A Case Based Reasoning aluminium thermal analysis platform for the prediction of W319 Al cast component characteristics

G. Pelayo [a], J.H. Sokolowski [b,*], R. Lashkari [c]
[a] General Dynamics Canada, 1020 - 68 Avenue N.E.,
Calgary, Alberta, T2E 8P2, Canada
[b] Light Metals Casting Technology Research Group, University of Windsor,
218 Essex Hall, 401 Sunset Avenue, N9B 3P4, Windsor, Ontario, Canada
[c] Department of Industrial and Manufacturing Systems Engineering,
University of Windsor, 331 Essex Hall, 401 Sunset Avenue,
N9B 3P4, Windsor, Ontario, Canada
* Corresponding author: E-mail address: jerry@uwindsor.ca.

Materials

ABSTRACT

Purpose: This paper presents the research on the development of the Aluminum Thermal Analysis Technology Platform (AlTAP) utilizing a Case Based Reasoning (CBR) Caspian shell for interpretation of industrial cooling curves and predicting alloy and cast component characteristics.

Design/methodology/approach: CBR being a branch of Artificial Intelligence (AI) that solves problems based on understanding and adaptation of previous experiences is suitable for interpretation of the AlTAP results since this is a knowledge intensive activity which requires a fair amount of experience.

Findings: The integrated AlTAP and CBR system was found to be useful for the prediction of melt thermal characteristics, cast component mechanical and structural properties.

Practical implications: Industrial trials confirmed the technical capabilities of the AlTAP/CBR Platform for the on-line quality control and prediction of 319 melt characteristics and the aluminum engine block's (Cosworth casting process) engineering specifications.

Originality/value: An automated AlTAP Platform integrated with a CBR system is a new Quality Control concept in the area of the aluminum automotive casting.

Keywords: Case Based Reasoning; Thermal analysis – Universal Metallurgical Simulator and Analyzer (UMSA) and AlTAP Technology Platforms; W319 aluminum alloy

1. Introduction

Cased Based Reasoning is a problem solving technique in which a case library of previously solved problems is explored to find one or more similar cases whose features of interest resemble the current problem. The most similar case is selected based on a measure of similarity [1] and the solution for the old case is applied to the current case making changes (adaptation) to account for the differences between the new and old cases. When the solution for the new case is considered successful it can be appended to the case base to increase its robustness.

Industrial/laboratory TA of the cooling curve technique is based on the computer assisted analysis of a Temperature-Time plot that is obtained during the solidification process of a test sample of the metal or alloy. The objective is to relate the characteristics of the cooling curve and its first derivative to the structural features and mechanical properties of the solidified test sample and consequently the cast component.

CBR is a technique that is suitable for cooling curve interpretation since this is a knowledge intensive activity in which several metallurgical factors (including Solidification Rate (SR), Silicon Modification Level (SiML), Grain Size (GS), alloying and impurity elements, etc.) interact and affect the cooling curve characteristics and consequently the as-cast and post processed component(s) properties. Specifically, the cooling curve can be considered a "global high spatial resolution finger print" of the melt chemical composition and its treatment(s), solidification process parameters, etc. resulting in unique microstructures and properties of the tested alloy and cast component. The cooling curve can be utilized for a quantifiable description of the "past and new experience". Identifiable differences between the cooling curves' parameters of the individual metallurgical reactions can be captured in the adaptation module of the CBR system to be used for future data interpretation. For years the TA technique aided by the AI approach was used in the cast iron industry to evaluate the quality of the melt prior to the casting operations [2]. In order to improve robustness of the aluminum casting operations and the reliability of the automotive cast components this technique will be incorporated into the routine Quality Control procedures in the aluminum plant environment.

Physical simulations of complex metal casting and heat treatment processes and development of novel materials, etc. requires a more advanced TA Platform capable of providing information about both heating and cooling cycles that replicate the actual industrial environment (melt treatment, casting and solidification as well as heat treatment). Researchers from the University of Windsor, Canada and the Silesian University of Technology, Poland developed the "Method and Apparatus for Universal Metallurgical Simulation and Analysis" (UMSA) Technology Platform (US Patent #7,354,491, Canadian Patent #2,470,127) [3] that fulfils these requirements.

1.1. Case Based Reasoning

In a general and simplified manner, the CBR process can be defined as a cycle composed of four main activities:

a) **Matching a new case with a case stored in the case library** – In CBR systems inexact matching is possible due to the concept of similarity. Several functions for calculating similarity have been developed to date and have been summarized by Liao and Zhang [4].

b) **Retrieving the solution for a historical case** – Normally two approaches are used for the purpose of case retrieval, one is the similarity approach and the second one is the indexing approach.

c) **Adapting the solution according to the differences between the new and old cases** – When the most similar case in the case library has been retrieved, it is still possible for it to be significantly different from the current problem. Adaptation requires additional background knowledge which can be represented in the form of rules similar to rule-based systems where new attribute values for the solution case can be specified. Several other methodologies such as null adaptation, parameterized solutions, abstraction and specialization [5] as well as case-based adaptation [6] have been developed.

d) **Retention of the new case and its solution** – Once a historical case has been successfully retrieved and adapted, it can be integrated into the case library. If the added cases are carefully revised, continuous improvement of the CBR system can be achieved.

