# Residual Stresses, Distortion and Heat Transfer Coefficients of 7075 Aluminum Alloy Probes Quenched in Water and Polyalkylene Glycol Solutions

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## ABSTRACT

A comparative study of residual stresses and distortion in cylindrical samples of Aluminum Alloy 7075-T6, quenched in aqueous solutions of PAG©UCON A, with concentrations of 10, 20 and 30 % in water and under different conditions of agitation, is presented in this article.

In order to discuss the comparative advantages of such aqueous solutions as quenching media with control of cracking and distortion, the ABAQUS/Standard Finite Element Software was applied to assess such parameters during the heat treatment, with previous calculation of the heat transfer coefficients as dependent of the temperature, by means of the INC-PHATRAN Code.

Based on the experimental cooling curves obtained by direct readings of thermocouples placed at the center of each sample, the INC-PHATRAN Code solved numerically the corresponding inverse heat conduction problem calculating the heat transfer coefficients.

Valuable conclusions about the use of PAG © UCON A aqueous solutions, intended to minimize distortion and cracking problems during heat treating, are the results of the present work.

## 1.- INTRODUCTION.

In the field of heat treatment of metallic alloys, the importance of computer modelling is nowadays of vital importance. Heat transfer phenomena, coupled with solid phase transformations electromagnetic induction, diffusion of interstitial as well as substitutional solute elements through the lattice of the matrix phase, and the subsequent stress distribution and non-linear distortions, can be clearly understood by numerical simulation.

If computer modeling is combined with cooling curve experimental measurements, the result is a powerful and confident tool for the prediction of distortion and residual stresses in metallic components being processed by heat treatment.

Among the several quenching media used in the alluminum industry, there should be mentioned mainly water, some types of oils and aqueous solutions of polymers. Aqueous solutions of Poly Alkylene Glycol (PAG) are used to improve the cooling characteristics of the quenching medium and to reduce the machining requirements after the heat treatment

PAG concentrations vary from 4 to 30 %, depending on the type of product being processed. For the heat treatment of aluminum alloys, such polymeric solutions have been widely applied during more than 30 years [1-4].

The present work consists of a comparative study of the distorsion and residual stress distribution in cylindrical samples of Aluminum Alloy 7075-T6, quenched in aqueous solutions of PAG © UCON A, with concentrations of 10, 20 and 30 % in water, with different rates of agitation. The samples used were of 0.5, 1.0, 1.5, and 2.0 inches in diameter.

Based on the experimental cooling curves obtained by direct readings of thermocouples placed at the center of each sample, a finite element computer simulation operation was carried out applying succesively the following two codes:

a) **Code INC-PHATRAN (INverse Conduction coupled with PHAse TRANsformation)** [5-11]**.** This code is used to simulate a great variety of heat treatment processes in planar as well as in axisymmetric geometries. With its application, the complete temperature distribution pattern throughout the full sample can be obtained. Once this is done and by means of an algorithm for numerical optimizing, an inverse heat conduction problem is solved, which consists on the calculation of heat transfer coefficients that minimize the difference between the measured and calculated temperature distribution patterns.

b) **ABAQUS/Standard** [12]**.** This is a general purpose finite element análisis code that was used, in this case, to simulate the distortion and the residual stresses produced in the studied samples, as a consequence of a heat treatment process, with previous calculation of the temperature distribution pattern in each case, based on the heat transfer coefficients obtained with INC-PHATRAN.

A series of valuable conclusions about the use of PAG © UCON A aqueous solutions, intended to minimize distortion and cracking problems during heat treating, have been obtained , in accordance with previous quantitative results published in the literature[4], comparing the aqueous solutions with pure water for this purpose.

## 2. INC-PHATRAN CODE.

The INC-PHATRAN Code may be applied to simulate a great variety of heat treatment processes, in planar as well as axysimmetrical geometries. The corresponding heat transfer coefficients can be calculated with its help, if cooling curves taken from different locations of the heat treated component are provided. The program has been presented at several international conferences [6-11] and is being used, at the present, for industrial applications in the USA, Colombia and Argentina.

The model is based on a numerical optimization algorithm which includes a module responsible for calculating on time and space the temperature distribution and its coupled microstructural evolution. In the present model, the transformation from austenite to ferrite and perlite is governed by the appropriate TTT curve and also by Avrami's approximation. Whereas the temperature distribution in a two dimension domain with axial symmetry is calculated using a finite element approximation, the time variation is approached using a Crank-Nicholson finite difference scheme. The temperature evolution, as measured by thermocouples at different positions in the component, are used as input for the program. The program calculates the time variation of the heat transfer coefficients, together with the temperature and distribution of phases, and their variation in time throughout the component.

