Controlling Residual Stress
in
High Strength Aluminum Alloys -

One Engineer's History, Approach and Opinions.

By

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INTRODUCTION

The problem of excessive residual stresses in high strength aluminum alloy forgings reached its peak in the 1960's and early 1970's. Most aerospace companies were faced with stress corrosion cracking problems that resulted in serious problems throughout the industry. Planes had to be taken out of service with cracked parts, parts would crack overnight while sitting on a shelf and machining suppliers were faced with the problem of parts moving all over the place during machining operations. With the development of the newer alloys and T7 type tempers in the 1970's, the problem seemed to subside for a period, but with the recent progress in much larger aircraft, resulting in much larger and thicker high strength forgings, the problem has again reared its ugly head. Vendors are again having problems with excessive machining distortion, dimensional stability has been harder to achieve, and even stress corrosion cracking is again becoming a problem. As I near full retirement, this paper is meant to review some of my experiences and successes over the past 50 years in combating the problem of residual stress in the airframe industry so that it may help those newcomers who are now starting to face the upcoming problems.

EXPERIENCE AT NORTHROP

I first became deeply involved in the problem of controlling residual stress in high strength aluminum alloys when in the 1960's, as a Senior Lead Metallurgist at the Northrop Aircraft Corporation, we first experienced stress corrosion cracks in high strength aluminum landing gears. Shortly thereafter, we had a serious problem of stress corrosion cracks and excessive machining distortion in many of our structural wing spars. In one case, a 17 foot spar had a 14-inch bow in the part and ripped out the 3/8 steel bolts that were holding down the parts as it was being machined. My group had the responsibility of solving the problems in order to keep the production line functioning.

Regarding the landing gear problem, in conjunction with Alcoa, we conducted extensive studies and found that the residual stresses due to the quenching procedure involving a cold water quench were extremely high, (approximately 35,000 psi). At the time, cold water quenching was the required practice at Alcoa for this alloy because it was designed to be used in thicker sections than the 7075 alloy. In order to achieve adequate properties in these thicker sections, Alcoa required it to be cold water quenched. It became clear that in our case, in order to achieve acceptable parts, that a process had to be developed to reduce the stresses in the part to avoid cracking. Reviewing available data received from Alcoa regarding the effect of quench water temperature on residual stress, the effect of quench sensitivity of different alloys, and the ability of different quenchants in achieving quenching rates that would provide acceptable properties, we conducted a test program and determined that cold water quenching of our parts was not necessary because of their specific thickness. For the thickness of the parts that we were producing, a much hotter water (185°F) could be successfully used to reduce the residual stresses significantly while still maintaining the strength levels required. Discussions with the Alcoa technical personnel were held and they agreed with our findings, conducted their own tests and developed a new temper for the 7079 alloy which they called 7079-T611, which then required a 180-190°F water quench in order to reduce the residual stress levels. All future landing gears were manufactured to that procedure, and the stress corrosion cracking problem for the landing gear was solved.

Because of the widespread stress corrosion cracking problem that we were experiencing at that time, we also instituted other provisions regarding the manufacture of high strength aluminum forgings. For instance, we no longer accepted the practice of fully heat treating an as-forged product and then machining the part. We required that all high strength forgings be rough machined to within 0.125-inch of final thickness before heat treatment to minimize the residual stress that was being induced by the quenching process. The data received from Alcoa showed that the residual stress level of a heat treated part increased almost exponentially with a thickness increase. Also, we required that specific parts like the landing gear be shot peened on all surfaces to ensure compressive surface stresses to reduce the propensity for cracking. All high strength aluminum forging drawings were revised to require these practices on all existing aluminum forgings.

About the same time, Northrop, as every other aerospace company, was experiencing excessive distortion when quenching all of their sheet metal products. We were approached by Boeing to review a

recent development of theirs (the result of work by Russ Lauderdale, [1] [2]), which involved a new method of quenching aluminum sheet metal, using solutions of a polyalkylene glycol product called Ucon® Quenchant A, manufactured by the Union Carbide Corporation and distributed by Tenaxol Inc. This new product was able to precisely control the cooling rate occurring during the quenching process from very fast to very slow. The Lauderdale's work proved that most sheet metal quenching distortion could be completely eliminated with the proper use of this method. I was assigned to review their process at their Seattle facility and was extremely impressed. This led to an internally funded effort by Northrop to develop sufficient data to convince the Air Force to use this process at Northrop. The program was conducted by two of my engineers, Ed Lauchner and Bert Smith. This program emphasized the approach of studying the effect of different quenchants and the quenching sensitivity of different alloys to determine which products could be successfully manufactured possessing the appropriate mechanical properties but at the same time eliminate the distortion problem that occurred during the quenching process. After completion of this test effort, the Air Force reviewed and approved our work and Northrop prepared the first heat treating specification (Northrop HT-25)approved by the military to allow quenching of high strength sheet metal products in glycol. Mr. Lauchner and Smith published a company report [3] showing the results of our efforts. Northrop then charged three quench tanks with glycol solutions in conjunction with large drop bottom furnaces. Two tanks of Polyalkylene glycol at 32% and one at 24% were charged. This was necessary because it was determined that slightly higher quench rates and thus a lower glycol concentration were necessary for the 2024 alloy in order to ensure resistance to intergranular corrosion, even though mechanical properties could be achieved at the higher concentration. The production results were amazing. Immediately after changing the quenching procedure from the original cold water quenchant to the glycol products, 80 of 84 check and straighteners were either laid off or transferred to other departments. We were able to completely handle all check and straightening operations with just four people where before over 80 personnel were required because distortion was for all practical purposes completely eliminated. The huge cost savings was obvious.

