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USING GLYCOL TO EFFECTIVELY CONTROL DISTORTION AND RESIDUAL STRESSES IN HEAT TREATED ALUMINUM ALLOYS

BY

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ABSTRACT

Glycol quenchants were introduced into the aluminum heat treating industry in the mid 1960's and immediately became the most important tool for reducing quenching distortion in sheet metal alloys. Later, the feasibility and benefit of glycol quenching thicker products, such as

castings and forgings (which were normally quenched in hot or boiling water), was proven. Specifications were changed to permit glycol quenching of forgings and castings. However, because of a lack of understanding of the technology, the original benefits achieved in sheet metal distortion control and optimum distortion and residual stress control of thicker products has diminished. Currently, there is a significant lack of understanding regarding glycol quenching and as a result the full benefit of this technology is not currently being utilized. Distortion of sheet metal products and precision forgings has increased, resulting in increased check and straightening costs and higher residual stresses being imparted to parts. The realization of the benefits of glycols being able to reduce residual stress and ultimately machining costs is waning due to the reluctance of many engineers to recognize and understand the benefits of expanding the limits of the technology to achieve results not heretofore achievable.

It is the purpose of this paper to review the basic concepts regarding glycol quenching of high strength aluminum alloys and to present recommendations for optimum control of distortion and residual stresses using the products. Specific illustrations showing that the proper use of glycol quenchants can provide the producer significant savings by (1) reducing quenching distortion and (2) minimizing residual stresses (which significantly improve machining practices and reduce the generation of scrap) are provided.

The author would appreciate any comments on this material and a dialogue with others in the industry who have had unique experiences with this technology. He may be reached by email at <tom@croucher.us>, or by phone at his office at 888-502-8488.

INTRODUCTION

Glycol quenchants were introduced into the aluminum heat treating industry in the mid 1960's and immediately became the most important tool for reducing quenching distortion in sheet metal alloys. The first product available was Ucon® A, a polyalkylene glycol, produced by the Union Carbide Corporation. All work and test data referenced in

this article pertain to this product. After the initial test programs at Boeing (1) and Northrop (2) proved successful, other companies (3) (4) (5) (6) (7) tested the product and installed glycol quenching systems to reduce heat treat distortion. By 1974, quenching distortion of aluminum sheet metal products in the aerospace industry had essentially been eliminated.

After further work, the feasibility and benefit of glycol quenching thicker products, such as forgings and castings (which were normally quenched in hot or boiling water), was successfully proven. Then came a strange phenomenon. Forgings and castings normally required glycol concentrations which were much lower than were used for controlling the distortion of sheet metal products. Specifications were changed to permit glycol quenching of forgings based on the results of the Amec zero delta approach. (See discussion later in this article.) Also, most heat treatment of aerospace products shifted from the primes who conducted the original glycol research to commercial job-shop heat treaters. The current philosophy by most of these job shops limits their glycol concentrations to only one which they hope will cover all situations. Unfortunately, the original benefits achieved in sheet metal distortion control were sacrificed in order to permit the quenching of forgings because of the lack of understanding by heat treaters as to the proper approach to each technology. There is also an economic aspect to this issue. When the heat treating was performed by the primes themselves, reducing the total cost by minimizing the check and straightening operations was of prime importance. They dedicated their heat treat facility to just sheet metal parts since they rarely heat treated thicker products such as forgings. Now that most sheet metal parts are procured from sub-contractors, heat treatment is performed by a job shop heat treater, Since they get paid extra for the check and straightening operations, it is not in their financial interest to optimize the warpage problem and to provide for multiple quenching tanks.

It is the purpose of this paper to review some of the basic concepts regarding glycol quenching of high strength aluminum alloys, to present recommendations for optimum control of distortion and residual stresses by appropriate use of the products. Further, we will provide specific illustrations how the proper use of glycol quenchants can provide the producer significant savings.

DISTORTION AND WARPAGE

Distortion is a manifestation of the "lack of dimensional stability". The dictionary defines distortion as "to twist awry or out of shape; to make crooked or deformed". The term distortion is commonly used in heat treating plants interchangeably with the term "warpage" which is defined as "to bend or twist out of shape, especially from a straight or flat form." For the sake of the discussion in this presentation, we will use the generic term "distortion to mean "part movement that can occur any time" while we will limit the term "warpage" to mean "that distortion which occurs during the heat treating process."

When aluminum parts distort during heat treating or other fabrication operations, the parts are simply reacting to the dynamic forces which occur as a result of the processing operations. The most common source of distortion in aluminum alloy parts is the heat treating operation. Part movement may occur immediately upon heat treatment, sometime later in a subsequent processing operation, or possibly on a shelf or in service. Parts that may be machined, cast or formed to accurate dimensions prior to heat treatment, often emerge from the heat treating operation with significant changes in their dimensional configuration. In many cases, the distortion that occurs is exhibited by part warpage such as bowing or twisting of sheet metal, canning of machined pocket areas, and other forms of part movement which necessitates extensive "check and straighten" procedures after quenching. Other examples of part distortion is exhibited away from the heat treat shop, sometime after heat treatment. Parts will apparently move while just sitting on a shelf for a period of time. Some parts will crack when, to the untrained eye, there appears to be little or no reason for the part to move or crack. A common occurrence is the movement or cracking of a part during a subsequent cutting or machining operation. The most serious case involves movement of the part while in service completely rendering it useless to perform its designated function.

Part distortion stems from many different causes during the fabrication process. The most common and observed source of part distortion is the heat treating process, although distortion can be observed when machining, welding, or performing other fabrication operations.

For the sake of this discussion, we will consider three types of part distortion:

- 1) warpage which occurs immediately as a direct result of heat treating processes,
- 2) distortion which occurs later, but is caused by the heat treating process, and
- 3) distortion which is caused by processes other than heat treatment.

It is important for the heat treater to understand all three types, for in many cases, it is he who is responsible for the part distorting or cracking in a machine shop three months after he has heat treated the part. Also, the heat treater may be blamed for distorting a part during heat treatment, when the primary cause of the part movement (usually due to improper machining techniques) occurred days before the parts were heat treated and the resulting distortion was not his fault.

CONTROLLING HEAT TREAT WARPAGE

FACTORS AFFECTING DIMENSIONAL STABILITY AND WARPAGE

Warpage of parts in the aluminum heat treat plant is a constant source of concern. Distortion of parts during and after the heat treating process is due to many factors. Some parts will warp for reasons the heat treater can control, but others will distort for causes that occurred before the heat treater received the parts and are beyond his control. With the exception of the presence of prior stresses, most factors which influence part movement during the heat treating process can be controlled by the heat treater. The following factors all have an effect to cause part movement. Understanding and controlling these factors allows the heat treater to minimize the occurrence of heat treating warpage and to preclude the inducement of high levels of residual stress during heat treatment which will minimize later distortion. Each of these critical factors will be discussed in the order in which they occur during the heat treating process.

- Relief of pre-heat treat residual stresses

- Expansion and contraction of parts during processing
- Inadequate racking procedures
- Quenching too fast
- Proper quenchant selection
- Uneven quenching due to inadequate agitation or spacing
- Improper quench immersion rates
- Furnace air flow design in relation to part orientation

When heat treating delicate, thin gage aluminum sheet metal, forged and cast parts, the two most critical factors are:

- quench rates which are controlled by quenchant selection and
- the integration of racking procedures with immersion rate.