1.2. Thermal analysis

On-line Thermal Analysis (a non-destructive technique) that is employed in some advanced metal casting facilities can rapidly quantify the solidification process characteristics of metals and alloys. A Temperature-Time plot is recorded for the liquid, semi-solid and solid states and the resulting information is used to provide insight into the characteristics of the micro and macro structure that will be developed during the solidification process of the cast component. The structural characteristics including size, shape and distribution of the alloy's specific constituents, dictates the mechanical properties of the material and consequently the performance of the cast components.

Three main reactions are detected during the W319-Al alloy solidification process (Figure 1, Table 1).

(1) The formation of the α-Al dendrites,
(2) Solidification of the Al-Si eutectic phase,
(3) The formation of the Al_2Cu and other low melting point eutectics (i.e. Mg_2Si).
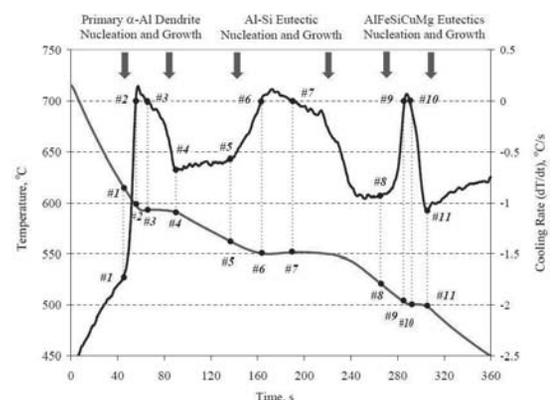
Fig. 1. Cooling Curve and its first derivative for the W319 Al alloy showing the TA parameters

Table 1.
Selected measured and calculated TA metallurgical characteristics

	Metallurgical state	Temp. Symbol (°C)
1	α Al. Nucleation Temperature (liquidus)	$T^{\alpha,DEN}_{NUC}$
2	α Undercooling Temperature	$T^{\alpha,DEN}_{MIN}$
3	α Al Growth Temperature	$T^{\alpha,DEN}_{G}$
4	α Al Dendrite Coherency Point	$T^{\alpha,DEN}_{COH}$
5	Al-Si Eutectic Nucleation Temperature	$T^{AlSi}_{E,NUC}$
6	Al- Si Eutectic Minimum Temperature	$T^{AlSi}_{E,NUC}$
7	Al- Si Eutectic Growth Temperature	$T^{AlSi}_{E,G}$
8	Copper Rich Phases Nucleation Temperature	$T^{AlSi\,Cu}_{E,NUC}$
9	Copper Rich Phases Minimum Temperature	$T^{AlSi\,Cu}_{E,MIN}$
10	Copper Rich Phases Growth Temperature	$T^{AlSi\,Cu}_{E,G}$
11	End of Solidification (Solidus Temperature)	T_{SOL}

The magnitude and duration of these metallurgical reactions that are determined using both the cooling curve and its first derivative curve that depend on the alloy composition, the melt treatment, and the solidification conditions, etc. The melt treatments that are applied to the experimental W319 Al alloy can be quantified using Thermal Analysis and include:

Determination of the Grain Refinement - Aluminum alloys normally form coarse grains during a slow solidification process. Control of the grain size in an aluminum alloy cast component is called "grain refinement". The most common method to achieve grain refinement is the addition of grain refiners in the form of master alloys. The most potent particles dispersed in the master alloy aluminum matrix are Titanium Aluminates and Aluminum Diborides (Al-Ti, Al-B and Al-Ti-B master alloys). Grain refinement has the potential to improve the soundness of the cast component and results in increased fatigue life, tensile strength, elongation and in some cases machinability. It was observed that the Al-Si alloys having more than 3wt%Si (and other elements including Zr, Li and Cr) responds poorly to grain refinement. Since the effective mechanism of Si and other elements is not universally accepted and there is a high level of uncertainty in terms of an efficient amount of grain refiner for a given melt chemistry and solidification parameters, etc. therefore, the TA methodology seems to be the best for the optimization of the grain refinement technology. The effect of grain refinement on the cooling curve characteristics is shown in Figure 2. Several time and temperature parameters for the cooling curve and the first derivative curve have been related to the grain size of the castings [7, 8, 9, 10]. In this work the recalescence temperature ($T^{\alpha\,DEN}_{G}$) was used as a measure of grain refinement efficiency.

Prediction of the Eutectic Silicon Modification Level (SiML) – Manufacturing processes for Al-Si cast components must comply with the very stringent requirements for determination and preservation of the critical SiML in order to consistently produce the desired microstructures. Both, the over and under modified melt will reduce mechanical and other properties of the cast component. In order to minimize the deleterious Sr effect on porosity, macro-segregation of some alloying elements (i.e. Cu) and consequently cycle fatigue, the SiML must be optimized for a given critical section(s) and engineering application(s).

