, quench and temper" to conform to a certain HRC. Instead there are defined conditions that are more like landing zones as opposed to re-temper zones that steel processing so kindly affords. You will become more familiar with the various conditions as you read on. Knowing these key properties allows us to navigate the zones that are defined by process steps as well as minimum mechanical properties. I have also included a few actual case studies written in layman's language to help clarify the processing of aluminum.

Condition O

The full-annealed condition is the softest, most ductile and most easily workable of all aluminum conditions. This condition in age-hardenable alloys (2000, 6000 and 7000 series) is arrived at by soaking at a setpoint below the solution-treating temperature followed by a controlled slow cooling

(above) **Workers push the auxillary liquid-nitrogen tank from under a drop-bottom solution heat-treat furnace on a track to where the aluminum components can be removed. The furnace is designed for solution treating of small batches of aluminum parts to large forgings and castings. PHT operates two identical solution-treating systems, primarily to serve the aerospace industry. The systems quench with liquid nitrogen, glycol and glycol/water.**

6061 aluminum forging of a physical vapor deposition (PVD) vacuum chamber that is used in the semiconductor industry. PHT built specialized tooling to lift and move large forgings, such as this, of varying shapes and sizes. The Brinell mill bed will support components weighing up to 600 pounds.

Close-up image of the large Brinell testing equipment that PHT modified to test large aluminum forgings and castings.

typically to 500°F (260°C). The ductility can be enhanced by reducing the descent in temperature as a function of time. Soak time at the high-temperature phase of the cycle must be carefully controlled to prevent grain growth.

Condition AQ or W

This condition is extremely unstable and will vary based on the degree with which the maximum solubility of the alloying agent has been brought to complete solid solution by the soak and quench steps (commonly called the solution-treating process). In order for this condition to maintain its maximum formability, it must be quickly stored at 0°F or lower. Many alloys will continue to naturally age at temperatures as low as 0°F (-18°C), which is why the use of dry ice for storage and transport is encouraged. The 2000- and 7000-series alloys are especially vulnerable to this low-temperature natural-aging process.

Condition T-4

T-4 is the condition typically referred to as the "natural age" since it occurs at room temperature. The standard timeframe associated with the natural-aged condition is 96 hours. When the degree of complete solid solution is high, the reaction time for reaching this condition can be reduced. While the minimum hardness may be met in less time than the 96-hour standard, the material will continue to transform itself until the maximum hardness (for the combination of alloy composition), degree of solid-solution attained, rate of the quenching and room temperature of the surroundings are met.

Condition T-3

T-3 condition is very similar to T-4 with one slight variation – it receives a cold working, stretching or rolling after the quench phase and prior to the natural age hardening. The bonus of the T-3 over the T-4 is the increased yield strength. This provides the designer with a greater range of applicable uses but comes at the loss of ductility. The reduced ductility and general formability make it useful for large surface-area parts with limited bend radii. Gentle bends are OK, squared corners are not.

Condition T-6

T-6 is the highest-strength condition for most alloys that have not received cold working (work strengthening) after the quench phase. It is extremely stable in its mechanical properties and can be subjected to lower-temperature stress-relief processes without degradation of these properties. This state is achieved by an artificial-age process after the solution-treat and quench steps. It is referred to as "artificial" since it requires setpoints greater than room temperature. The cycle times can range from four hours all the way to 36 hours followed by an air cool.

Condition T-7-3, T-7-4, etc.

These conditions are often referred to as the "over-aged" condition. This means that the material will be lower in mechanical properties than T-6 but have unique properties based on the alloy. In some cases, it will allow for use at elevated service temperatures without loss of strength. For example, the corrosion resistance of 7075 is increased due to this over-age process, which increases its service life. T-7-3 is often used in aerospace manufacturing, where corrosion resistance on nonflying structural components is critical

Terminology

Finally, there is much confusion about the correct wording in the processing of aluminum, specifically that caused by the

Phil Kinney performs a preliminary Brinell inspection on 2014 aluminum forgings. The forgings will be machined into turbocharger components used on electromotive diesel engines. PHT modified the Brinell to include a larger mill bed and masthead that raises 32 inches high to increase capacity for testing large, bulky aluminum forgings.