RUNNING A JOB SHOP HEAT TREAT COMPANY

In 1968, I left Northrop. I had numerous discussions with Tenaxol about the feasibility of quenching forgings and castings using the glycol products. I felt that this approach was possible because these forgings and castings were currently being quenched in hot or even boiling water, so it seemed that equivalent cooling rates could be achieved using the glycol product at different concentrations which might possibly not only reduce quenching distortion problems but might also reduce the residual stresses left in parts. We entered into a joint research contract with Tenaxol, and during the next two years conducted extensive cooling rate and mechanical property studies in the laboratory to determine the feasibility of glycol quenching products other than sheet metal using the glycol technique. At the same time, with Tenaxol support, we initiated the construction of the first commercial job shop heat treating facility with the main emphasis of producing distortion free parts using the glycol method. Two years later, we inaugurated that facility and started to produce distortion free parts for the local community. By that time, we had developed sufficient data to prove full mechanical and corrosion properties could be achieved when heat treating castings and forgings using the glycol method. We published three articles [4], [5] and [6] in 1970, 1971 and 1973. The first article was co-authored by Dan Schuler, who was the chief metallurgist at Hughes Ground Systems in Fullerton. Mr. Schuler had been conducting extensive research on the feasibility of using the glycol technique with 6061 dip brazements and Hughes later published their work [7]. It should be noted that recently, I was invited by Dr. George Totten to publish a general summary of the glycol method and it was published by ASTM in 2008 [8].

Initial Glycol Quenching of Forgings

At that time, about 1970, no aerospace heat treating specification allowed for the quenching castings and forgings using glycol. Hot water, with all its problems was required. We contacted a number of the local forging producers who were having distortion problems. These included Harvey aluminum (later Martin Marietta Aluminum), Alcoa Vernon Works, and a number of the no draft, precision forge companies in the area. Our first big success was with Harvey Aluminum. They had contracts with Boeing and Lockheed to manufacture many different forgings, the highest volume being

window frame forgings for both the 747 and 1011 passenger aircraft. After reviewing our reports and data, they approached Boeing and obtained permission to use the technique, as long as Harvey monitored the process to ensure that all structural properties were maintained and guaranteed by Harvey. Initially, Harvey wanted it proven that we could obtain successful results in production quenching, so after establishing our parameters, a prototype load of about 250 forgings was processed using a 32% solution. Only one of the 250 forgings was found to be out of tolerance after quenching in the glycol product requiring virtually no check and straightening whatsoever which would have induced additional residual stress. After that, we obtained contracts to solution heat treat and quench all of their widow frames and for the next five years, produced many thousands of parts. As with the Northrop situation, the cost savings were large. Prior to us doing their heat treating, Harvey had a line of approximately 36 personnel performing check and straightening on the window frames. I was told that it took about 30 minutes to straighten each frame after quenching in the hot water. After we entered the picture, the time to check and straighten the frames was reduced from about 30 minutes per part to 30 seconds per part, and the straightening staff was reduced to about four personnel and most were transferred to other departments.

Initial Effort in Controlling Residual Stresses in Forgings

During that time, we started to investigate the influence of the glycol quenching technique on reducing residual stresses in forgings. Tenaxol also funded some research work with the University of Wisconsin. Both programs showed that significant reductions in residual stress could be achieved by quenching in glycol solutions of concentrations of 20% or better. (We later reported that work in Reference [9].) At the same time, Northrop, with their success in using the glycol quenching for production sheet metal, also initiated research into the feasibility of quenching thicker products. They funded a program with us to determine the cooling characteristics of the glycol in thicker sections and to compare with the results with hot water quenching. Mr. Lauchner produced a company technical report [11] and the data was also presented to the SAE Amec committee, who had responsibility for the AMS heat treating specifications. Amec then conducted an extensive joint test program, which showed that castings and forgings could be properly be heat treated using the glycol technique. Their heat treat specifications, AMS 2770 and AMS 2772 were then updated to allow the method based on their research data.

We continued our work regarding the influence of glycol quenching on achieving reductions in residual stresses through the 1970's. In 1980, at the invitation of Heat Treating magazine, we published two articles regarding dimensional stability [9] and [10]. In the second article, we showed how the use of a glycol quenching technique could be used to achieve significant reduction in residual stresses, particularly when using concentrations above 20%. We also showed that more than acceptable properties could be achieved in even quench sensitive, high strength alloys when using concentrations of 20-30%. It was also found that when using a 30-40% concentration, the residual stress level was essentially minimized. This fact was later confirmed by the work by Dr. George Totten and his associates [12] where they noted that residual stresses in some section thicknesses were completely eliminated by quenching in 30% glycol. It should be interesting to note, that because of the lack of further research, here we are now 35 years later, and no specification allows the use of these higher concentrations because of the lack of additional research and understanding of the process.

The use of our systems analysis technique for determining optimum glycol concentrations for different alloys based on an understanding of quenching severity of different quenchants and the quenching sensitivity of a specific alloy is best illustrated by two situations that occurred about 1973.