The transformation of silicon particles from flake to fiber is called modification and may be accomplished by the addition of modifiers, control of the Solidification Rate (SR), by Solution Treatment (ST) or by a combination of these factors. Modification is frequently accomplished through the use of strontium usually in the form of a master alloy (either Al-10%wt Sr or Al-90%wt Sr) prior to casting. As the amount of strontium in the melt increases (to the optimum level) the level of modification also increases.

Melt chemical analysis can provide the actual Sr content; however, it cannot determine the activity of the Sr in the melt (i.e. "dead Sr", Sr fading, negative and positive interactions like Sr-Sb and Na-Sr respectively) or subsequently predict the SiML.
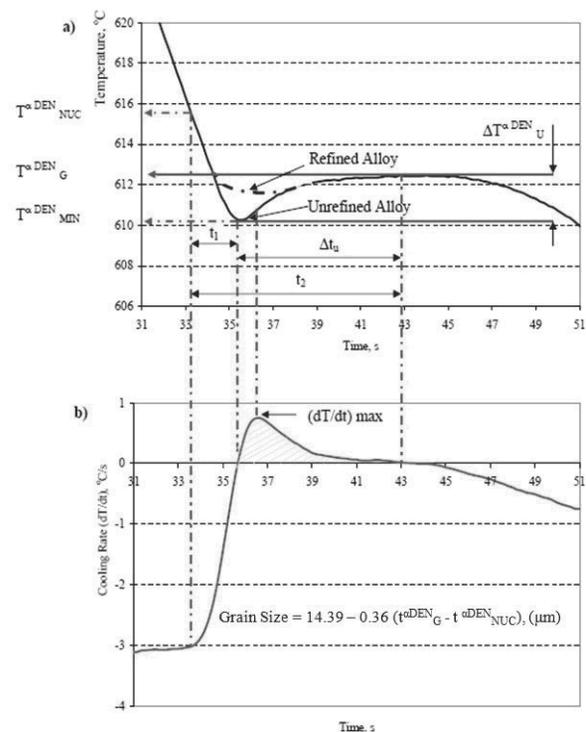
Fig. 2. Thermal Analysis parameters associated with Grain Size determination

Where:
t_1 - the time interval between $T^{\alpha DEN}_{NUC}$ and $T^{\alpha DEN}_{MIN}$
t_2 - the time interval between $T^{\alpha DEN}_{NUC}$ and $T^{\alpha DEN}_{G}$
$\Delta t_U = t^{\alpha DEN}_{G} - t^{\alpha DEN}_{MIN}$, (sec)
$\Delta T^{\alpha DEN}_{U} = T^{\alpha DEN}_{G} - T^{\alpha DEN}_{MIN}$ (undercooling temperature)
$T^{\alpha DEN}_{NUC}$ - α-Al Dendrite Nucleation Temperature
$T^{\alpha DEN}_{G}$ - α-Al Dendrite Growth Temperature
$T^{\alpha DEN}_{MIN}$ - α-Al Dendrite Minimum Temperature

The on-line prediction of the SiML is very important for Quality Control. Conventionally, the SiML is estimated by destructive sampling and manual microscopic analysis of the structure. The structure is compared with the American Foundry

Society (AFS) Chart for Microstructure Control in Hypoeutectic Al-Si Alloys [14]. In this chart the entire range of the modification level is divided into six classes based on the morphology of the eutectic silicon particles. A fully modified structure falls into Class 5-6, partially modified into Class 2-4 and unmodified into Class 1. Based on visual comparison, the specimen is assigned a modification level, where the structures of the specimen and AFS chart are closest. This method is time consuming, subjective and is not suitable to be used as an online method to predict the SiML.

The University of Windsor's method for assessment of the SiML using the TA technique, in which the $\Delta T^{Al-Si}_{E,G}$ parameter of the cooling curve is correlated to the SiML that was empirically determined via Image Analysis (IA) [20]. The $\Delta T^{Al-Si}_{E,G}$ parameter is the difference in the Al-Si eutectic growth temperature between the modified and unmodified alloys.

The TA technique can be used to determine the aluminum-silicon eutectic morphology before and after the addition of strontium and can account for the effect of the Solidification Rate. The net effect of the additions of strontium on the cooling curve of the W319 alloy is the depression of the nucleation and growth temperatures of the main aluminum-silicon eutectic reaction (Figure 3) [15, 16]. When the strontium level is increased from 8 to 96 ppm the $T^{Al-Si}_{E,G}$ temperature decreases from 563.5°C to 552°C.
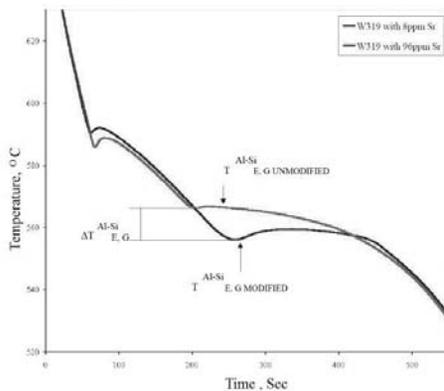
Fig. 3. Cooling Curves showing $T^{Al-Si}_{E,G}$ for modified and unmodified alloys