The most common source of heat treating warpage occurs during the quench when parts are too thin to resist the movement which is triggered by "unequal" expansion or contraction of the metal. If one area of the part is contracting as its temperature is lowered, and another area of the part has not yet started to achieve the lower temperature or has already completely cooled, the part will bend toward the area that is starting to shrink as it is cooled, causing it to warp. Residual stresses occur when the part is thick enough to resist the bending forces caused by the expansion/contraction reactions which are below the yield strength of the material. Thus, because the configuration is so massive, the forces being applied by the expansion/contraction occurrence are not sufficiently high enough to make the part bend or twist. However, these forces are high enough to impart high residual stresses to the component which can cause dimensional instability at a later time.

Optimum distortion control is achieved by a thorough understanding of each of these factors and by selecting

production procedures that reduce the possibility of part movement at any time. To completely control distortion in all phases of processing, a complete systems approach must be taken that considers the possible distortion in all phases of processing, pre-heat treat, heat treatment, and post heat treatment.

EFFECT OF TEMPERATURE CHANGES

Compared to many other metals, aluminum has a high coefficient of thermal expansion -- in plain words, it will expand or grow significantly when its temperature is raised. The thermal expansion and contraction of aluminum alloys has a significant effect on the measured dimension of a part. Significant effects can be seen from thermal expansion changes not only when heating to an elevated temperature but also with changes that can occur with temperature variations near room temperature. The coefficient of thermal expansion for aluminum at room temperature is approximately 12×10^{-6} inches per inch per degree Fahrenheit. This coefficient by itself has little impact to the average observer until one considers the practical aspects of what can occur due to temperature changes in a fabricated aluminum part. Consider, for instance, a long, slender 16 foot heat treated aluminum alloy spar which contains a precise bolt hole pattern for the future installation of a number of fastening bolts. If it were necessary to maintain a tight dimensional tolerance over the total length of this part, the inspection temperature must be clearly specified. The reason is simple and is illustrated in the following example: Let us assume that a $+0.015$ -inch tolerance was specified between the center of two bolt holes drilled six inches from either end of the part, i.e., 14 feet apart. Let us also assume that the part was originally heat treated and inspected in a standard plant environment at 65°F and met the tolerance requirements. On a hot day, however, say at 100°F , due to the thermal expansion of the part, the 14 foot dimension would increase by $.071$ -inches. At this temperature, the part could not meet the established dimensional tolerance of $+0.015$ -inches.

When considering use of elevated temperature processing operations for aluminum alloys, reviewing the thermal expansion characteristics is extremely important for achieving maximum dimensional stability. Let us assume that in a particular processing operation, the 16 foot

aluminum alloy part previously discussed was heated from room temperature at 68°F to 1000°F. Computing the expansion that would occur between the 14 feet bolt hole dimension by raising the temperature shows that the part length would increase by over 2 inches. If the spar were to be quenched, a sudden contraction back to its original dimension would occur and the part would shrink two inches. If the part is not allowed to expand or contract uniformly, without restriction, significant residual stresses or distortion will result, during the quenching procedure. Because of these expansion characteristics, the use of test fixtures for elevated temperature processing operations (forming, welding, heat treating), must be carefully planned so that large differentials between the expansion characteristics of the part and its fixtures do not impart high levels of residual stress to the part leading to dimensionally instability.

THE PROBLEM WITH EXPANSION AND CONTRACTION

As previously discussed, when heated from room temperature to about 1000°F, the afore mentioned sixteen foot long aluminum spar will grow approximately two inches. A wise old aluminum heat treater once related to the author that "one cannot heat treat a sixteen foot part in a sixteen foot furnace". This statement came from his direct experience where the heat treater had available a sixteen foot high, vertical gantry furnace and had to solution heat treat some sixteen foot long extrusions. These extrusions were placed into the furnace in a vertical mode and were literally packed in from one end to the other. When the parts were heated to the solution heat treating temperature, the parts grew two inches in length. As they pressed against roof and door of the furnace, the parts severely twisted and bowed causing severe pressure on both the roof and the door. When the operator attempted to open the furnace doors to quench the parts, the doors would not freely open and the parts sprung against and jammed the doors and thus jammed the parts in the furnace. The growth of the parts during heating had caused the expansion which resulted in the entire load of extrusions being scrapped. It took a maintenance crew two days to cool the furnace down to room temperature, remove the parts from the furnace and repair the damage.

Unequal expansion can occur in the furnace due to

inadequate racking and support of parts and can cause part to warp in the furnace before the quench. Unequal contraction occurs during the quenching operation when improper quenchants are used, improper immersion rates are employed and large section transitions within the part are quenched at the same time.

THE PROBLEM WITH IMPROPER RACKING PROCEDURES

The subject of racking is a comprehensive subject. Proper racking is the key to distortion control. Parts must be positioned, supported in the furnace correctly and enter the quenching fluid properly at the optimum rate if warpage or distortion is to be minimized.

A number of physical characteristics of each aluminum part must be carefully considered when racking parts in order to prevent distortion in the solution heat treat furnace.

1) Thermal Expansion: As we have observed, aluminum alloys have a high coefficient of expansion and will grow as the part is heated to solution heat treat temperature.

If the part is restricted in any manner and not allowed to grow freely, the restriction will cause the part to distort. This distortion is frequently encountered when parts are tied too tightly to steel baskets or racks that are used to position the parts in the furnace. It also occurs when parts are racked too close together. At room temperature, it may appear that there is sufficient spacing between the parts. As the temperature of the load is raised in the furnace, the expanding parts (if spaced too closely) will exert pressure on each other as they attempt to expand. Since the yield strength of the aluminum alloy is extremely low at elevated temperature, the parts relieve the contact pressure by moving or bending to conform to the space available. When the parts are quenched, the distortion that has occurred in the furnace will not change and in many instances, it is erroneously concluded that the parts have warped in the quench.

Restriction by racks, bars or wires used to position the parts during the heat treating operation, may cause a

similar effect if the holding device is not sufficiently flexible to allow for the part to expand and contract freely. Any device used for positioning parts must be sufficiently loose to allow for thermal expansion and contraction.

During the quench, the problem of differential contraction between the part and the supporting baskets and fixtures must also be considered. When quenching thin gaged aluminum parts, the entire cooling process is completed in a matter of seconds or less, so the contraction of the part is almost instantaneous. Restricting the parts movement during the contraction is a major cause of warpage. If the parts are positioned by pins or bolts in a fixture, slotted holes are an absolute necessity. Also, the length and position of the slots should be computed, allowing for differential expansion of the part and the fixture. Centering the pin in the slot also may cause problems because the direction of the expansion and contraction will not be based on the central location. Clamping the part too tightly may even cause dings in the part as the part expands into the clamp during heating.

2) Elevated Temperature Strength Characteristics: When aluminum alloys are heated to high temperatures, the elevated temperature strength is extremely low and the material becomes very soft and pliable.

3) Part Support: The part must be supported properly, and not allowed to sag during the heat and cooling operations.

4) Condition of the Rack or Fixture. Distorted racks and fixtures make distorted parts.

5) Furnace Design in Relation to Part Orientation. Parts need to be oriented in the furnace with the air flow passing evenly over all surfaces of the part.