## 3. EXPERIMENTAL PROCEDURE.

Aluminum Alloy 7075 cylindrical samples of 0.5, 1.0 and 1.5 inches in diameter, with a length 4 times its diameter, were used to simulate infinite cylinders. They were quenched in aqueous polymer solutions with 10, 20 and 30 % of PAG © UCON A, as well as in water, with and without agitation.

The first three columns of Table 1 shows the quenchant, the size of the samples and the agitation rate of each of the samples identified in the column 4. Thermocuples were inserted in the center of each sample. A specially prepared testing apparatus was used to control the PAG © UCON A concentration, the temperature and the agitation rate.

The thermocouples were connected to a computer to carry out the data adquisition process, with a known frequency. These curves were then kept in numerical files which were afterwards used to feed INC-PHATRAN Code.

Experimental details about the measurement procedures as well as about the agitation and quenching devices, are described elsewhere (see refs. 1 and 3).

| Quenchant | Sample diameter [inch | Agitation [fpm] | Probe identification. | Heat transfer coefficient [w/m$^2$K] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 150°C | 200 °C | 250 °C | 300 °C | 350 °C | 400 °C | 450 °C |
| Water | 1.0 | 25 | # 91 | 8978 | 14264 | 17705 | 17057 | 15910 | 11870 | 349 |
| | | | # 92 | 8578 | 4045 | 14204 | 14803 | 14124 | 11331 | 1915 |
| | 2.0 | 25 | # 93 | 5147 | 10953 | 17895 | 22085 | 20110 | 12688 | 4788 |
| | | | #94 | 5586 | 9815 | 18034 | 24738 | 28090 | 15481 | 1037 |
| 10% UCON A | 0.5 | 0 | # 1 | 4048 | 6008 | 6040 | 5847 | 5398 | 4305 | 964 |
| | | | # 2 | 4337 | 6072 | 6811 | 6072 | 6297 | 4657 | 771 |
| | | 50 | # 3 | 4947 | 6584 | 7681 | 6783 | 6483 | 4568 | 557 |
| | | | # 4 | 5306 | 6584 | 7561 | 6623 | 6304 | 4489 | 638 |
| | 1.0 | 0 | # 5 | 3148 | 5012 | 5815 | 5911 | 6072 | 4815 | 2249 |
| | | | # 6 | 4149 | 5546 | 6065 | 5885 | 5727 | 5027 | 2294 |
| | | 50 | # 7 | 4049 | 5686 | 6424 | 6085 | 5805 | 5007 | 2833 |
| | | | # 8 | 4329 | 5446 | 6424 | 6504 | 6085 | 4728 | 1775 |
| | 1.5 | 0 | # 9 | 4150 | 5885 | 5845 | 6284 | 7162 | 6224 | 2534 |
| | | | # 10 | 3232 | 4948 | 5466 | 6164 | 6843 | 6065 | 1995 |
| | | 50 | # 11 | 4568 | 6085 | 6184 | 6483 | 6683 | 6364 | 2992 |
| | | | # 12 | 3271 | 5386 | 6145 | 6045 | 6503 | 6583 | 3192 |
| 20% UCON A | 0.5 | 0 | # 37 | 1975 | 3650 | 4219 | 4264 | 3650 | 2588 | 868 |
| | | | # 38 | 1990 | 3591 | 4294 | 4489 | 3980 | 2813 | 1047 |
| | 1.0 | 0 | # 39 | 1107 | 2603 | 3666 | 4219 | 4100 | 3546 | 1571 |
| | | | # 40 | 1810 | 3202 | 3890 | 4234 | 3920 | 3082 | 1062 |
| | 1.5 | 0 | # 41 | ---- | 2379 | 3561 | 4429 | 5087 | 4713 | 1945 |
| | | | # 42 | 2050 | 3232 | 3845 | 4848 | 6005 | 4730 | 1780 |
| 30% UCON A | 0.5 | 0 | # 55 | 997 | 2174 | 3002 | 3072 | 2314 | 1386 | 598 |
| | | | # 56 | 1177 | 2434 | 3092 | 3072 | 2394 | 1396 | 489 |
| | | 50 | # 57 | 1337 | 2254 | 3042 | 3192 | 2663 | 1735 | 768 |
| | | | # 58 | 1317 | 2204 | 3102 | 3381 | 3022 | 2444 | 928 |
| | 1.0 | 0 | # 59 | --- | 1417 | 2264 | 2933 | 3331 | 3012 | 1107 |
| | | | # 60 | --- | 1985 | 2953 | 3381 | 2973 | 1905 | 588 |
| | | 50 | # 61 | --- | 2035 | 2723 | 3132 | 2833 | 2015 | 519 |
| | | | # 62 | --- | 1815 | 2963 | 3381 | 3212 | 3022 | 1556 |
| | 1.5 | 0 | # 63 | --- | --- | 2374 | 3282 | 2853 | 1825 | 658 |
| | | | # 64 | --- | --- | 2982 | 3591 | 3272 | 2294 | 848 |
| | | 50 | # 65 | --- | --- | 2643 | 3401 | 3022 | 2075 | 688 |
| | | | # 66 | --- | 1845 | 2952 | 3621 | 3391 | 3800 | 1277 |