The degree of aluminum-silicon eutectic modification has been correlated with the depression of the aluminum-silicon eutectic growth temperature ($\Delta T^{Al-Si}_{E,G}$). The $\Delta T^{Al-Si}_{E,G}$ was determined according to the following formula:

$$\Delta T^{Al-Si}_{E,G} = T^{Al-Si}_{E,G,\,UNMODIFIED} - T^{Al-Si}_{E,G,\,MODIFIED}$$

where:
- $T^{Al-Si}_{E,G-\,UNMODIFIED}$ - Al-Si eutectic growth temperature is the maximum temperature that is achieved during the recalescence period from the nucleation temperature at a level of 8 ppm strontium, (residual level in unmodified ingot).
- $T^{Al-Si}_{E,G-MODIFIED}$ - Al-Si eutectic growth temperature is the maximum temperature after addition of strontium (from 27 to 96 ppm) that is achieved during the recalescence period.

- $\Delta T^{Al-Si}_{E,G}$ - Depression of the Al-Si eutectic growth temperature, represents the temperature difference between the modified and unmodified Al-Si eutectic growth temperatures. The larger the magnitude of $\Delta T^{Al-Si}_{E,G}$ the higher the degree of silicon modification.

From the knowledge of the $\Delta T^{Al-Si}_{E,G}$ parameter the SiML can be calculated using Equation 1.

$$SiML = \frac{-17.0741}{\left\{1 + \frac{\exp[(\Delta T - 13.42472)]}{2}.04788\right\} + 18.06746}$$

(1)

This method improves the precision and accuracy of the SiML assessment because it eliminates the operator bias and subjectivity. This method gives a digital criterion for the assessment of SiML based on the AFS concept and can be used on-line.

According to AFS specifications, when the strontium concentration is 8 ppm the structure is coarse and a further addition of strontium to 96 ppm produces a finer fibrous silicon eutectic structure (Figure 4a, 4b).
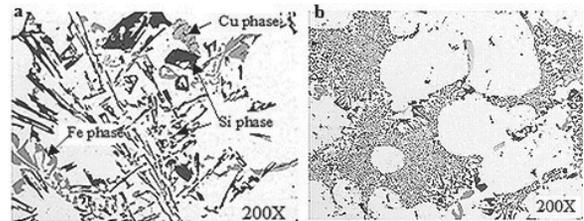
Fig. 4. Light optical micrographs of the AlSi eutectic morphology as a function of the Sr level. (a) Fully unmodified, coarse Al-Si eutectic microstructure (8 ppm Sr). (b) Very fine Al-Si eutectic microstructure (96 ppm Sr)
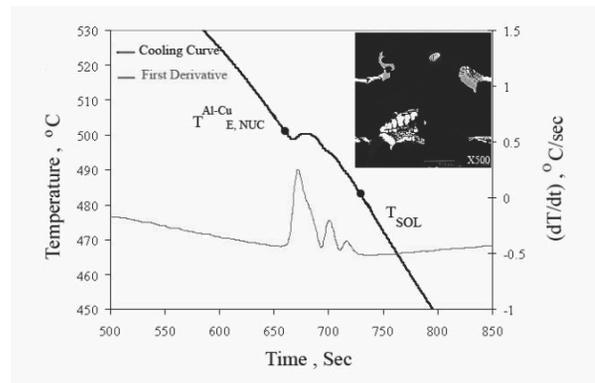
Fig. 5. Thermal Analysis parameters associated with the Al-Cu-Mg rich phase(s) region

Thermal Analysis is also applied for the determination of Cu and Mg rich phase characteristics. Figure 5 shows the peaks associated with the Al-Cu-Mg reactions. Parameters such as the nucleation temperature of the Cu, Mg phases ($T^{Al-Cu-Mg}_{NUC}$) and the solidus temperature (T_{SOL}) are indicators of the Cu content of the alloy and also of the effect that elements such as Sr have on

the proportion of the different Cu phases. Sr has been found to increase the nucleation temperature of the Al-Cu eutectic and the end of solidification as well as increasing the proportion of blocky Al_2Cu particles, (Figures 6a and 6b).
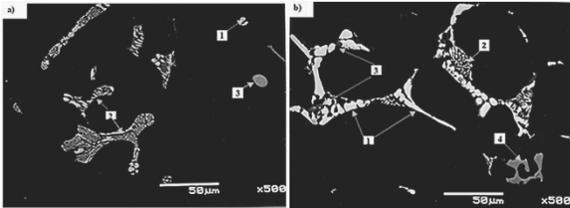
Fig. 6. SEM micrographs (BSE mode) of samples with (a) 8 ppm and (b) 96 ppm strontium respectively [24]. (1) - blocky Al_2Cu eutectic, (2) - fine $Al-Al_2Cu$ eutectic, (3) - fine $Al_5Mg_8Cu_2Si_6$ eutectic, (4) - iron phase

The SR of the casting section has a definite influence on the resulting type of microstructure including Secondary Dendrite Arm Spacing (SDAS) as well as the size and distribution of porosity. A faster SR results in a finer and more homogeneous microstructure with higher Ultimate Tensile Strength (UTS), ductility and fatigue properties.