Peter Hushek stands in a nitrogen cloud next to a mobile auxiliary liquid-nitrogen tank after a solution-anneal process has been completed. Aluminum components in the tank were processed to condition AQ prior to final forming. They will be removed from the liquid nitrogen and temporarily stored in dry ice for the customer to pick up. After forming, the customer will return the components to PHT for final aging.

terms annealing, solution annealing and solution treating. Annealing will result in condition O and never age harden to condition T-4. This mix-up happened decades ago, and the confusion exists to this day. Aluminum becomes soft when solution treated, so shop managers named it solution annealing instead of solution treating. Solution annealing, or more properly solution treating, will naturally age to T-4 after the quench step.

There you have it. Someone thinking that the solution-treating process was an annealing process started the chain of confusion. Hopefully, this sets the record straight.

Now that you are familiar with the crazy nomenclature that defines aluminum processing, it's time to wade into some of the different product forms you may encounter and the hidden land mines that can happen without warning. Similar to early GPS devices, you may eventually get to your destination, but be careful when trekking into uncharted territory.

Case Study 1

Wrought stock aluminum is often purchased and sold in its final mechanical property condition (e.g., T-6). Your customer has the simple task to machine a part from this thin 6061 plate (0.250 inch x 16 inches x 24 inches). It's easy. Simply load the program into the CNC and walk away, and parts will be perfect, right?

After all of the machining is complete, the parts are released from the tooling only to find that the simple sealing groove that you machined in and a set of counter-sunk holes have induced enough stress on one side that you can slide a pencil under the bow in the part. To compound the problem, someone suggests flipping the way the plate is cut from a larger sheet to run cross-grain. This time you get an oilcan effect from opposing corners. The machinist says that this never, ever happens with cold-rolled steel. And if it did, he could send it to the heat treater to stress relieve it between plates to remove the stress. Alas, aluminum is no such animal, and the challenge can be a bit more complicated if you aren't careful. But it's not a formidable task.

The aluminum comes to you in T-6, already through the entire heat-treating sequence – solution treated at 985°F (530°C) and spray, deluge or air-knife quenched to create the solid-solution condition. It then makes its way to flattening rollers because no one will purchase a wrinkled sheet or plate of aluminum.

Now the plate looks really pretty and is precipitation hardened to T-6 at a low setpoint of 350°F (177°C). But the varying amount of subtle cold finishing performed after the quench and before the precipitation harden (age) step creates a dynamic balance with the opposing sides. If one side receives more cold finishing (slight reduction) than the other, it has the potential to spring when material is selectively removed from one side. It's like cutting a wedge from an onion and watching the opposing layers immediately start to pull away from the opening to change the shape of the onion. Now imagine that hundreds of tiny wedges are selectively extracted from your flat onion plate. In reality, the mill needs to sell you flat plate or round straight bar, and caveat emptor rules the day.

What is the answer? Knowing the enemy is the first order of the day. The second is to not rip away the material just because it's soft, and you are not worried about tool life. The other important task is to start a lessons-learned log. Keep track of processing results with detailed notes on differing attack strategies based on part design, material type and (most of all) the symmetry or lack thereof. Symmetry will be a reoccurring theme to keep in mind prior to starting or even bidding a project. It's much like checking on weather conditions before you drive into a storm.

An answer may be to recook the onion before you make cuts on the rough blank. In other words, re-solution treat, quench and age to T-6. This process will most likely release some of the bound-up energy from the cold finishing at the mill. Once the energy is released, the opposing forces and dynamic balance is minimized. This allows you to remove material from either side without the potential energy induced with the cold finishing throwing the dimensions out of balance. Imagine the semi-cooked onion that you cut the wedge out of, and the layers didn't pull against each other.