***Table 1.-*** *Heat transfer coefficient evolution as dependent of the temperature, calculated by the INC-PHATRAN code.*

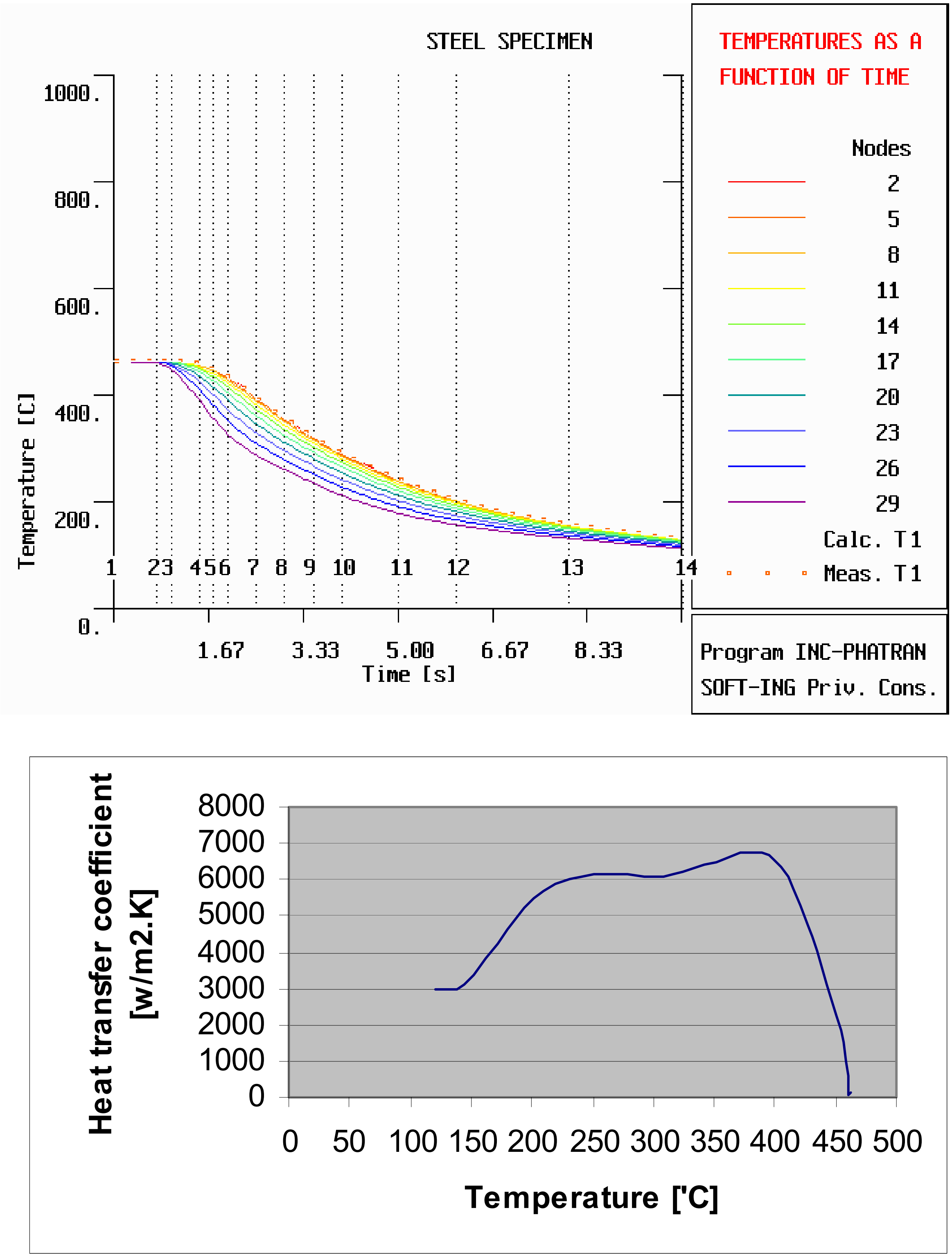


***Figure 1.-*** *Results obtained after mathematical simulation of sample # 12. Quenching medium: 10%UCON A; Sample diameter: 1.5 in.; agitation: 50 fpm*