It is not unusual for process engineers to use the start and end of solidification temperatures of the Al-Cu-Mg rich phases for determination of the optimum ST parameters. This approach is fundamentally wrong since the metallurgical hysteresis between cooling and heating cycles could reach up to an approximate 40°C difference in temperature. Thus, the ST temperature and time must be determined using heating curve characteristics [25-27].

2. An overview of the Aluminum Thermal Analysis (AlTAP) Platform

The AlTAP is a Thermal Analysis Platform developed by the University of Windsor's Light Metals Casting Technology (LMCT) Research Group. The Platform consists of a test stand which has two thermocouples consistently located in the centre and near the wall of the test sample. The Platform has a high resolution data acquisition module and propriety software for mathematical and metallurgical analysis of the cooling curves and first derivatives. This module is able to calculate a base line [17] for the estimation of Fraction Solid (FS) and to detect over 50 cooling curve parameters using derivative analysis, and to calculate the SiML and other parameters.

3. Case Based Reasoning - AlTAP Technology Platform Development

The Case Based Reasoning Module for the AlTAP was built using a CBR shell developed at the University of Aberystwyth (UK) [18]. Caspian creates a case base from a case file written in

CASL, a language used for Case Based Reasoning [18]. Caspian uses this case file to create a case base in the computer's memory which can be accessed to solve problems and to append new cases to the library. Figure 7 shows the blocks that form the case file.

Introduction: Description of the program.

Case definition: Definition of the fields that form the problem part of a case. The definition of a field includes the name of the field, the type of value and the weight assigned to it.

Index definition: Definition of fields that will serve as indexes.

Modification Definition: Definition of values of the fields that will be considered similar during the matching process. A symbol can be considered an abstraction of other symbols, or it is possible to define ranges over which numbers will be considered similar.

Repair Rule Definition: Contains rules that are applied as a result of differences between the new and the stored cases and are able to change fields in the solution part of a new case.

Cases: Groups of cases that form the case base. Each case has a name, a set of input (or problem) fields and a set of solution fields.

Fig. 7. The AlTAP's CBR system block diagram
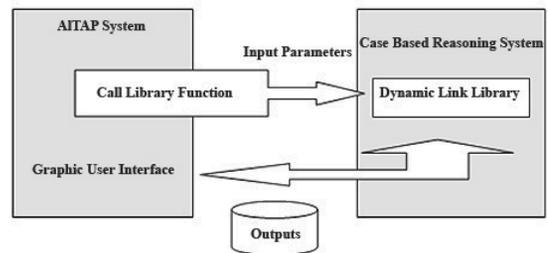
Fig. 8. Integration of the AlTAP software and the CBR system

Three steps were followed for the integration of the CBR system into the AlTAP software:
a) Modification of the Caspian Source Code,
b) Linking of the AlTAP and Caspian Software,
c) Visualization of the CBR outputs into the AlTAP Graphical User Interface (GUI).

Originally, Caspian accessed the input values from the keyboard and presented the results in a DOS environment. These features were modified in order to read inputs automatically from the parameters generated by the AlTAP and present the results in the AlTAP GUI (Figure 8).

3.1. Experimental procedure for data acquisition

For the development of the CBR system it was necessary to implement the AlTAP at a casting plant in order to obtain, for their established process conditions, a preliminary mapping of the values of the AlTAP parameters together with the mechanical properties and microstructure of the critical sections of the engine blocks produced at that plant. This mapping was then used by the CBR system for the prediction of mechanical properties and microstructure characteristics. Prior to the collection of data a Repeatability and Reproducibility (R & R) study was carried out to ensure that the measurements obtained in this study were adequate.

The chemical composition of the alloy analyzed in this work is presented in Table 2. This composition corresponds to the standard processing condition(s) at the casting plant, which were obtained using observational study or passive data collection, as the aim was to establish base line processing conditions in the casting plant environment.

The input fields of each case are formed by TA parameters and the output fields of each case are formed by the chemical composition, characteristics of the microstructure and mechanical properties of the sections of the castings' critical section (bulkhead) with the slowest SR.

Table 2.
Chemical Composition of the W319 Alloy (wt%)

Alloy	Si	Cu	Fe	Mn	Mg	Ni	Zn	Ti
W319	6.5-8.0	3.0-4.0	0.4	0.2-0.3	0.10	0.02	0.15	0.25

For this purpose, both TA samples and castings were obtained simultaneously. The castings were analyzed in the T6 condition. The following features were measured for each casting bulkhead section:
- 2% Yield Strength (YS), Percent Elongation (%EL) and Ultimate Tensile Strength (UTS),
- Brinell Hardness, (HB),
- Silicon Modification Level (SiML),
- Area Percent Cu Based Phases,
- Porosity Characteristics.