PROPER QUENCHANT SELECTION

Selection of the proper quenchant is a most important criteria for obtaining optimum warpage control and minimum residual stresses when quenching aluminum parts. The ideal quenchant for any given part is one that is (1) sufficiently rapid through the alloy's critical range to avoid precipitation during the quench thereby lowering

properties and (2) sufficiently slow to minimize quenching distortion and residual stresses. Proper quenchant selection cannot be made unless two criteria are known and understood – the quenching sensitivity or hardenability of the alloy being heat treated and the behavior of the quenchant being considered under different conditions of concentration and temperature. Unfortunately, too many heat treat facilities select their quenchants based on what others have done which may not be optimum in the first place. Also, an understanding of the quenchant's characteristics capability to cool through different temperature ranges will go a long way to selecting one that is the most ideal for the alloy and thickness being heat treated. Although a hot water quench and a specific glycol/concentration combination may achieve the same cooling rates in certain temperature ranges, their properties are completely different when considering the characteristics of the entire cooling curve. Hot water tends to delay the start of cooling during the early stages, and then tends to cool rapidly later on. Glycols tend to start cooling earlier in the process and provides a more gentle cool during the intermediate stage of quenching.

To effectively achieve the desired properties in a particular aluminum alloy part, it is necessary to ask the following questions –

(1) How fast must the parts be quenched (defined as the "critical quench rate") in order to effectively retard atom movement so that full properties will result? In some aluminum alloys, this rate is extremely fast as 900°F per second, while for other more quench insensitive alloys this rate is extremely slow i.e. 10°F per second

(2) Is the maximum thickness of the part such that this critical rate can be achieved with a quenchant that can be used to minimize distortion and residual stresses? If so, what quenchant, concentration and agitation level should be used to minimize quenching severity?

(3) Does the furnace being used possess an immersion rate that is commensurate with the selected quenchant so that balanced cooling can be achieved? If an extremely fast quenching rate is needed, a rapid immersion rate will probably be required. Part configuration may also dictate that a slower immersion rate be used.

(4) If it is not possible to achieve the critical cooling

rate, what happens at rates that are slower than this critical rate, but faster than an extremely slow cool? Most forgings and thicker products are cooled at rates slower than the critical rate. Can a particular quenchant that cools slower than the critical cooling rate be used and still obtain the desired properties?

(5) Is the agitation system adequate for achieving a balanced quench for the part in question and not too fast to mask the beneficial effects of the selected quenchant?

The ideal quenchant for distortion control is an air blast, spray quench, or properly applied boiling water quench. Liquid nitrogen is used also sometimes in this regard. Boiling water is often used for achieving low residual stresses. Although these approaches are sometimes used in the job shop, the slow cooling rates achieved by these methods parts are not fast enough to preclude precipitation during the cooling process for most aluminum alloy parts. Thus the slower quenching process, although achieving excellent distortion control, will not produce acceptable properties.

Cold water, brine and dilute solutions of some polymers achieve the fastest cooling rates and have the greatest ability to achieve the highest properties. Although these techniques are necessary in some instances to achieve the desired tensile properties, the use of these quenchants normally leads to a high level of distortion and residual stress since they cool much too fast, particularly in the case of sheet metal.

Between the two extremes fall the glycol quenchants, which when used at varying concentrations, provide the complete gamut of quenching rates from very fast to very slow. This allows for a truly engineered system whereby the optimum quenchant can be selected to achieve the required properties while at the same time minimizing distortion and residual stresses.

IMPROPER IMMERSION RATE

Ideally, if a part like a large flat sheet is quenched on all surfaces equally at the same time, no warpage will occur. In batch operations, however (such as quenching from a drop bottom furnace) this situation never occurs. As the part is

immersed in the quenching fluid, the first section of the part cools very rapidly while the last section cools much later, leading to unequal contraction and severe warpage.

The rate of immersion of the part into the quenching fluid is extremely important in minimizing distortion. This "immersion rate" is the speed, measured in feet per second, at which the part enters the quenchant. This term is often confused with the term "quench delay." The "quench delay" is the total time from the opening of the furnace doors until the parts are submerged in the quenchant. As a normal rule, a faster immersion rate results in less distortion (particularly with sheet metal parts with a large surface area) because more uniform cooling is achieved from all surfaces. However, because of the problem of fluid resistance, all parts cannot be immersed rapidly. From experience, immersion rates are usually in the range of from 0.5 to 10.0 feet per second and the more modern furnaces are designed with controls to allow the operator to pre-select the required rate depending upon the parts being treated.

The next two figures shows the results of a case where the immersion rate was too slow for the conditions of a particular part. Both sheets had been quenched in 32% glycol from the same furnace into the same tank. The badly distorted sheets, shown in Figure 1, were quenched at too slow an immersion rate, while the same racking procedure with a faster immersion rate resulted in flat sheets (Figure 2) with little distortion.

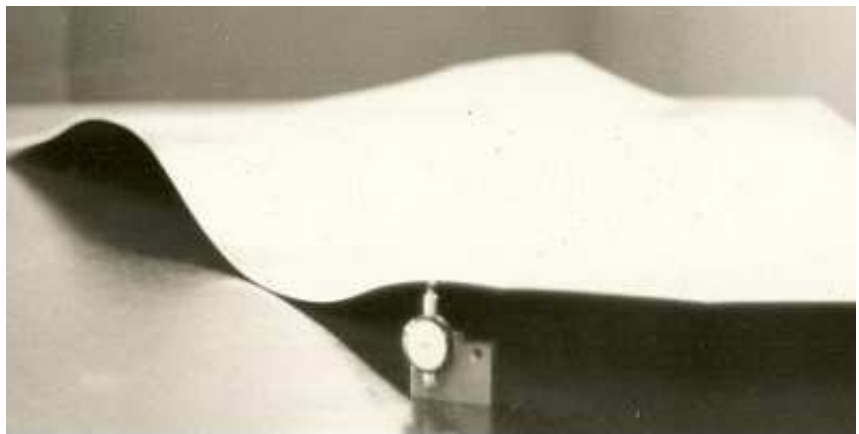


Figure 1 – Severely Distorted Sheet Metal Parts Quenched At Too Slow An Immersion Rate.

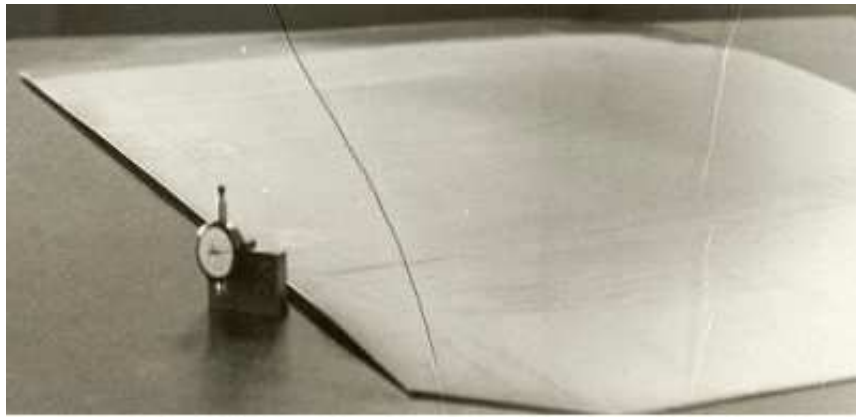


Figure 2 – Acceptable Part Quenched At The Correct Immersion Rate.