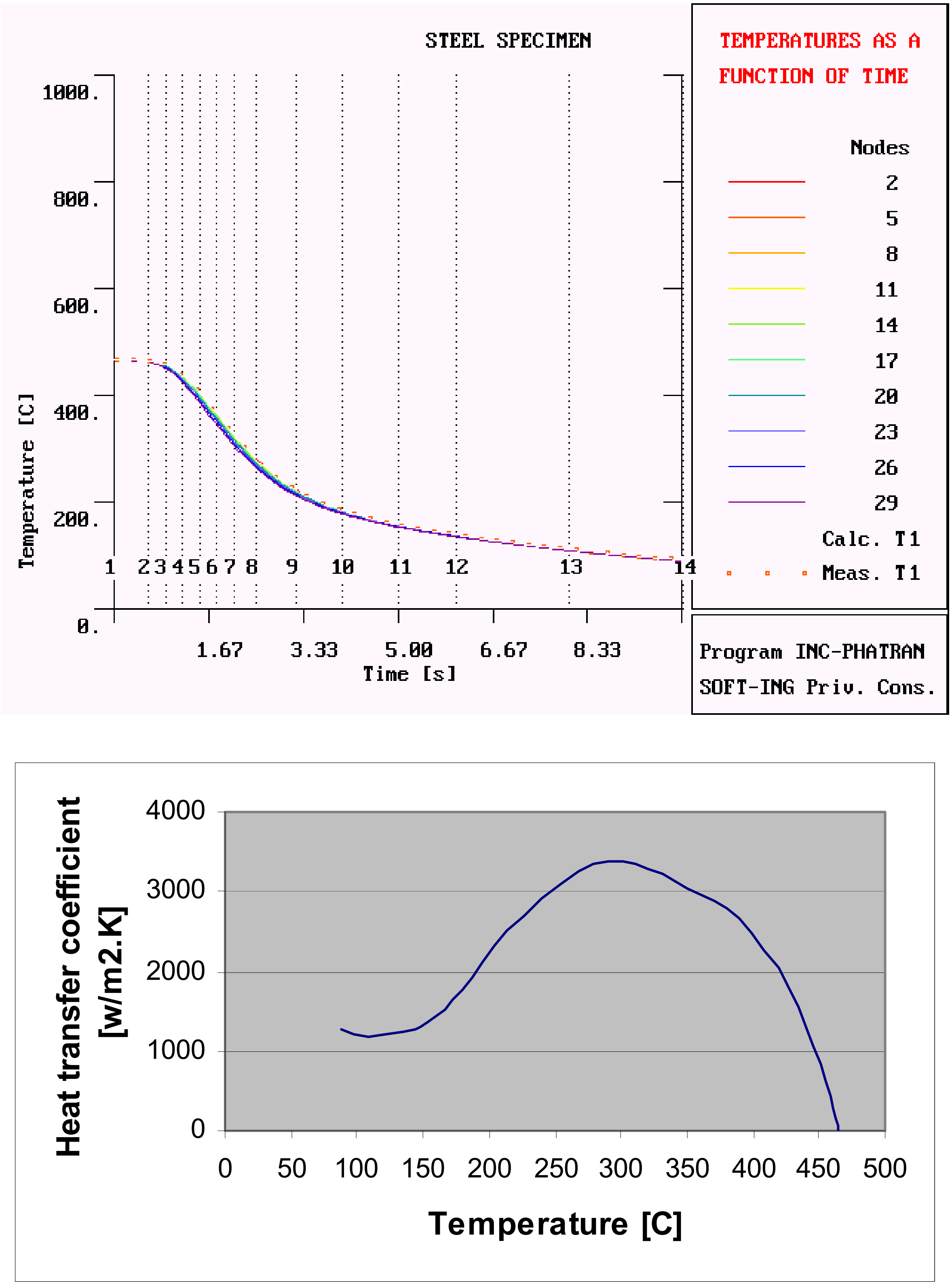


***Figure 2.-*** *Results obtained after mathematical simulation of sample # 58. Quenching medium: 30%UCON A; Sample diameter: 0.5 in.; agitation: 50 fpm*