1) 2014 Forged Wheels

Normally, alloy 2014 forged wheels are routinely quenched in boiling water in order to achieve the minimum residual stress possible. I was approached by the forging metallurgist at Harvey Aluminum about the possibility of glycol quenching 2014 forged aircraft wheels. At the time, Harvey had been quenching all 2014 forged wheels in boiling water, and were still having random problems with residual stress and sometimes meeting required tensile properties. After researching the problem, and reviewing comparable cooling rates achieved for a glycol quench versus a boiling water quench, we determined that a 60% glycol would achieve about the same cooling rates as boiling water. (These curves are shown Reference [13]). When we told the Harvey

metallurgist what we had determined and wanted to try a 60% Ucon® concentration, he initially thought we were crazy. After reviewing our quenching data with him, he agreed to try. We set up a small 60% tank, and quenched out a number of wheels in the 60% concentration and returned the wheels to him for aging and testing. The results were outstanding. He reported back that the tensile properties were slightly higher than he was obtaining with the boiling water quench, and the residual stresses were more consistent and lower. I never did receive the actual data, but he put it into a report which he submitted to the wheel company indicating that they were ready to start quenching their wheels in glycol, instead of the boiling water. When the metallurgists at the wheel manufacturer reviewed that data, they first were extremely enthused about the possibility of achieving consistently lower stresses with better properties. However, they did not understand the basics of controlling quench rates with different concentrations, and as their specification only allowed the quenching of forgings in a 16% glycol concentration, they insisted that the 16% be used by Harvey, not the 60% we had used in our experiments. A load of forged wheels was thus quenched in their required 16%, and as we expected from our data, significantly higher residual stresses resulted than were being seen from the boiling water quench. The resulting conclusion by the wheel company was that glycol quenching provided no benefit. Thus the project was cancelled and the process returned to the boiling water quench with all its problems. Here we are, 35 years later, and most personnel still do not understand the fundamentals of when and how to apply the process correctly. I personally would not recommend a facility setting up a 60% solution for such an endeavor, but other efforts we have conducted, particularly on forged 6061 and 2618 rings for engine companies, definitely show that a concentration range of 35-50% could probably be used to achieve the lowest residual stress level in these alloys with the highest properties when compared to a boiling water quench.

2) 2219 Forged Cone with Extremely Tight Dimensional Tolerances

The application of the systems approach we used to achieved dimensional stability is clearly illustrated by the process used to manufacture a number of 2219-T6 cones, which were part of a missile system which was to be launched into space. We reported the results of this effort and summarized our systems approach to achieve these results in reference [14]. These cones had to possess extreme dimensional stability and had very tight dimensional tolerances and were extremely thin in their final configuration. Because of schedule limitations, it was necessary to machine the final configuration from a solid hand forged billet which measured 7 1/4 inches in diameter by 17 inches long. The final cone had to meet the following criteria:

(1) Full T6 properties;
(2) Extremely close dimensional tolerances (±.001-inch);
(3) A high level of dimensional stability with minimum residual stress.

The task was made more difficult by the fact that some areas of the cone wall were as thin as .060-inch. By applying a systems analysis, a manufacturing procedure was developed to achieve the objectives. The study included consideration of the quench sensitivity of alloy 2219, residual stress data, and the quenching response of the alloy in different polyalkylene glycol quenchants, which was determined by quenching sections of different thicknesses in various concentrations and developing a quench sensitivity curve.

At first, the prime contractor contacted the forge company to request that they supply the finished parts. The forge company refused. In their refusal, they indicated that with their current level of technoloy, trying to maintain the ±.001-inch tolerances requested was impossible. They said that they would supply the 2219 hand forged billets, but that is all the responsibility that they would undertake. At the suggestion of the forge company, the prime company's buyer contacted us to review the situation. After reviewing the problem, we believed that we could produce the parts to the required tolerances, but we would have to use procedures that were not approved at the time, (such as quenching the parts in a high concentration glycol and final

aging at higher than normal temperatures) and we would have to direct all machining operations. That was agreed to by the prime's buyer and he indicated that they would perform the machining at their facility under our direction. A few days later, the buyer called again and indicated that he had another problem. Their machine shop felt because of the reputation of 2219 of having a "memory", they felt that they could not meet the extremely tight machining tolerances required and he asked if I could find a machinist to assist in producing the parts. We agreed and contacted a machinist we had worked with in the past. He was a graduate mechanical engineer, and was well versed in machining aluminum parts to tight tolerances.

At first, even our machinist expressed reluctance as to the feasibility of manufacturing such a part to a $\pm$ .001 tolerance, mainly because of the reputation that 2219 had for moving during and after processing. When asked if he could machine the part to the tight tolerances required, he asserted that he could meet the specified tolerances, but he was concerned and had two questions: (a) would the parts move during machining and (b) after completion, would the parts be sufficiently stable to retain those tolerances. We assured him that if all of the steps of the systems approach that we had presented were followed, the parts would be stable.

The final procedure called for procuring the forgings in the 01 temper and rough machining the part to a closely engineered envelope. The exact dimensions were determined by balancing the quenching-mechanical property parameters with the machine shop tooling requirements necessary to achieve the precise tolerances in the very thin walls. The parts were then conventionally solution treated and quenched in a 42% concentration of the chosen glycol quenchant. This quenchant was shown to essentially achieve almost zero stress in the parts because of their final thickness before solution heat treating. The quenching severity of this quenchant was also shown to be adequate to produce sufficient cooling rates to easily ensure that full T6 properties were achieved after the final aging treatment. It was also decided that in this case, because we were able to achieve such low levels of residual stress through the quenching procedure, that stress relieving after quenching by the uphill process would not be necessary.