Controlling the immersion rate begins with furnace design. Most aluminum solution heat treating furnaces of the drop bottom design, are manufactured in such a manner that only one rate of drop of the basket from the furnace to the quench tank is provided. The design criteria that establishes this drop rate is governed by the specification requirements that control the quench delay requirements that are in most specifications. When quenching sheet metal, most specifications require that the quench delay (the time measured from the instant the furnace door starts to open until the parts are completely immersed in the quenching fluid) cannot be in excess of 6–10 seconds. The manufacturer thus designs his system so that the combination of the doors being opened and the part being quenched will meet these quench delay requirements. No consideration is given as to how fast the basket and/or the parts are moving at as the part is being quenched. Further, no current heat treating specification addresses this fact. The problem is that distortion control is a function of the immersion rate of the part, not the quench delay requirements of the heat treating specification.

ADEQUACY OF AGITATION

Agitation of the quenching fluid has a significant effect on the condition of a heat treated aluminum part. The subject of agitation is complex and is usually a problem caused by extremely bad tank design. Inadequate or uneven agitation can cause severe temperature gradients leading to unacceptable warpage. There are cases where it is

important for the operator to consider certain aspects of the agitation flow in the quench tank before a critical part is racked. This precaution is particularly true when a tank pumping system with a single entry port is used to agitate the quenching fluid. If a part was racked so that it were positioned directly in the path of the fluid flow, the violent action of the moving fluid will cause excess movement or vibration in the quench tank and cause a part to distort by the excessive fluid pressure on the soft metal part. This type agitation system can also cause uneven agitation in the tank resulting in "dead spots" in the tank where there is little or no agitation causing differential cooling and resulting in warpage.

QUENCHANT SELECTION

The most common quenchant used for aluminum alloys is water. The main advantage of using a water quenchant is that water can provide the rapid quenching rates necessary for obtaining high properties in many different alloys. Water is also cheap and readily available. Further, water is reasonably flexible in that its quenching characteristics can be altered somewhat by varying the temperature of the water.

COLD WATER QUENCHING

The use of ambient or room temperature water (commonly termed cold water quenching) is the most common practice for quenching aluminum alloys. The water bath is usually controlled over the temperature range from 60–90°F. Most government and company specifications require that the temperature of the water be below 90°F at the start of the quench and not rise more than 10°F after the quench. This requirement governs the design of most quench tanks regarding the total volume of fluid in the tank. It may also limit the amount of material that can be loaded into the furnace, and thus is a critical factor in the design of fixtures, racks and baskets. If the combined weight of the rack and baskets is too heavy, the net load of parts could be severely restricted by the temperature rise criteria if the quench tank is too small.

Most product forms such as sheet, plate, extrusions and some forgings and castings are quenched in cold water. The major problems resulting from water quenching these

forms are twofold:

1. Many parts will warp during the quenching process and consequently require extensive, costly check and straightening operations.
2. Large, thick parts can achieve a high level of residual stress.

HOT WATER QUENCHING

The problem of quenching distortion or warpage has been one of the major problems facing the aluminum heat treater for decades. Many approaches have been used, each with varying degree of success and each with its own limitations. In an attempt to achieve

(1) maximum distortion control in forgings, castings and thin sheet metal parts, and

(2) minimum residual stresses in forgings and castings,

hot water quenching, (particularly boiling water), is sometimes used with moderate success. The quenching characteristics of water are significantly changed by heating the water. To illustrate this fact, cooling rate curves for water quenching baths at different temperatures are shown in Figure 3 and cooling rates for various water temperatures for different thickness of metal are shown in Table 1. It can be seen that as the temperature of the water is increased, the quenching characteristics of the bath are significantly changed. At higher temperatures, much slower cooling rates are achieved. When the water temperature is raised above 160°F, the effectiveness of the water quench is drastically reduced as the quenching speeds are lowered. When the bath temperature reaches boiling, a very slow quench rate is achieved.

As a result of slower cooling rates, increasing the water temperature can result in a significant loss in hardness and tensile properties when the part is later aged. This occurs especially when heat treating the more quench sensitive 2000 and 7000 series alloys such as 7075, 7049 and 7178. Figure 4 illustrates this effect for one inch 7075 plate heat treated to the T6 temper. An 82,000 psi tensile strength was achieved in cold water while the strength dropped to 64,000 psi when boiling water was used – a loss of 25%. In

general, significant loss in tensile properties may result when the water temperature is raised above 160°F as the cooling is not sufficient to freeze the solute atoms during the quench. Lower, but significant property losses are often observed in thicker products when the water temperature is increased above 120°F.

Because of the rapid change in the quenching characteristics of water above 160°F, control of quenching rates at various locations in a quench tank is difficult when using a hot water quench. Consequently, precise temperature control and resulting quenching speeds at different locations within a given tank, in different tanks, and in sequential loads within the same tank, is difficult to achieve in hot water production quenching operations. At higher water temperatures, to keep the water temperature constant and achieve consistent part properties, close control of agitation is required.

BOILING WATER QUENCHING

Quenching in boiling water can be both beneficial and troublesome. It is definitely beneficial because lower residual stresses are achieved when compared to cold or hot water quenching. For instance, quenching 2014 forgings can achieve a 60–80% reduction in the stress level when compared to cold or hot water when quenched in boiling water. The disadvantage is that for most alloys, there is a significant reduction in the strength level achieved due to the reduction in the cooling rate. In order to allow boiling water quenching of the 2014 alloy, the part's design properties need to be reduced sufficiently since lower properties will be realized from the boiling water. Consequently, a special temper was defined. The T6 temper is used for cold or hot water quenching and the T61 temper is used when the products are quenched in boiling water. In instances where the boiling water quench is employed, the dimensional stability of the material is much more important than the strength level desired, so the strength has been sacrificed for dimensional stability.

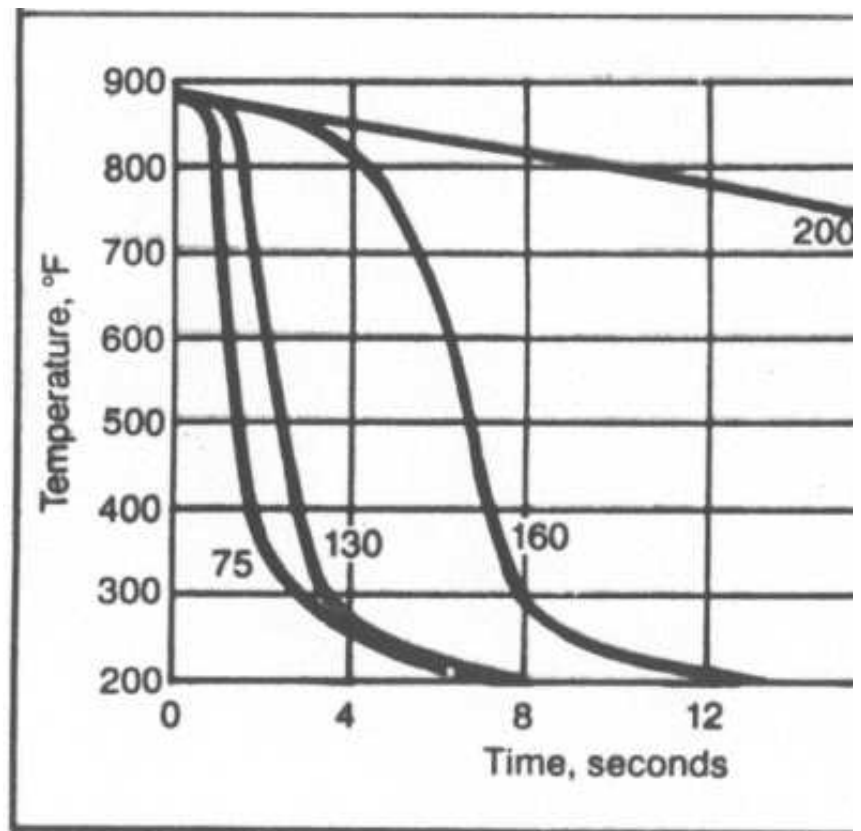


Figure 3. Cooling Curves For Water At Different Temperatures.