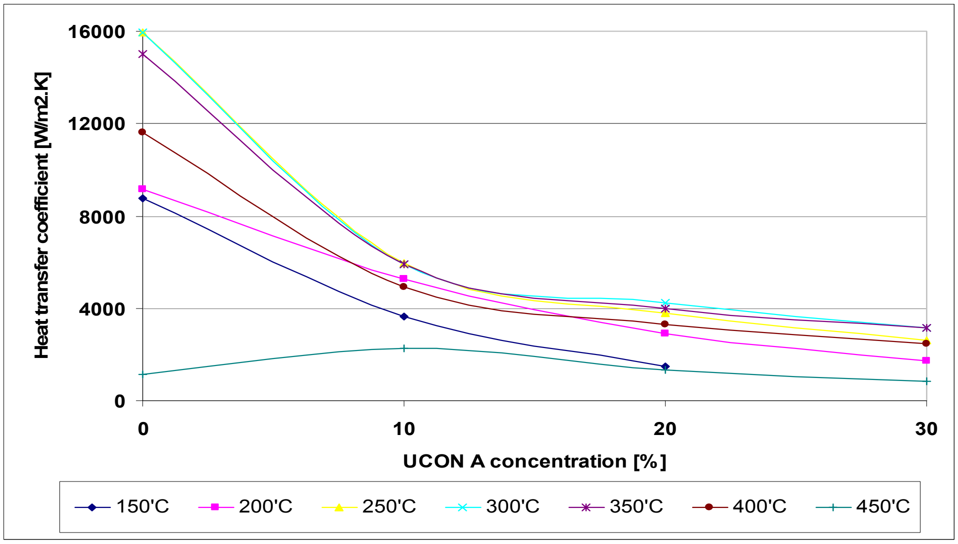


***Figure 3.-*** *Heat transfer coefficient variations computed for samples of 1" diameter without agitation, for several temperature values, as a function of UCON A concentration.*

## 4.- RESULTS OF COMPUTER SIMULATION.

As an example of the results obtained with the INC-PHATRAN Code, time variations of the calculated temperature are shown in figure 1 (upper) for 10 different points placed along the radial coordinate, corresponding to the sample # 12, with a diameter of 1.5 inch, quenched in a solution of 10 % of UCON A in water and with 50 fpm of agitation. In the lower part of the same figure, the obtained heat transfer coefficient as a function of the temperature are ploted for the same sample. Similar results are shown in figure 2, obtained for the sample # 58 of 0.2 inches diameter, quenched in a solution of 30 % of UCON A and with 50 fpm of agitation rate.

The values of the heat transfer coefficient as a function of temperature obtained for all the samples analized are listed in Table 1.

The heat transfer coefficient for different temperatures are shown in figure 3, only for the samples of 1 inch diameter, without agitation, as a function of the UCON A concentration of the quenching bath.

The most important results obtained with ABAQUS/Standard are shown in Table 2 for all the samples studied, which are the maximum equivalent (von Mises) residual stresses at the end of the heat treatment process, which result on the lateral surface of the samples, and the maximum transversal and longitudinal distortions.

In figures 4 and 5 the maximum equivalent von Mises residual stresses are shown, which were calculated considering absence and presence of agitation respectively. The comparative, calculated maximum residual stress for different sample sizes and polymer concentration, with and without agitation, are shown in figure 6. Total distortion of sample of 2.0 inch diameter, quenched in pure water, are shown in figure 7.

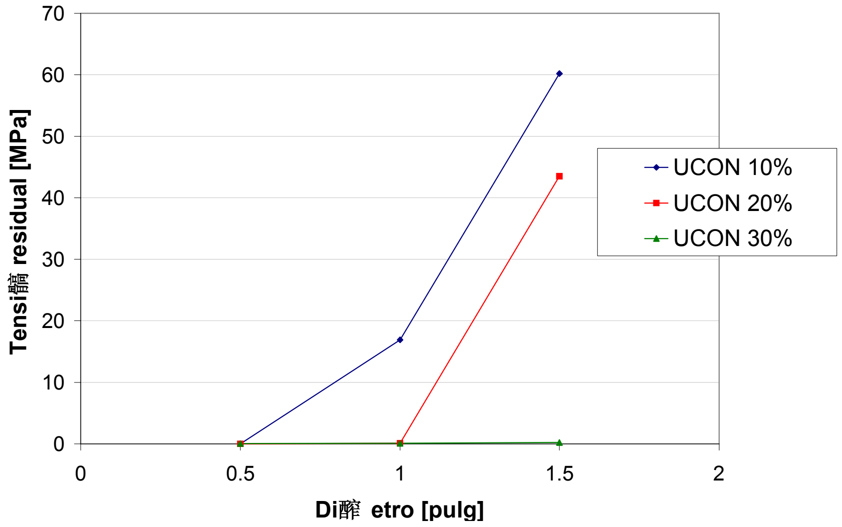


***Figure 4.****- Maximum equivalent (von Mises) residual stresses. Heat treatment with UCON A solutions without agitation.*