Care was taken to ensure that residual machining stresses were not imparted to the part during the final machining operation. The part temperature was controlled during the final machining operations. Adequate cooling and proper cutters, feeds and speeds were used. Initially, consideration was given to applying interim thermal stress relieving procedures during the machining operations prior to taking the final cuts. However the machinist felt that he was able to properly control the tool geometry, feed, and speed parameters in order to successfully minimize the heat generated during the machining operation so that he would not impart stresses to the part during machining. Thus, interim thermal stress relieving treatments were not used and in the end, he was proven correct.

An aging treatment was selected that assured full -T6 properties and allowed for maximum stress relief during aging. Following aging, the final machining was completed. Six production parts were successfully manufactured using this systems approach.

Upon receipt of the parts by the customer, his inspection proved that all final dimensions were within the tight tolerances that he had specified. He tested the tensile bars processed along with the parts and proved that the required T6 tensile requirements were easily met.

Prior to us undertaking this project, the forging producer asserted that this part could not be manufactured to the specified requirements using conventional water quenching techniques, even with TX52 stress relieving treatments. This project, which was completed in the early 1970's, clearly illustrates, even at that time, that if one clearly understands the theory regarding the sources and possible procedures needed for residual stress control and part movement in heat treated, high strength aluminum alloys, and a systems approach is developed for that part, that any part can be produced which is dimensionally stable and exhibits acceptable property levels. One other aspect of this case needs understanding. In the past almost 40 years since this project was completed, most engineers still do not understand the value of quenching different alloys in the polyalkylene glycols. Today, most specifications still do not allow 2219 alloys to be quenched in any glycol, let alone one of high concentration.

STARTING MY CONSULTING COMPANY

In 1979, I decided to go into consulting, and started my consulting company. I concentrated on not only consulting and providing training for local heat treating companies, but also providing seminars for companies like Alcoa, Kaiser Aluminum, Boeing, Lockheed, Bell Helicopter, and Pratt and Whitney. Working with some of the local heat treating companies, we were also able to continue our research involving residual stresses and providing stress free components to customers. Most of our research efforts were involved with a startup company, Newton Heat Treating Inc, with whom we had numerous discussions regarding the necessity for controlling residual stress. With our help, they installed a glycol quenching facility and we introduced the owner to a technique of residual stress control, originally developed by Alcoa in the late 1950's [15] called thermo-mechanical stress relieving [15] and later more commonly called "uphill quenching" At our urging, Newton established an excellent uphill facility using the original Alcoa method of uphilling with high velocity steam. One unique feature of their facility is that also at our urging, they procured a Rigaku residual stress measurement device so that production measurement of residual stress is achieved as a quality tool. Today, most materials which are processed at Newton to achieve low residual stress levels are routinely processed to rigidly fixed plans and are routinely checked for their residual stress level before final shipping. This process ensures that the customer is actually receiving the stress free part that is desired.

One main problem with the uphill technique is that currently, there is no universal specification for the process, even though many companies in the US embrace it, have specifications for its use and use it routinely. With my involvement with the SAE Amec committee, I volunteered to create such a document with the help of Newton personnel. One circulation for ballot has been completed, and at the end of that circulation, because of my health problems I turned the task over to Robert Sutton of Newton, who is currently continuing to develop the document for the SAE-Amec committee.

Since 1979, we have conducted extensive research into the uphill method, and in 1983, we published an article regarding our application of the technique in Heat Treating Magazine [16]. Alcoa, despite being the original developer, essentially abandoned the technique because they felt it was not applicable to their type of business. However, we felt at the time, and have successfully proven since that it would be an ideal method for integrating into our systems approach for eliminating troublesome residual stress in complex parts. In recent years, we have expanded our research, and in 2009 (at the urging of Dr. Totten) we published an article in an ASTM publication [17]. It should be noted that during the 1980's, I tried to encourage a number of companies, including Union Carbide and a number of the American aerospace primes to help in developing an alternate method using high temperature polymers to the high pressure steam approach, but no one was interested in helping in the effort. It should also be noted, that recently, the Chinese are conducting extensive research involving the use of a high temperature polymer as the heating method, and have been reasonably successful [18]. Our efforts have shown that with the use of high velocity steam, complex parts can be successfully stress relieved, and Newton Heat Treating has provided services to customers all over the US for years. One major aerospace prime contractor has decided that it is so beneficial to their manufacturing operation by eliminating machining distortion, that all of their high strength forgings are processed using the uphill method, and they send a truck once a week from the midwest to California. They have completely eliminated their machining distortion problem. Bell helicopter has many of their high strength aluminum rotating components processed in this manner and has verbally reported that it has increased the life of some parts by orders of magnitude. Boeing Helicopters also has embraced the process and has many of their high strength aluminum components processed in this manner.