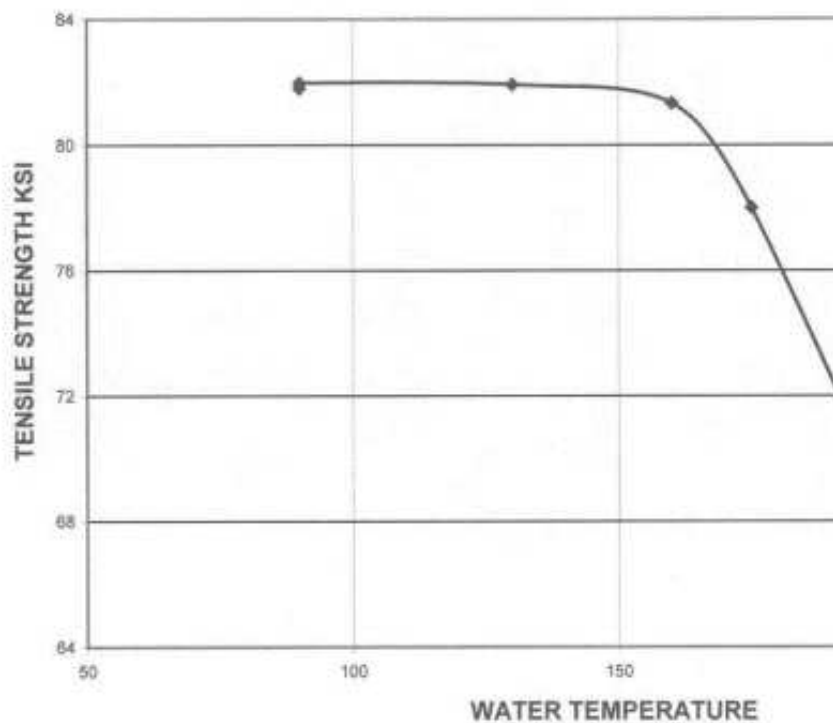


Figure 4. Effect Of Quench Water Temperature On The Tensile Strength Of 1-inch 7075 Aluminum Plate.

Table 1

Typical water quenching cooling rates for various thicknesses of aluminum alloys

	QUENCH MEDIUM COMPARISONS			
THICKNESS-INCHES	0.030	0.070	1.00	
QUENCHANT	QUENCHING RATES - DEGREES F PER SEC			
90 F WATER	10,000	6,000	220	
130 F WATER	3,000	1000	160	
160 F WATER	900	300	65	
190 F WATER	250	105	8	
212 F WATER	90	30	4	

Some forgings are quenched in boiling water, but in the case of other wrought products such as plate, extrusions etc, only the less quench sensitive alloys are quenched in boiling water. In some instances, specific tempers of other alloys such as 2014-T61 are required to be quenched in boiling water to achieve the highest level of dimensional stability. Therefore, it is recognized for specific applications, that the dimensional stability is more important than high tensile properties. As a result, high strength is sacrificed somewhat in favor of a more dimensionally stable part.

When quenched in boiling water, the part is actually being quenched in a continuous vapor pocket, particularly during the early stages of cooling. Depending upon the agitation of the tank, the breakdown of the vapor pocket may occur at different times at different locations of the part. Because of this fact, quenching in boiling water is sometimes uneven and uneven residual stress levels can be experienced. Experience has shown that quenching in high concentration glycol quenchants can provide both higher and more consistent properties with consistently lower residual stress levels than are realized from boiling water.

Specific Requirements for Different Alloys

Most specifications allow forging alloys to be quenched in

hot water in order to achieve less distortion than would result from cold water quenching. In these cases, the forging material specification usually takes into account any loss in properties that may result particularly when quenching thicker sections. In practice, many aluminum parts (especially forgings and castings) which are prone to distortion, are quenched in either hot (140–160°F) or boiling (212°F) water although some forging alloys are quenched in 180°F water.

Many aluminum casting alloys are quenched in boiling water because the quench rates developed are sufficient to achieve the required properties and minimizing the warpage of the casting is a prime consideration. However, in cases where premium properties are desired, (such as castings alloys A357 and A201), the use of colder water or a glycol quenchant at the proper concentration is recommended.

PROPER SELECTION AND USE OF GLYCOL QUENCHANTS

Sheet Metal vs Water Quenching

The first work in aluminum sheet metal quenching with glycols was performed by Lauderdale at Boeing(1). He clearly demonstrated that the Ucon® A glycol product was ideal for reducing warpage when quenching aluminum sheet metal parts. His data, Figure 5, showed that when quenching 0.040–inch sheet metal, a 5000 degrees per second cooling rate was achieved when cold water quenching. When quenched in 40% Ucon® A, a quench rate of 1800 degrees per second was still achieved, which was many times faster than needed to achieve full properties in all sheet metal alloys. He also showed in Figure 5 that the percent distortion was reduced significantly as the concentration was increased and the optimum concentration for full distortion control was 40%. A production facility was established which resulted in huge financial savings when the quenching technique for sheet metal parts was changed from cold water to glycol quenchants.

The first military efforts using glycol were at Northrop and Hughes Ground Systems. The work at Northrop, first

directed by this author and later by Lauchner (2) , clearly demonstrated the fact that when water quenching sheet metal, the quench rates achieved were far in excess of those needed to achieve acceptable properties. Water quenching sheet metal parts always resulted in excessive warpage.

Hunsicker (8) earlier had provided data that showed that there was a critical quench rate whereby quench rates above the critical rate always achieved full properties. For example, when cold water quenching sheet metal in the .030-.062 -inch thickness range, quench rates of 4000-10,000 degrees per second were achieved but that for 7075 sheet metal, only 200-300 degrees per second was necessary to achieve full properties. The work at Northrop fully categorized the thickness/ glycol concentration/ quench rate parameters for sheet metal products, shown in Figure 6.

Scott (7) at Hughes clearly demonstrated the beneficial effect of quenching sheet metal and dip brazed assemblies in high concentration glycols as he completely eliminated the problem of quenching warpage. He clearly illustrated that hand quenching a formed sheet bull nose cap, shown in Figure 7, into a 28% glycol solution would completely eliminate the need for any further check and straightening.