For comparison with the as-cast condition, the following features were measured from the test samples:
- Characteristic Temperatures and Parameters of the Cooling Curves and their first Derivatives,

- Silicon Modification Level (SiML),
- Area Percent Cu Phases,
- Porosity Characteristics,
- Vickers Micro Hardness (HV25).

The chemical composition of the melt was obtained by Optical Emission Spectrometry (OES). Simultaneously, the temperature of the alloy at the holding furnace and the hydrogen level of the melt were measured using an AlSCAN Hydrogen Analyzer Unit.

Metallographic specimens were prepared using standard grinding and polishing procedures on an automatic polisher to produce the surface finishing required by the Light Optical Microscope (LOM). A Leica 550IW Image Analysis System was used to assess the SiML of the polished TA test samples. The system was programmed to automatically scan and analyze the 30 predetermined fields in the sample.

3.2. Case Based Reasoning System

In this system the following two parameters were used as indexes:
A. Index for SiML – This index can be taken from one of three pre-established values: modified, unmodified or partially modified according to the AFS Chart for Microstructure Control in Hypoeutectic Al-Si Alloys.
B. Index for the SR of the Casting Section –This index separates the case base into four possible Solidification Rates that correspond to 2 different critical sections of 2 different engine blocks (0.3°C/sec, 0.2 °C/sec, 0.45°C/sec, 0.6°C/sec).

Control limits calculated as 95% Confidence Intervals (CI) were obtained for the TA parameters (measured and calculated between the non-equilibrium liquidus and solidus temperatures) are used to define the ranges over which the values of the parameters can be considered similar. For example, the values for the lower and upper boundaries are between 604.1 and 606.0°C for the liquidus temperature while for the solidus temperature it is 471.1 and 475.6°C.

The system includes the following rules:
A. A rule to increase the weight of the characteristic temperature $T^{\alpha-DEN}_{REC}$ when its value corresponds to a grain refined melt. For grain refined melts $T^{\alpha-DEN}_{REC}$ this will have a more relevant role in the retrieval of similar cooling curves.
B. A rule to modify the value of the liquidus temperature ($T^{\alpha-DEN}_{NUC}$).
This rule was included to verify the value of the liquidus temperature of the multi-component Aluminum alloys $T^{\alpha-DEN}_{NUC}$ that is incorporated into the CBR system as a mathematical equation [19].

Repair rules were defined in order to modify the solution of the cases to account for differences between the new case and the existing cases:

A. Rules to determine the exact Sr content.
The Sr content of the melt is calculated using the relationships between the level of SiML, as defined by the AFS, and the Sr content of the melt and the parameter $\Delta T^{Al-Si}_{E,G}$ developed by the University of Windsor's LMCT Group [20].

B. The rule related to the Thermal Sand Removal (TSR) temperature recommends an optimum ST temperature according to the alloy chemistry to avoid incipient melting of the Cu-based constituents. The recommended TSR (and ST) temperature is calculated using the results of studies of the UMSA heating and cooling cycles [21].

C. A rule to determine whether Strontium additions to the 319-Al melt are needed. This rule verifies that the level of Sr in the melt is the same as the target level defined by the user. If there is a discrepancy between these two levels, the system recommends the amount of Sr that should be added to the melt to reach the target level.

D. A rule to change the sample microstructure display. The micrograph of the microstructure is changed to display the correct morphology of the silicon particles.

E. A rule to evaluate that the characteristics of the test sample are adequate (mass and initial temperature) according to the repeatability criteria.

4. Operation of the AlTAP integrated platform

The parameters that are transferred from the AlTAP to the CBR system after every TA test include Time, Temperature and Fraction Solid (FS) parameters that define the α-Al (including the Dendrite Coherency Point (DCP)), Al-Si Eutectic and Al-Cu Eutectic Reactions.

The following groups of parameters were retrieved from a historical case and adapted by the CBR system, sent back to the AlTAP GUI and then presented to the User of the Platform:

- Fields that evaluate the quality of the test sample.
- Fields that predict the SiML and the estimated Strontium content.
- Fields related to the feeding conditions of the alloy and the probability of gas or shrinkage porosity. These fields include the Hydrogen level as measured using an AlSCAN unit when the case data was obtained, the observed solidification range of the alloy, the Grain Size observed during micro structural evaluation by Image Analysis, the propensity to shrinkage porosity based on the Fraction Solid that forms between coherency and Al-Si nucleation [22] and the Area Percent Porosity of the casting section quantified via Image Analysis.
- Fields that evaluate the characteristics of the Cu rich phases, such as the Area Fraction of Cu phases in the casting section (after heat treatment). Quantified by Image Analysis and the recommended TSR temperature.
- Fields that predict the mechanical properties of the specified casting section, Micro Hardness (HV25) of the α-Al matrix, Percent Elongation, Ultimate Tensile Strength, Two Percent Yield Strength, and Brinell Hardness.
- Sample Microstructure – Micrograph illustrating the typical microstructure of the engine block's critical section.
- Fields that presents comments regarding any special conditions observed during data collection and that give recommendations to maintain the process in control.