EXPERIENCES WITH THE C-17

Even with all our successes in the 1970's and 1980's, McDonnell Douglas experienced severe distortion problems trying to manufacture the first C-17's in the late 1980's. Many do not realize that early schedule delays for producing the aircraft were due mainly to the fact that the C-17 involved the use of numerous forgings made from the newer alloy 7050 and significant problems were being encountered when trying to produce parts to drawing tolerances. Many of the parts were extremely complex, and at the time were being processed in the same manner as they had previously processed their 7075 alloys in previous aircraft. The results included not only excessive warpage during the quenching parts but also excessive distortion of parts during the machining process. In 1989, I was invited to present a number of seminars at the Douglas plant. The title

of the seminar was "Impact of Manufacturing Process on Producibility of Large Aluminum Structures" and the gist of the presentation was "What is wrong with 7050"? We presented the seminar about seven times, and included in the audience were most of Douglas's top management, including several vice presidents, and the last seminar included both representatives from the Air Force and the Navy. As a result of these seminars, Douglas made extensive changes to their manufacturing procedure and eventually solved their distortion problems. We later made similar presentations to the management staff at Alcoa Cleveland and at a seminar conducted by ASM in San Francisco in 1995.

Somewhat later, I was contacted by Douglas engineers to help reduce the machining distortion that they were experiencing in the banjo fitting for the MD-11 aircraft. That fitting was a massive fitting that attached the rear tail engine to the fuselage of the aircraft. Working with a local heat treating company, (Alumatherm) and Mr. Louie Caldarera, a Douglas machining specialist, we worked out a technique for glycol quenching the finished machined fitting from a vertical salt bath, and Douglas permitted the part to be quenched in a 16-18% glycol bath. Mr. Caldarera made numerous changes in their machining procedure based on my recommendations and his vast machining experience. Later he published and article which summarized the success of the program [19].

There were other successes that we were involved with during the C-17 program. One involved the problem of quenching a rather large wing forging made from 7050 that had high section transitions. The hub of the forging was about 7-inches thick and many other machined areas were less than a half an inch in thickness. At the time, Douglas did not allow quenching of thickness greater than 3 inches in glycol due to a lack of data. Water quenching of the part was causing so much distortion, that the check and straightening operations were taking extremely long times that it was affecting the schedule. The heat treater convinced Douglas to fund a test program which I directed. Seven inch hand forgings from two different suppliers were processed using the normal hot water quench, and three different glycol concentrations in their production tanks. The results showed that there was no significant difference in the mechanical properties or fracture toughness values of the material between the hot water quenched and glycol quenched parts, so the Air Forced approved the glycol process for this part. Using the glycol method significantly reduced the distortion problems and the heat treater was now easily

able to keep up with the required Douglas schedule. We presented these results in a report to the Amec committee in 2007 [20]. Currently, as the Amec responsible engineer for AMS 2770, I have been trying to extend the thickness limits for glycol quenching thicker sections and some other alloys, and presented data both in a presentation and a report in 2009 to justify this approach. However, so far, I have been unsuccessful in convincing some of the members of the commodity committee to allow this method because they do not understand the process and want to see additional data, especially fracture toughness values.

PROBLEMS WITH FORGED RINGS FOR AIRCRAFT ENGINES

In 1999, I was contacted by Pratt and Whitney regarding distortion problems that they were having with aluminum forged engine rings. Even with mechanical stress relieving (both stretching and compressive stress relief techniques), they were still having extensive movement of their parts during their final machining operations. After conducting a seminar in their Maine production facility, we were asked to propose a test program to determine if applying glycol quenching techniques to their forged rings would help solve the problem in two different alloys, 6061 and 2618. We first had to develop a quench sensitivity curve for the 2618 alloy. We already had extensive experience in working with 6061, so we were able to use existing data. Working with two different forging venders and a local heat treating company, we quenched a number of 2618 and 6061 rings in a 36% glycol tank. These rings received no additional stress relieving treatments after quenching. Pratt then machined the rings making extensive dimensional measurements to determine the amount of movement that they were experiencing. The results showed that the glycol quenched rings without a subsequent stress relieving process provided greater stability than the water quenched rings that underwent a mechanical stress relieving operation. The results of this effort were published both in the Amec report [20] and my recently published book [21]. The original program was intended to progress into a Phase II effort, where we were to conduct additional studies on other larger rings of different thicknesses, and assist in developing processing standards, but unfortunately Pratt ran out of research budget and the program was cancelled, so these tests were never conducted. Recent discussions with local heat treaters have indicated that they are still having problems today with mechanically stressed relieved product from different vendors.

REGARDING MACHINING INDUCED RESIDUAL STRESSES

Regarding the influence of machining techniques in imparting residual stress to aluminum alloys, this fact is true but sometimes not recognized by many. It the early 1980's, Northrop found a problem whereby deep plunge machining without adequate cooling was actually annealing parts machined from 7075-T73 plate and causing some distortion in the bottom of the pockets. The problem was discovered when inspectors noted a significantly different color to the finished parts after they were anodized. We later reported this incidence in reference [21]. About the same time in 1982, Allen McMechan had been conducting studies at McDonnell Douglas Canada Ltd. and found that excessive high temperatures created at the tip of the cutter could actually develop sufficient heat to anneal the parts [22]. The heat generated by the machining of these parts also induces residual stress due to the differential heating and cooling of different areas of the part. In the work conducted by Calderara, he expressed to me the fact that too many machine shop management personnel are worried about the life of a cutting tool due to excessive tool heating during machining, but they do not worry about the temperature created in the part. His approach was to make sure that the cutter geometry, feeds and speeds were developed to ensure that the temperature of the part was controlled during machining, even if it had to allow greater temperature in the tool. Our experience has shown that when machining high strength aluminum alloy, adequate cooling must be directed at the part to ensure that the part does not get hot during the machining process.

When investigating the effects of machining on residual stress in aluminum alloys, it is essential to separate those stresses that are imparted during the machining process from those quenching stresses that are being relieved during the machining operation. Too many times, people confuse the two.