Further work by Schuler (9) at Hughes disclosed that even extremely thin dip brazements could be quenched in 40% glycol with no distortion whatsoever. Figure 8 shows a dip brazed assembly, fabricated from 0.020- 6061 sheet material, that was solution heat treated at 985°F and hand quenched into a 40% solution of Ucon® A. There was no distortion of the assembly after the heat treating process. Attempting to cold water quench these and other similar parts resulted in a 100% scrap rate.

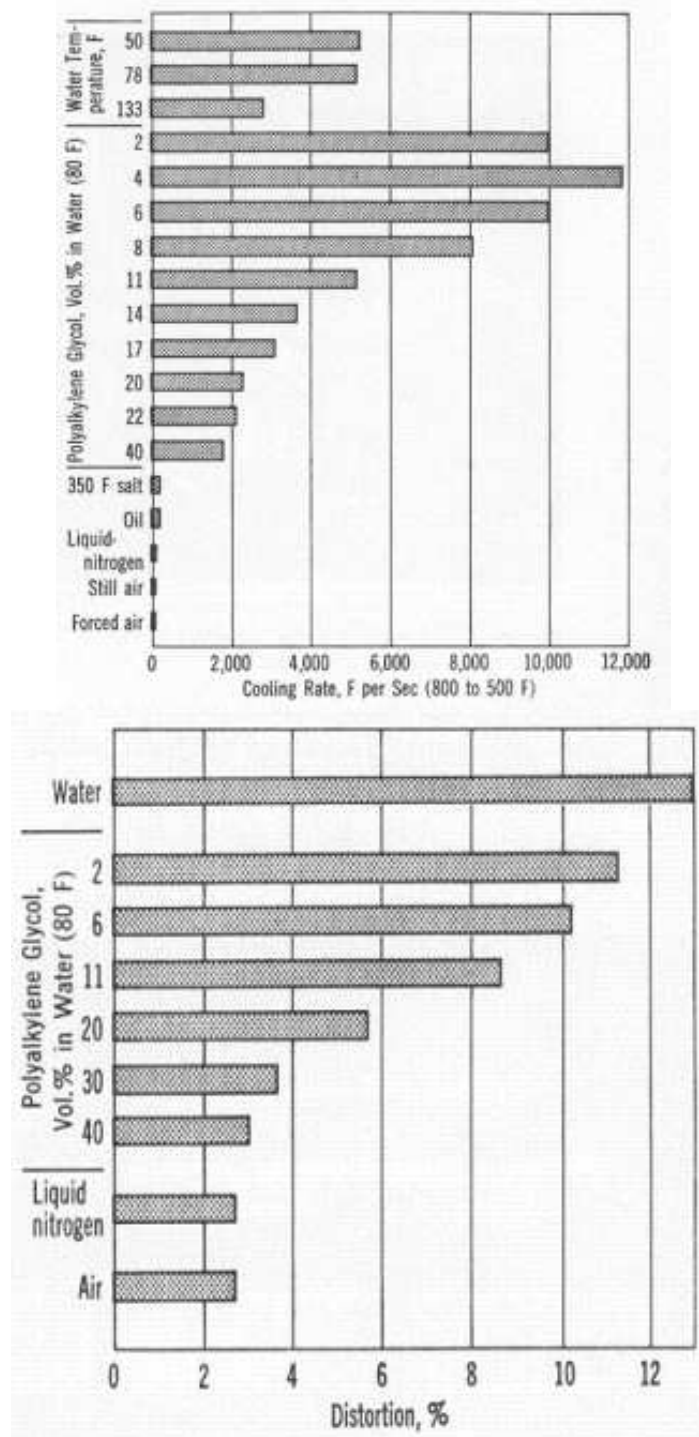


Figure 5 – Effect of Glycol Concentration on the Cooling Rate and Distortion Level When Quenching 0.040 2024 Sheet Aluminum. (1)

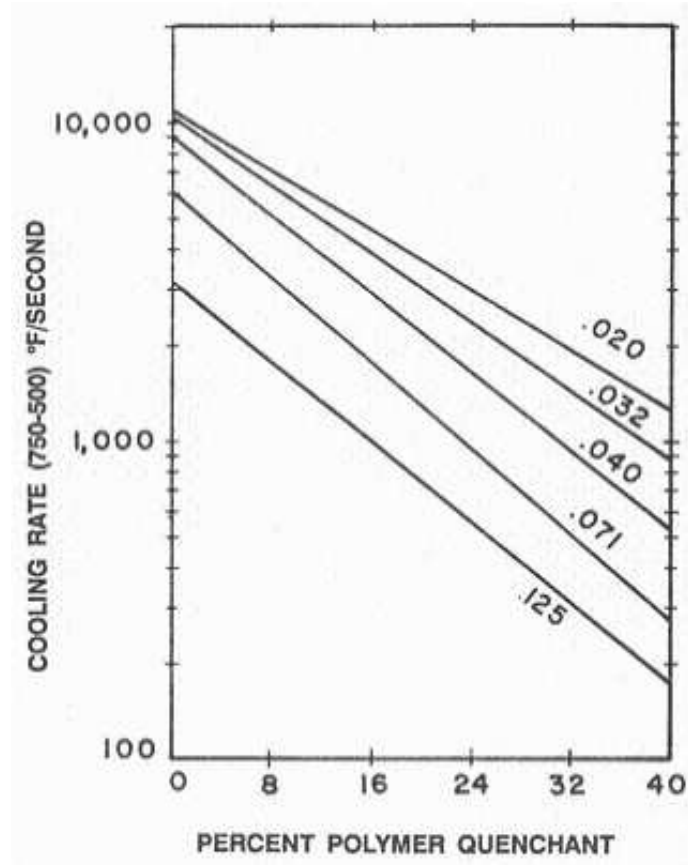


Figure 6 – Effect of Glycol Concentration On The Quenching Rates Of Different Thickness OF Sheet Metal. (2)

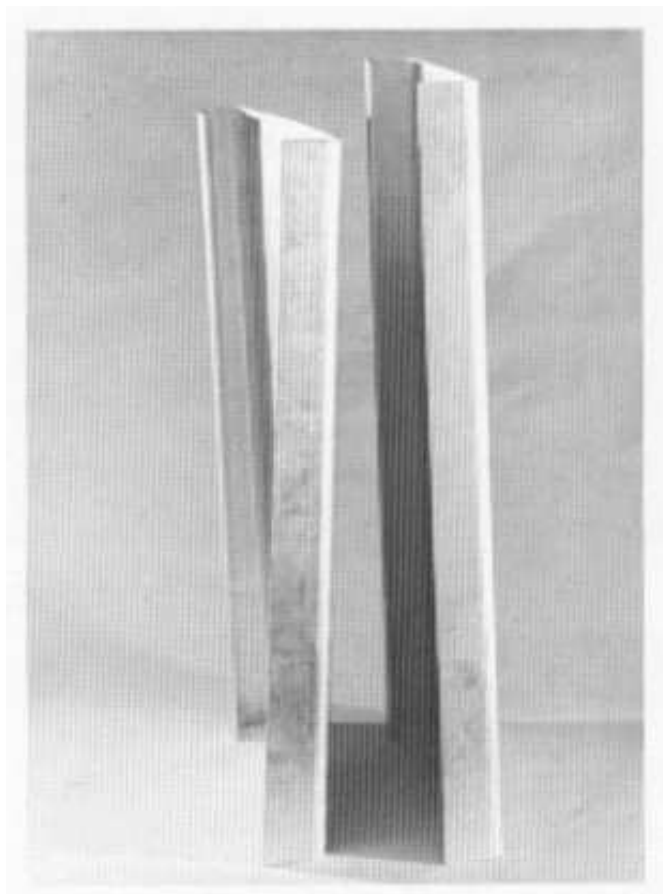


Figure 7. Distortion Comparison of 6061 Bull Nose Cap - Water vs. 28% Glycol. (6)