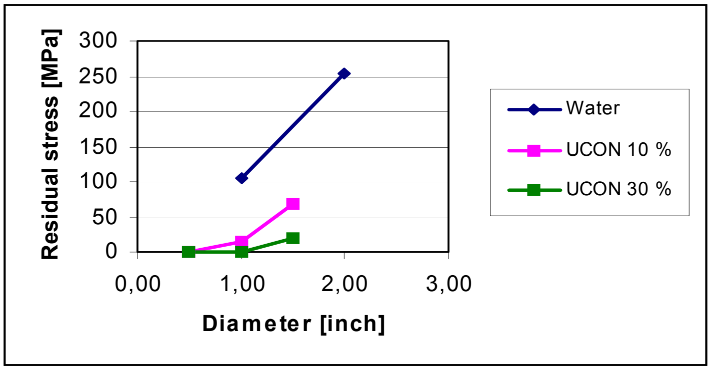


***Figure 5****.- Maximum equivalent (von Mises) residual stresses.Heat treatment with UCON A solutions without agitation*

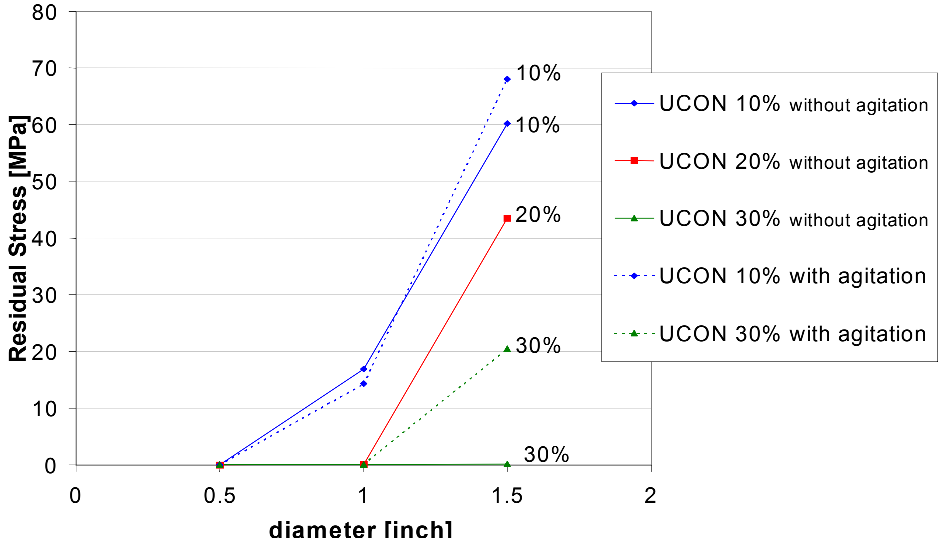


***Figure 6****.- Maximum equivalent (von Mises) residual stresses. Heat treatment with UCON A solutions with and without agitation*