Another C-17 incident illustrates this point. A local heat treater was heat treating rough machined C-17 forgings supplied by two different machine shops. The heat treatment processing, particularly the quenching operation was exactly the same. The parts from one machine shop, when quenched, were completely distortion free, while the parts from the second shop distorted greatly, and had to go

through excessive check and straightening operations to bring them back into tolerance. Because of these induced quenching and straightening stresses, the vendor also had problems of movement during final machining which the first machine shop did not have. The second machine shop kept blaming the heat treater for their problems. A visit by Douglas personnel (Mr. Caldarera) to their plant finally convinced them that they were machining the parts incorrectly, thereby inducing high residual stresses to the parts which caused the parts to move in the furnace when they were heat treated and that the problem was theirs, not the heat treaters.

Much of the problem of achieving stability in finished aluminum parts results from inadequate drawing and planning requirements as well as insufficient specification parameters, which, coupled with a lack of understanding by purchasing personnel of the residual stress problem, can lead to disaster. The problem of defining specific procedures required for achieving a dimensionally stable part is illustrated in the following scenario. (This event has been previously published in References [17], p 9 and [21], p 172)

RESIDUAL STRESSES IN ALUMINUM CASTINGS

In 1993, I was contracted by a large parts producer to audit production procedures involving a large (approximately 3 ft. x 4 ft (0.91 m x 1.22 m) electronic chassis housing, cast from A-356 alloy, which housed electronic components in a nuclear submarine. When the production contract to the foundry who had been successfully producing the part, came up for renewal, it was given to a new foundry and a new heat treat company. While the new order of castings was being machined at the prime contractor, severe distortion and cracking occurred in all castings due to the high residual stresses in the part. Cracks and part movement up to 1.0- inch (25.4 mm) occurred in some areas. An audit of the procedures revealed that the problem occurred from the lack of control while purchasing the parts. The original vendor, aware of the problem, had been solution heat treating the parts, quenching them in 22% glycol, and then applying an uphill quench procedure to relieve the residual quenching stresses. When the parts went out for re-bid, to save money, the purchasing department eliminated the requirement for the glycol quench/uphill quench procedure because the requirements were not on any drawing or in any specification. They agreed to a contract with the new foundry without these provisions.

Thus, the new foundry and heat treater needed only to follow normal heat treat specification requirements that called for a hot water quench and no uphill stress relieving because the provisions for uphill quenching were not on the drawing and were not part of the contract. Eliminating these requirements had left extremely high residual stresses in the parts that led to the cracking during the machining operation. The problem was easily resolved by returning to the systems approach of glycol quenching followed by the uphill quench of the production castings which were then specified on both drawing and processing specifications.

REVIEWING OUR APPROACH

A short summary of our current approach for eliminating residual stress in high strength aluminum alloys is the following:

1) Have a part produced to as close as possible to final dimension before heat treatment. The thicker the part, the higher the stress that will be imparted upon quenching. However, with parts of large section transitions, sometimes it is better to leave some excess material on the thinner sections to attempt to achieve equal cooling in all areas of the part and machine if off later.

2) Avoid imparting stresses into the part in the first place. Be sure that machining is performed in a manner to eliminate induced stresses. Adequate cooling and proper selection of cutters, feeds and speeds is necessary to avoid any heat build up in the part while machining. High speed machining can remove a lot of material but if not done properly, can impart huge stresses into the material.

3) Make all effort to ensure that any part is stress free before solution heat treating. If parts have been previously heat treated and aged, they need to be annealed and brought into tolerance before final heat treatment. For parts that have undergone excess forming operations by bending etc., they also should be stress relieved and the dimensions checked before final heat treatment.

4) Before solution heat treating, a detailed racking plan and immersion procedure needs to be developed and put into place that will ensure even cooling in all areas of the part during quenching. How a part is racked is critical to achieving a uniform distribution of stress throughout the part during cooling. Also, immersing the part at an

incorrect angle or immersion rate can result in differential stresses from the first area that hit the fluid from the last are, particularly when using faster quenching rates.

5) When solution heat treating, use a quenchant that will achieve low residual stresses. The selected method must be slow enough to achieve low stresses, but fast enough to achieve all required properties. Avoid water, prefer glycol or spray if possible. Boiling water quench is sometimes acceptable.

6) After quenching, check the quenching method to determine if you have achieved the low level of stresses in the part that is desired. We recommend X-Ray diffraction to measure the stress level but other techniques are acceptable.

7) If a stress relief method is required, refrigerate the parts at -10°F or lower to avoid any natural aging that can increase the yield strength of the part and cause problems with the stress relieving process. Stress relieving procedures, whether mechanical or cryogenic, must be performed when the material is in its softest condition. Significant natural aging can reduce the effectiveness of the stress relieving process.

8) Apply the stress relieving process if required. In many instances, if a slow enough quenchant is used, low residual stresses will result and additional stress relieving will not be necessary. If stress relieving is required, consider uphilling with high velocity steam. Avoid using hot water as the uphill media, as it is only partially effective. If it has been proven that hot water will reduce the stresses sufficient for an individual case, the process might be acceptable.

9) Measure the resulting stresses after the stress relieving process. If the level of stress is acceptable, go directly to aging the part. If the stress level is unacceptable, uphill one more time, again measure stresses and then go to age. Lately we have found, that in contrast to earlier work, that sometimes more than one uphill procedure may be necessary. This is especially true with extremely thick parts.