The main screen together with the AlTAP summarizes the input and output parameters and is included in Figures 9, 10, 11 respectively.

NOTE: The AlTAP responds to cases not included in the library with a non-matching index alarm, Figure 9. If a case cannot be automatically matched AlTAP offers the possibility to match cases manually.
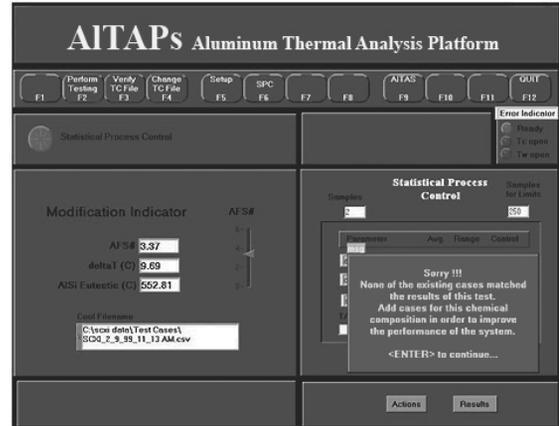
Fig. 9. Main Screen of the AlTAP Platform
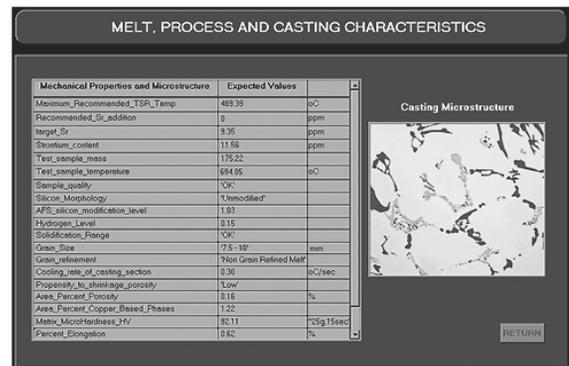
Fig. 10. Screen showing the predicted microstructures and mechanical properties
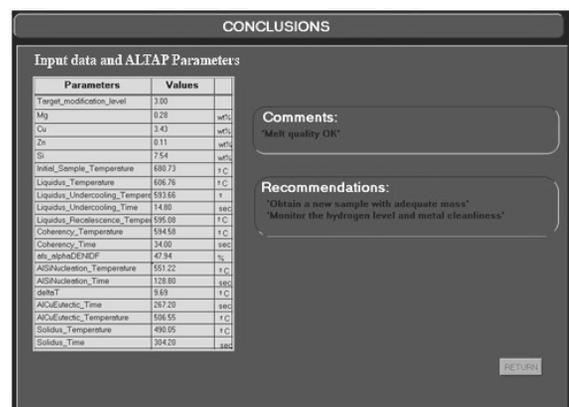
Fig. 11. Screen of the program showing a summary of input parameters and Conclusions and Recommendations for the User

4.1. Verification and validation procedures

A methodology proposed by Gonzales et al. [23] was followed to validate the AlTAP's output. This methodology uses the case library itself to evaluate the retrieval and adaptation functions of the CBR shell with respect to the domain included in the case library. This method offers advantages such as eliminating the subjectivity of the testing procedure and minimizing the involvement of domain experts.

This methodology is known as the Case Library Subset Test and includes the following three stages:

a) Retrieval test,
b) Adaptation test,
c) Domain coverage test.

During the present validation the first two tests were carried out as indicated in the methodology. The validation criterion in this test is based on the evaluation of two parameters:

a) ***Result Acceptability Criteria (RAC)*** – For numerical outputs, the RAC can be defined as the Relative Error, Equation 2 of the solution when compared to a standard.

Relative Error (RE)

$$RE = \frac{(|a - b|)}{b} * 100 \qquad (2)$$

Where:
a is the calculated value of the parameter,
b is the real value of the parameter.

b) ***System Validity Criteria (SVC)*** – the percentage of the test cases that must be acceptable (above the RAC threshold) in order to consider the CBR system valid. During validation this parameter is compared to a "Correctness Ratio" as defined in Equation 3.

Correctness Ratio (CR)

$$CR = \frac{(c)}{t} * c \qquad (3)$$

Where:
c is the number of correctly appraised cases,
t is the total number of cases used during validation.

4.2. Retrieval test

This test is carried out to evaluate the correctness of the retrieval function of the AlTAP/CBR program, (Figure 12). This test evaluates the indexing and case classification functions and is carried out using the same set of cases included in the system's case base.

Twenty cases were tested during the validation procedure. For all tests the validation criteria were defined as follows: RAC = 20% and SVC = 95%.