Case Study 2

For those more familiar with steel processing, it comes as no surprise that materials respond to quenching differently. The same is true of aluminum alloys, and this becomes critical when 2000- and 7000-series alloy forgings are being processed. These alloys are considered more quench-rate sensitive than, say, 6061. There needs to be a heightened emphasis on agitation uniformity in order to reduce residual stresses that happen during the cold-finishing operation at the mill.

When roughing in steel parts prior to processing, the standard thought is to have no sharp-entrant angles. As long as the part does not crack during quench, everything will be fine on subsequent machining operations. This is another major difference in aluminum processing, especially in the 2000- and 7000-series alloys. Balancing the section size, even to the point of leaving stock in place to enhance symmetry, will allow the residual stresses induced at the quench to be in a dynamic balance.

For example, a forging with cross sections of 2, 3, 4 and 5 inches were solution treated and double aged to condition T-7-3. All the properties were verified by hardness, electrical conductivity and tensile testing. But the parts were not stable during the post-process machining operations. After several stress-relieving steps, the tight dimensional tolerances were lost in a few forgings.

Rather than waste more time and material, it was decided to run a test on a single forging that was roughed into a much narrower band of cross sections. Instead of the 3-inch range, the maximum difference was reduced to a little over 1 inch. Additionally, the material removed was designed to allow uniform quenchant flow following the solution-treating step. The double precipitation age was completed, and inspection of hardness, electrical conductivity and tensile strength again affirmed acceptance. During post-process machining operations, the movement due to residual stresses from quenching and machining induced stresses to less than 25% of the previous movement experienced.

Case Study 3

Aluminum is often sold in the annealed condition (condition O), where it is blanked, formed and then sent through solution treat, quench and precipitation aging to its final condition. These simple formed parts are again not symmetrical. The location of the formed angles, weight-reducing holes or just a general lack of symmetry in its final form can cause distortion to rear its ugly head during the quench step.

In some cases, the distortion is so bad that parts cannot be salvaged unless the sequence of events is changed to be more in line with the heat-treating processes. The drastic temperature change from the solution-treating setpoint to the quench temperature produces an extreme thermal shock. This shock, combined with the fact that the material strength at setpoint is significantly reduced, allows the force of the quenchant (water or water/glycol) to warp the part into an unusable shape. In cases such as this, it is advantageous to hang a blank of partially formed material so that it passes through the surface tension of the quenchant. At the point immediately after the quench, the part is in a metastable condition often referred to as AQ or W condition. As long as the parts are immediately placed in a freezer or on dry ice the metastable condition is maintained.

The AQ or W condition is also considerably more ductile than T-4, which allows the parts to be sent back to the customer for final forming to the desired dimensional shape. The fact that the partial radii received additional cold forming creates stiffening, which allows the part to hold the final dimensions and tolerances. The following process coordination takes effort, but it beats the difficulty of attempting to work an oilcan condition out in the final aged condition.

- Preform
- Solution treat and quench
- Return to customer on dry ice
- Final form
- Final precipitation harden

This is an example of when processing aluminum to achieve a final form requires close coordination and communication with the client.

Conclusion

Hopefully, these examples illustrate some of the crucial differences that exist between steel and aluminum processing. And, even though the processes are each very unique, the characteristics of both material types and quench rates play significant roles in desired outcome. Yes, aluminum is a different animal, but it should not be ignored when you can add production volume, attract new customers and even prevent a catastrophic customer loss due to changing market dynamics.

For more information: Contact Peter Hushek, owner and president of Phoenix Heat Treating, 2405 W. Mohave, Phoenix, AZ 85009; tel: 602-258-7751; email: phushek@phxht.com. The Nadcap-certified company is currently celebrating 50 years of business in Phoenix. Its family heat-treating heritage spans four generations and 100 years, beginning in Milwaukee, Wis., in 1915.