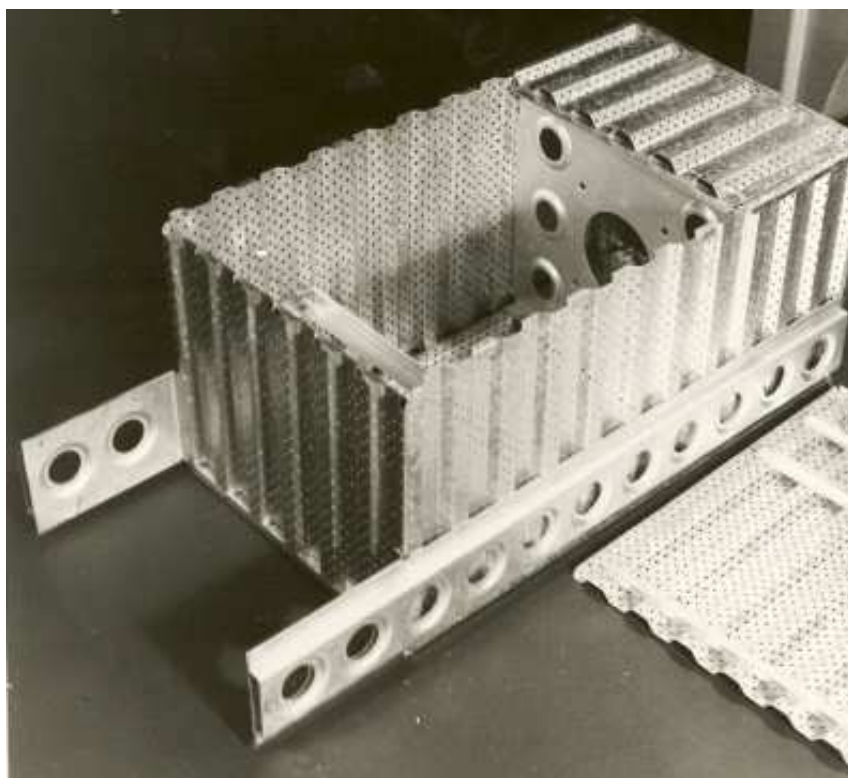


Figure 8. Complex Dip Braze Assembly – 0.020–6061 Sheet Aluminum Quenched in 40% Ucon® A. (8)

Lauderdale's, Scott's and Lauchner's work provided the basis for the establishment of the first production facilities, and the integration of alloy/thickness/acceptable concentration parameters in their heat treating specifications. Both the Lauderdale and Lauchner data revealed that most sheet alloys and tempers could be quenched in glycol concentrations as high as 40%, and indeed both early specifications allowed quenching in 40% concentrations, particularly for 6061 and 7075 sheet material. Most early production glycol tanks had their concentration limits set to 32–40%. The one exception was the T4 or T42 tempers of alloy 2024, which required approximately 1000 degrees per second cooling rate in order to minimize susceptibility to intergranular corrosion. To achieve this rate, lower concentrations were required.

The resultant economic savings by reducing or eliminating check and straightening operations was huge. At Boeing, their initial investment of \$12,000 resulted in a cost savings of over \$600,000 the first year at just one facility using a 40% glycol tank adjacent to a salt bath. At Northrop, three glycol tanks were charged adjacent to drop bottom furnaces to quench sheet metal parts. Two tanks were at 32% and one tank was charged at 24%. The 24% tank was charged to allow the quenching of slightly thicker 2024–T42 sheet material. Immediately after initiating the production glycol quenching program, 82 of 86 check and straighteners were either transferred to other departments or laid off.

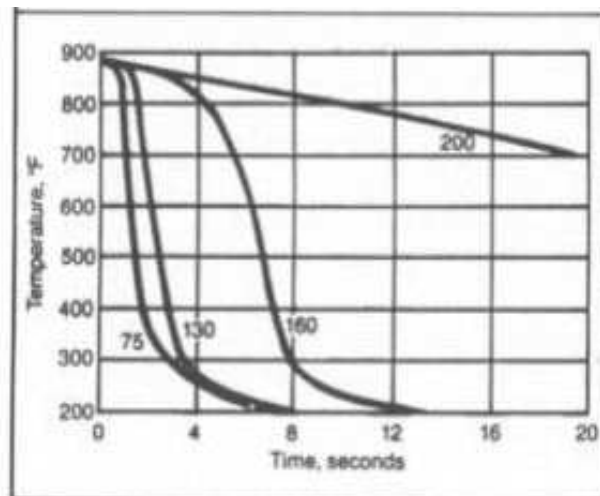
Similar efforts were conducted in the early 1970's by many other aerospace companies such as General Dynamics, Convair (3) General Dynamics, Fort Worth (4) Douglas Aircraft (5) North American Aviation (6) and Hughes Ground Systems (7) to name a few. One fact was clearly demonstrated by these efforts. Optimum warpage control was achieved by using as high a glycol concentration as possible that would still achieve full design properties. As stated previously, Lauderdale showed that warpage control increased directly with increasing glycol concentration and that optimum control was achieved in the 36–40% concentration range.

If optimum warpage control is desired when quenching

aluminum sheet metal products, it is normally recommended that a glycol concentration range of 32% – 40% be used. Some warpage control can be achieved at concentrations of 22–28%. Below 22%, the quench rates achieved for sheet metal, are too fast to provide significant control of quenching warpage. At 16% glycol, the quench rate achieved in a 0.040–inch sheet is approximately 3000°F per second which is ten times faster than that required to achieve full tensile properties in most alloys.

Quenching of Aluminum Castings and Forgings

While the early test programs involved with the glycol quenching of sheet metal products were being conducted, there was a prevailing opinion that the quench rates achieved by glycols were too slow to be effective for quenching aluminum castings and forgings. What many engineers were overlooking was the fact that these products were already being quenched in hot or boiling water and that these reduced cooling rates were already being used successfully to achieve properties. This author (10) (11) (12) conducted cooling rate studies comparing cooling rates achieved with hot water quenching with those achieved by varying the glycol concentration. What was surprising was that the Ucon-A product easily achieved cooling rates comparable to those achieved by hot water. Typical cooling curves for ½–inch plate, shown in Figure 9, showed that a 60% concentration of Ucon® A achieved a cooling rate equivalent to that of a 200°F water quench.