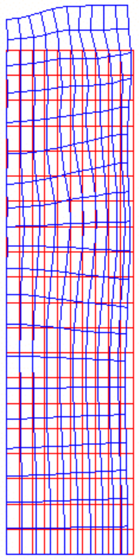
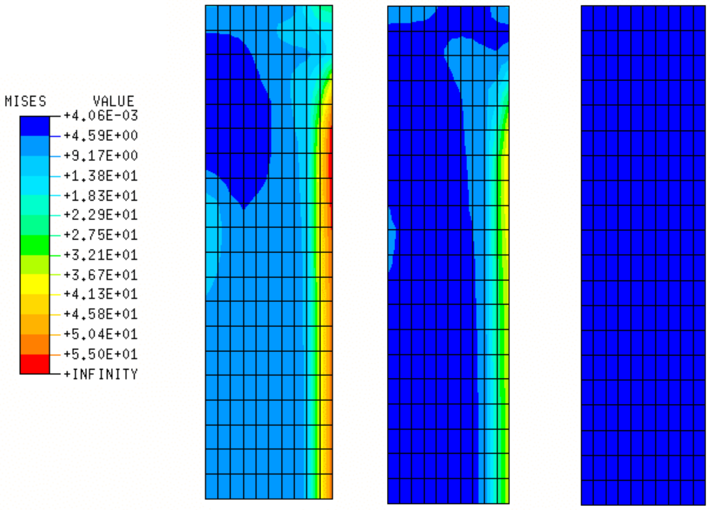
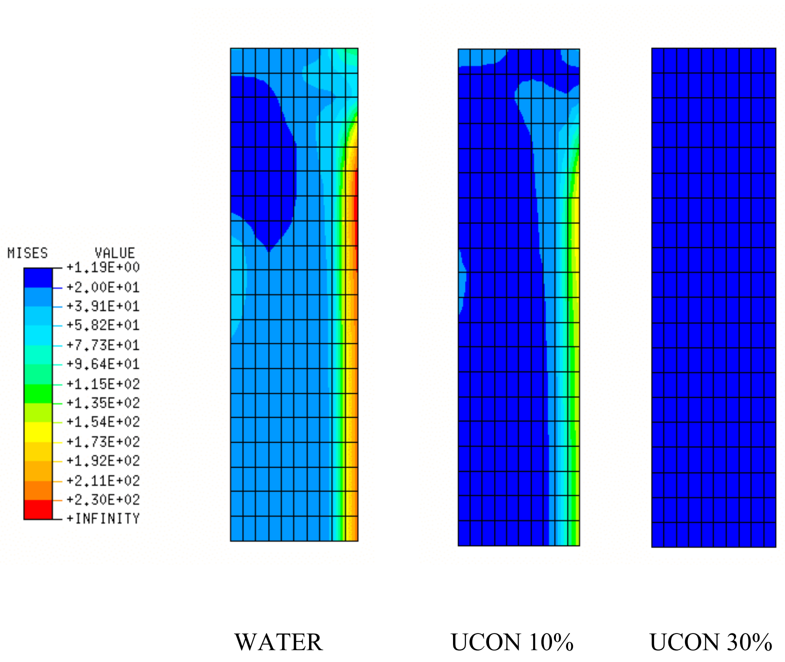


***Figure** 7.- Residual deformation of a 2.0 inch diameter probe quehched in water. Magnification factor: 200.*



UCON 10% UCON 20% UCON 30%

***Figure** 8.- Space distribution of the equivalent (von Mises) residual stresses within a probe of 1.5 inch diameter without agitation.*



WATER UCON 10% UCON 30%

***Figure 9**.- Space distribution of the equivalent (von Mises) residual stresses within a probe of 1.5 inch diameter with agitation.*

| Probe | Diameter [inch] | Quenchant | Agita-ción | Maximum values of the residual von Mises stress [MPa] | | Maximum transvers distorsion U1 [mm] | | Maximum longitudinal distorsion U2 [mm] | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | max | node | max | node | max | node |
| # 9 | 1.5 | UCON A 10% | without | 60.20 | 165 | -0.00128 | 165 | 0.01150 | 209 |
| # 42 | 1.5 | UCON A 20% | without | 43.51 | 154 | 0.00071 | 163 | 0.00794 | 198 |
| # 64 | 1.5 | UCON A 30% | without | 0.22 | 11 | 0.00053 | 11 | 0.00182 | 231 |
| # 6 | 1.0 | UCON A 10% | without | 16.91 | 154 | 0.00020 | 163 | 0.00164 | 187 |
| # 40 | 1.0 | UCON A 20% | without | 0.08 | 11 | 0.00035 | 11 | 0.00131 | 231 |
| # 60 | 1.0 | UCON A 30% | without | 0.08 | 11 | 0.00031 | 11 | 0.00116 | 231 |
| # 2 | 0.5 | UCON A 10% | without | 0.01 | 11 | 0.00006 | 11 | 0.00024 | 231 |
| # 38 | 0.5 | UCON A 20% | without | 0.01 | 11 | 0.00005 | 11 | 0.00018 | 231 |
| # 56 | 0.5 | UCON A 30% | without | 0.03 | 11 | 0.00022 | 11 | 0.00088 | 231 |
| # 11 | 1.5 | UCON A 10% | with | 68.03 | 165 | -0.00150 | 165 | 0.01300 | 209 |
| # 66 | 1.5 | UCON A 30% | with | 20.55 | 165 | 0.00030 | 163 | 0.00292 | 198 |
| # 8 | 1.0 | UCON A 10% | with | 14.35 | 133 | 0.00012 | 163 | 0.00116 | 187 |
| # 61 | 1.0 | UCON A 30% | with | 0.04 | 11 | 0.00013 | 11 | 0.00049 | 231 |
| # 3 | 0.5 | UCON A 10% | with | 0.00 | 11 | 0.00000 | 11 | 0.00000 | 221 |
| # 58 | 0.5 | UCON A 30% | with | 0.02 | 11 | 0.00008 | 11 | 0.00032 | 231 |
| # 91 | 1.0 | water | with | 105.40 | 154 | -0.00184 | 165 | 0.01437 | 209 |
| # 94 | 2.0 | water | with | 252.70 | 154 | 0.01355 | 138 | 0.04837 | 209 |

***Table 2.-** Maximum values of residual stresses (von Mises equivalent stress) and of the distortion calculated for different conditions.*

In figure 8 the different spatial distributions of equivalent residual stresses are compared for the sample of 1.5 in in diameter, with different UCON A concentrations, without agitation. Similar data are shown in figure 9 for the case of agitation.