We have used this approach for many years and have consistently proven that if our systems approach is properly applied, any high strength aluminum alloy part can be successfully processed to achieve a low residual stress level while at the same time, meeting all

required properties. This includes tensile properties, fracture toughness, and corrosion resistance.

EFFORTS FOR THE FUTURE - WHAT THE FUTURE HOLDS

Before considering the needs of the future in order to solve the dimensional stability problems currently facing the aerospace industry, an understanding of our present conditions and circumstances is needed.

Understanding the Present

How did we get to our present state? And what are the underlying factors that got us here? It must be realized that all residual stresses in aluminum alloys are the result of unequal expansion and contraction in a part during processing. This is true whether these stresses result from mechanical or thermal means. It also must be realized that 90% of our existing dimensional instability problems in high strength aluminum alloys result from residual stresses that are imparted during the quenching operation.

It needs to be understood that the quenching process is a freezing process that attempts to freeze the hardening atoms that have been positioned during the solution heat treating process, in place. To accomplish this freezing process, the cooling rates must be fast enough to prevent diffusion during cooling. With further aging, the strength increase due to further precipitation can be realized. The amount of diffusion that takes place during cooling is dependent upon the rate of cooling which is dependent upon the type of coolant, its temperature and the thickness of the part being processed. During the cooling process, the aluminum is not smart enough is know what it is being cooled by. It does not understand the difference between hot water or glycol. It only understands that it is being cooled at some rate which may or may not allow diffusion to take place. During cooling, two occurrences can happen which are centered around the factor called the “critical cooling rate”. At quench rates above the critical cooling rate, no diffusion takes place and full properties are achieved no matter what rate is being achieved. This situation occurs when sheet metal at various thickness are quenched in various media because the cooling rate is so rapid in any thickness that no diffusion occurs and full properties are always achieved. Below the critical cooling rate, however, some diffusion takes place and the properties are reduced somewhat during the cooling process. The level of strength reduction is dependent upon the quenching sensitivity of the particular alloy in question. Extremely sensitive alloys, such as 7075, will show significant reductions in strength at slower cooling rates while less sensitive alloys such as 7050 and 6061 generally will not lose significant strength properties when quenched at a slightly slower rate. This is what occurs during the heat treatment of thicker parts such as plate and forgings. If equivalent cooling rates are achieved by any method, the diffusion of the hardening elements will be the same, and the property levels achieved will be the same.

Use of Cryogenics

In order to select any process that will provide some stress relieving to aluminum alloys, it is important to understand the role that cryogenics plays in the stress relieving of high strength aluminum parts. Unfortunately, today, this phenomenon is greatly misunderstood by a majority of engineers. It is a common misconception that somehow just the exposure to the extremely cold temperature will relieve stresses. Just exposing the parts to low temperatures by immersing in liquid nitrogen or dry ice and alcohol does nothing to relieve stresses. Full understanding of the uphill process developed by Alcoa [15] is needed. The stresses are reversed or relieved by the sudden or violent temperature change from cold to hot which reverses the differential contraction areas of the part that are imparted during the quenching process - nothing more. Sudden shocking of a part is essential to cause a large differential expansion between the surface which is in compression and the center fibers which are in tension in order to achieve the desired stress relief. The level of stress relief achieved is a directly correlated to the temperature differential or delta temperature (ΔT) that is established between the surface and center fibers - a large ΔT provides maximum stress relief, lower ΔT's less. Alcoa showed that high velocity steam was the best heating medium to accomplish this large delta ΔT, and that other methods such as the use of boiling water was only marginally effective. We later confirmed the Alcoa results and will publish the results shortly.

Similarly, the practice of slowly cooling and heating aluminum parts in chambers from -323°F to higher temperatures such as +300°F also does not relieve stresses. This practice resulted from earlier attempts to check the stability of aluminum parts that were to go into space during the earlier days of the space program. In many instances, these parts would undergo large temperature changes while in service, so it was felt that if they did not move due to imparted residual stresses during a qualification or proof testing procedure, that they would not move during service at widely different operating temperatures. Thus, this procedure checks to see if the residual stress that are present might cause some distortion in service, but do not actually relieve any stresses.

Somehow, design and specification engineers need to be made aware of the proper role of cryogenics in combating residual stress so procedures are applied properly.

Future Needs - to expand usage and reduce costs

In this author's opinion, any high strength aluminum alloy part can be currently processed to achieve all the structural properties required and at the same time possess a low level of residual stress using our systems approach which we have used for years to achieve stress free parts. However, there are a number of considerations that need to be addressed if this approach is to gain greater acceptance and usage by the aerospace community. We have to first realize that one approach does not fit all, that the method to achieve a stress free part in one instance may not work in another, so a slightly different method may be needed. In order to further and optimize this systems approach, the following are needs for the future:

1) Allow the quenching of thicker sections in glycol if the cooling rates are the same or faster than the prescribed method. Measuring the cooling rates in two different media is an reasonably easy task and there already is much information published to prove this point.

2) Further research regarding the use of higher glycol concentrations, particularly with the newer less quench sensitive alloys such as 7050. We positively showed in references [20] and [21] that seven inch 7050 forgings would achieve the same property levels when quenched in 25% Ucon® A as compared to the allowable practice of using hot water and that 2014 could be

quenched in 60% glycol, which achieves the same cooling performance as boiling water [8].