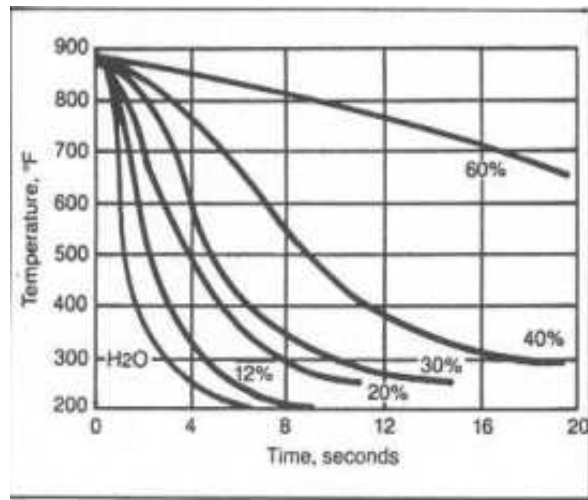


Figure 9. Cooling Curve Comparisons– Water vs. Temperature, Glycol vs. Concentration.

Later experimental work by the author with 2014-T61 landing gears showed that both higher tensile properties and lower residual stresses were achieved by quenching those gears in 60% glycol when compared to a boiling water quench. The misunderstanding of the basic concept of cooling rate equivalency was demonstrated clearly in this program that when the production quenching of these gears was initiated, the program managers of the prime contractor decided to use a 16% glycol solution instead of the 60% used in the experimental program. This was because 16% was the concentration allowed by their specification. These early production parts exhibited higher residual stresses so the production technique reverted back to the boiling water process. Unfortunately, the advantage of using higher glycol concentrations was never realized.

This author then categorized the quenching rates for greater thickness parts starting from 1/4-inch plates through 3-inch plates using the Lauchner approach. This data is shown in Figure 10. This data provided for the precise selection of specific glycol quenchant concentrations for achieving acceptable mechanical properties in any alloy when (1) the quench sensitivity data was available, and (2) when the existing minimum property level could be determined with the existing quenching method, i.e. hot water, boiling water etc.

The SAE Amec committee later developed quenching parameters for forgings of different alloys by using the

"zero delta" approach. They performed tensile testing on different forged alloys from different suppliers quenched in different glycol concentrations. They determined that they would allow the glycol quenching of forgings in their specification AMS 2770 if, when comparing the hot water quenching method directly with the glycol quenching method, there was no significant difference between the properties achieved (within variations from normal testing procedures) between the hot water and the glycol methods.

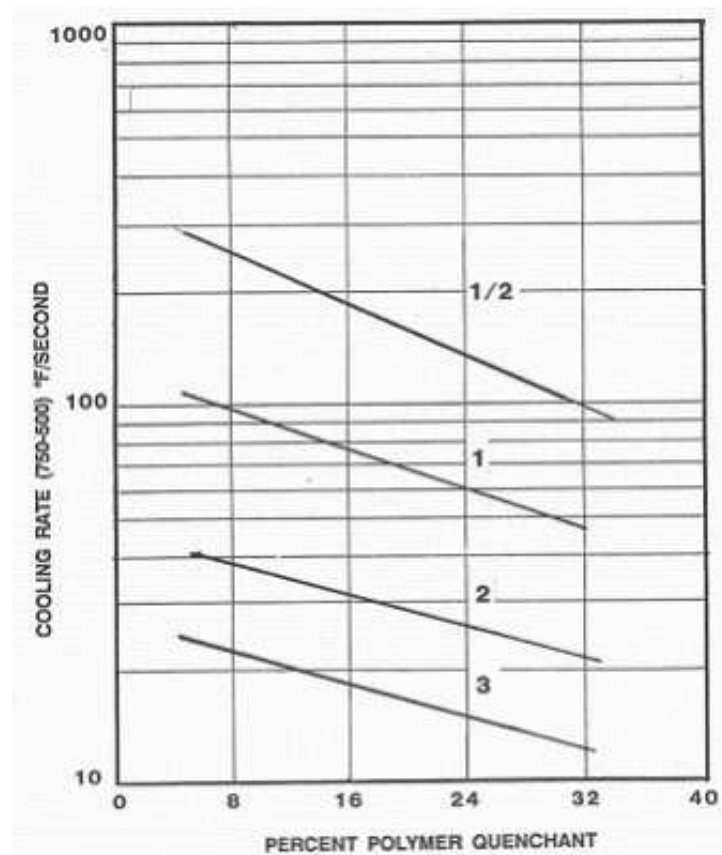


Figure 10. Interrelationship of part thickness and glycol concentration of quenching rates for gages from ½ inch to 3-inch thickness.

Later work has shown that Amec's zero delta approach was valid, but extremely conservative. For instance, glycol quenching of forgings of much thicker dimensions was not allowed by many specifications. However, it has been proven to be a viable alternative for achieving dimensionally stable forgings and casting with superior properties. One aircraft prime for many years used a 28%

Ucon-A concentration to achieve minimum warpage in some large 7075 forgings instead of the 16% permitted by specification. They verified every lot with tensile tests and never had a failure. Another extended the glycol concentration limits for their 7050 forgings to 4.5 inches to reduce the level of residual stress. Again tensile and random fracture toughness coupons were used to verify the results again with no reported failures. Recent work by this author has shown that in production quenching, equivalent properties were achieved by quenching a 7-inch thick 7050 forging in a 26% glycol solution when compared to quenching in a production hot water tank.

SUMMARY AND GUIDELINES

The following general rules apply when selecting the proper quenchant and concentration for achieving optimum warpage, residual stress and distortion control.

- 1) Avoid water quenching, wherever possible. For sheet metal quenching, the rates achieved by cold water are way too fast. For forgings, use of hot water (140–180°F) results in inconsistent control of the vapor pocket and thus inconsistent quenching.
- 2) For sheet metal parts, use as high a concentration as possible of Ucon® A commensurate with achieving mechanical and corrosion resistant properties. Concentrations of 32–40% are recommended for most parts.
- 3) If, because of other constraints, a 32–40% glycol solution is not available and the choice is cold water or a 16% glycol, use the 16%. Distortion control will not be optimum and significant check and straightening may still be required, but it will still be less than quenching in cold water.
- 4) For forgings, if glycol quenching is permitted by the controlling specification, use the highest concentration allowed.
- 5) For forgings, if there is no controlling specification, or if there is allowance for engineering judgement, use

existing data to determine the particular quench rates which will be achieved by your part when quenching in a particular glycol and select the optimum concentration. Verify with test bars. If there is no existing data, develop a quench sensitivity curve with the method of Reference 13.

6) If it is believed and can be proven that the controlling specification is ultra conservative, then present appropriate supporting data to the controlling authority and request deviation with justification based on cost savings. Use existing data to determine the particular quench rates which will be achieved by the part when quenching in a particular glycol concentration, and select the optimum concentration. Verify with test bars.

7) For castings, most casting heat treat specifications allow a wide range of quenching parameters. Select the highest glycol concentration commensurate with achieving properties.

8) In the case of machined parts, rough machine the parts prior to heat treating and glycol quenching. Lower residual stresses and increased dimensional stability can be realized by allowing a thinner part to be quenched in a higher concentration of glycol. In some instances, higher properties will also be achieved.

9) For forgings, castings and machined parts, consider the possibility of using uphill quenching to optimize the final residual stress level and reduce machining distortion. See References 15, 16 and 17.

10) Forget trying to apply some computer model for controlling distortion. Computer models do not take into account critical control factors such as racking methods, quench tank design and immersion rates which are critical in eliminating distortion during production heat treating. Fundamental knowledge and technical experience in the heat treating shop will go much farther than an inadequate computer model.

11) Don't believe a prevailing opinion that it can't be done. With the proper systems approach, virtually all distortion and residual stresses can be eliminated.

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