## 5.- CONCLUSIONS

Quenching in pure water originates the very high residual stresses, which are lowered by addition of PAG @ UCON A polymer quenchant to the bath. With increasing concentrations of polymer UCON A to the quenchant, lower residual stresses results. Quenching with a concentration of 30 % of this polymer gives a product free from residual stresses.

## ACKNOWLEDGEMENTS.

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## References.

1,- C.E. Bates y G.E. Totten: "Procedure for quenching media selection to maximise tensile properties and minimise distortion in aluminum-alloy parts". Heat Treatment of Metals, 1988.4, pp 89-97.

2.- G.E. Totten, E. Bates y L.M. Jarvis: "Quench Factor Analysis: Polymers vs. Hot Water". Heat Treating, May 1989, pp. 38-40.

3.- G.E. Totten, E. Bates y L.M. Jarvis: "Type I quenchants for aluminum heat treating". Heat Treating, Dec. 1991, pp. 16-19.

4.- G.E. Totten, G.M. Webster, L.M. Jarvis y E. Bates: "Effect of section size, quenchant concentration and agitation on the physical properties of Type I polymer quenched aluminum alloys". *Proceedings of the 1st International Non-Ferrous Processing and Technology Conference*, St. Louis, Missouri, USA, 10 - 12 marzo de 1997. Pp 7-16.

5. G. Sánchez Sarmiento y C. Barragán, “INC-PHATRAN: A computer model for the simulation of heat-treating processes, User manual”, SOFT-ING Consultores, Abril de 1997.

6. G. Sánchez Sarmiento, C. Barragán, E. Mues y C. Bunte: “Aplication of computer models to the determination of heat transfer coefficients of UCON quenchant solutions in heat treating operations”. *G.E. Totten et al, Eds.: Proceedings of the 2nd International Conference on Quenching and the Control of Distorsion*, ASM International, Cleveland, Ohio, 4 al 7 de noviembre de 1996, pp 275-281.

7. G. Sánchez Sarmiento, C. Barragán y J. Vega: "Predicting hardeness distribution after heat treating processes of steels by finite element simulation combined with the SAE Standard J406". *Milam et al, Eds: HEAT TREATING - Proceedings of the 17th Heat Treat EXPO & Technical Conference,* ASM - Heat Treating Society, Indianapolis, USA, 15 al 18 de septiembre de 1997, pp 347-354.

8. G. Sánchez Sarmiento, A. Gastón y J. Vega: "Inverse heat conduction coupled with phase transformation problems in heat treating process". *E. Oñate and S.R. Idelsohn, Eds.: COMPUTATIONAL MECHANICS - New Trends and Applications.* CIMNE, Barcelona, España, 1998. CD-Book. Part VI, Section 1, Paper 16.

9. G. Sánchez Sarmiento, M.A. Morelli y J. Vega: "Improvements to the SAE J406 Hardenability Predictor*". R. Colás et al, Eds.: Proceedings of the 1st International Automotive Heat Treating Conference*, ASM International, Puerto Vallarta, México, 13 al 15 de julio de 1998, pp 401-414.

10.- G. Sánchez Sarmiento, J. Vega, M.A. Morelli, J.C. Cuyás, A.I. Ledesma y M.J.A. Solari: "Predicting hardness of stainless steels in tempering cycles with variable temperature ". *Proceedings of the 19st ASM Heat Treat Expo & Technical Conference,* Cincinnati, OH, Nov. 1-4, 1999. In press.

11.- G. Sánchez Sarmiento y J. Vega: "Calculation of the hardness space distribution in the as quenched condition of a medium hardening tool steel". *1st International Conference on Thermal Process Modeling and Computer Simulation*, Shanghai Jiao Tong University, Shanghai, China, 28 al 30 de marzo de 2000.

12.- Hibbitt, Karlsson and Sorensen, Inc.: “ABAQUS/Standard. User’s Manual”. Versión 5.8-1. 1998.