3) Expand the use of glycol in specifications of other existing alloys such as 2014, and 2219 for which both cooling rate and some mechanical property data is currently available. There is absolutely no sound technical reason for prohibiting the glycol quenching of these materials.

4) Changes in specification philosophy is greatly needed. A primary metal producer can quench a high strength aluminum alloy in any manner that he feels is appropriate because he is working to AMS 2772. He is required to prove that the material that he is producing meets all requirements of a material specification. However, an aerospace company or job shop heat treater quenching the same part is not allowed to do it because he normally is only required to processed the part to AMS 2770 which requires him to only test the part to hardness and conductivity requirements and is not required to test for mechanical properties. If the job shop heat treater is faced with severe distortion or residual stress problems, why should he not be allowed to follow the same practice as the primary mill producer, and conduct all tests to prove that the material meets all requirements of the material specification?

5) Additional research and understanding needs to be undertaken regarding the different effects of heat treatment on fracture toughness values in the newer high strength alloys. Some research has shown that extensive slower cooling reduces fracture toughness values which is probably true. Because of this belief, and a prevailing opinion by some engineers that all glycols reduce cooling rates, engineers are reluctant to allow glycol quenching in some instances because of this fact. But we also know that slower cooling also reduces tensile properties. As we pointed out previously, if a material is cooled the same by two different media, the resulting properties, including both tensile properties and fracture toughness should be the same. The true effect of quenching rates on fracture toughness of different alloys needs to be researched further.

One other factor regarding fracture toughness values needs to be addressed. It is now widely recognized that residual stress left in a fracture toughness test specimen can have a significant effect of the final test results. Higher stresses, whether compressive or tensile can lead to erroneous results. In studying the effect of different quenchants on the resulting fracture toughness values, this fact needs to be taken into consideration.

6) Quenching studies need to be undertaken to determine the effective quench sensitivity of many of the newer alloys - such as 7055, 7085, 7136 and some of the recently developed 2000 series alloys, particularly those with low chromium levels and zirconium additions. These materials have reduced quenching sensitivity and allow much thicker sections to be produced and should allow slower quench rates to be used in order to produce stress free parts. Also, these materials need to be added to the parts specifications such as AMS 2770. It is naive to believe that in all instances, the parts will be only used "as produced" by the primary mill. At some point, some company is going to want to machine or form these materials, and later have them heat treated in a job shop in an effort to more effectively produce the final part. Coverage is needed for these materials.

7) Additional research needs to be undertaken involving the application of new quenchants developed since the early 1970's that could have significant impact on the aerospace industry. Because of the huge distortion problems that existed during the 1960's, extensive effort was undertaken involving one product, Ucon® Quenchant A (eventually placed into the AMS specification as AMS 3025, Type 1). Today, that product and is variants, is the only product allowed to be used extensively by the aerospace community. However, since that time, other quenchants have been developed and introduced to the market that are extensively used when quenching steel and other alloys, but they are not allowed to be used in aluminum plants. Our research has shown that products such as AquaQuench® 364 from Houghton, Ucon® E from Tenaxol and Breox® SP from British Petroleum showed a good potential for achieving similar results to the existing product, at a greatly reduced cost, especially in installation of new systems. However, no one in

this industry seems to want to investigate these products further to allow their use in the aluminum industry.

8) One of the biggest problems that exists today for engineers trying to solve residual stress problems in aluminum parts involves mass confusion, misunderstanding and mis application by designers, and specification engineers in putting forth a system that makes sense. In the early days, we only had one method of controlling residual stresses by stress relief, that of mechanical working by stretching or compressing. Since that time, the concepts of quenching control and residual stress relief by cryogenic means (uphill quenching) have come into practice, but currently we have no method on integrating them into a clear design or specification system, involving a systems approach that we advocate. If a designer desires to have a part that is stress free, the only choice he currently has is to specify that the forging, or plate to be supplied in a stress relieved temper which is accomplished by either stretching or compressing after quenching and thus achieves a specific temper designation i.e. T7351 and T7452. He assumes that he is hopefully obtaining a stress free part, but in many cases he is being led down an unfortunate path. There is no specification requirements as to how this process is to be performed except that the part must be somehow cold worked approximately 1 ½ to 5%. How this working is to be performed is strictly up to the producer, and the methods and results vary all over the map. Also, few producers have any type of a quality procedure to determine if their stress relieving process has achieved any stress relieving whatsoever. In addition, the method that the designer selects to place on his drawing often is not the ideal procedure for minimizing those stresses, but once the drawing leaves his possession, other more appropriate procedures cannot be used to obtain a better product because the drawing or controlling specification mandates that specific temper be provided, which allows only one stress relieving method. In numerous instances we have encountered situations where the drawing called for a stress relieved plate, or hand forged product, and the product was still full of high residual stress. Because of the drawing callout, the processor's hands are completely tied to use his expertise in producing a stress free product, because of the specification requirement that the material be compressed after solution heat

treatment which is now impossible and not recommended. We must understand that the designer’s goal is only to achieve a stress free part, and in reality does not care as how it is produced as long as it meets his strength requirements. Somehow, we have to develop a drawing and specification system that requires the manufacture of a stress free part, but allows the newer techniques such as cryogenic stress relief or quench rate control to be integrated into the system so that the fundamental objective of the designer to obtain a stress free product can be realized. Also, the routine addition of quality requirements regarding the measurement and certification of the final stress levels needs further consideration.

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