This means that 95% of the test cases must be retrieved with parameter values less than a 20% difference from their original values. The Retrieval Test was completed within the acceptable criteria (CR=0.95, CR≥SVC; one case file was retrieved with an error).
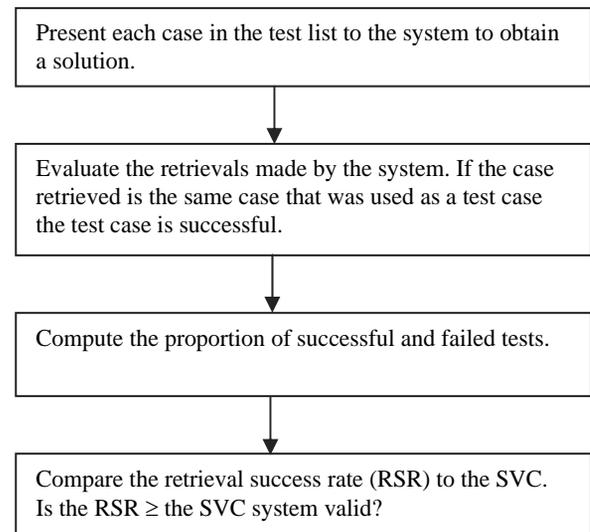
Fig. 12. Procedure for the Retrieval Test

4.3. Adaptation test

After retrieval has been determined to be successful, it is necessary to ensure that adaptations are correctly carried out. The adaptation test is based on the same set of test cases described above. During this test, the historical data presented to the CBR system must be deleted from the case library, so that the modified case library has only N-1 cases in it. The solution generated by the CBR system must be compared to the original solution of the case, and the Relative Error is calculated. If the Relative Error is within the RAC the test is considered successful. The proportion of successful versus failed cases, called the "adaptation success rate", is computed and must be compared to the selected SVC.

The criteria used in the retrieval test were also used in the adaptation test. The results of the adaptation test for the case files had a Relative Error (RE) between 0.06 to 0.20 for the successfully retrieved ones, and in one case, the file was retrieved with an error when the RE was 0.29. Since CR≥SVC the results of the Adaptation Test were valid. Table 3 includes an example of a successfully retrieved case and a case retrieved containing errors.

4.4. Domain coverage test

This test is used to determine the effect of the size of the case library and how well the CBR system can handle cases recently added to the case base. Because of the size of the case base the segregation of cases that is recommended by Gonzales et al. [23] was not possible and this test was not carried out. Instead, a set of unknown cases with different modification levels was presented to the system to evaluate the retrieval and adaptation functions. The system reacted to unknown cases either by adapting the solution or by giving a non-matching index alarm if the index parameters did not match the known values.

Table 3.
Examples of cases successfully retrieved and retrieved with errors during the adaptation test

	Successfully retrieved			Retrieved with errors		
	Case 3			Case 8		
Solution Parameter	Appraised Value	Real Value	RE%	Appraised Value	Real Value	RE%
Sample Mass	164.9	176.44	6.54	171.52	165.3	3.76
Sample Temperature	ok	ok	0.00	ok	ok	0.00
Sample Quality	ok	ok	0.00	ok	ok	0.00
Silicon Morphology	Unmodified	Unmodified	0.00	Unmodified	Unmodified	0.00
AFS Si Modification Level	1	1.0	3.09	1	1.0	1.01
Sr Content	7	7.33	4.50	7	8.14	14.00
H2 Level	0.138	0.114	21.05	0.114	0.138	17.39
Solution Range	ok	ok	0	ok	ok	0
Grain Size	ok	not ok	100	ok	ok	100
Grain Refinement	ok	ok	0	ok	ok	0
Casting cooling Rate	0.6	0.6	0	0.2	0.2	0
Propensity to Shrinkage	low	low	0	low	low	0
Area % Porosity	0.13	0.13	0	0.15	0.19	21.05
Area % Cu Based Phase	1.22	1.22	0	0.32	1.22	73.77
Maximum TSR Temperature	496.37	496.37	0	494.47	494.47	0
Vickers Harness	99	99	0	102	87	17.24
Elongation %	0.3	0.3	0	0.4	0.5	20
Ultimate Tensile Strength	212	212	0	215	214	0.46
Yield Strength	204	204	0	197	195	1.02
Brinell Hardness	92.6	92.6	0	100	92.6	7.99
Microstructure	Unmodified	Unmodified.	0	Unmodified	Unmodified	0
Comment	ok	not ok	100	ok	high h	100
Recommendations 1	ok	ok	100	ok	-	100
Recommendations 1	ok	ok	100	ok	-	100
Total RE=	435.19			548.23		
Total Possible RE=	2400			2400		
Overall RF= -	0.18			0.23		
RAC =	20%			20%		
Success=	ok			not ok		

RE - Relative Error
RAC - Result Acceptability Criteria
Unmodified - Unmodified Al-Si Eutectic

5. Conclusions

In spite of the research dedicated to establish the relationship between the chemical composition, process parameters and their resulting microstructures and mechanical properties, only a few authors have developed knowledge based technologies that are acceptable for industrial operations. Furthermore, the need to make this knowledge specific to individual casting processes will impose more challenges in the development of knowledge based Platforms.

This CBR application was developed using a shell that allows the use of functions and rules for modification of cases when these are available. If the functions are not available or the interrelationships between process parameters are not yet fully understood, case matching and retrieval provide a powerful means for reaching meaningful predictions.

This AI based approach is suitable for cooling curve interpretation because it allows for process knowledge and expertise to be explicitly incorporated without the risk of generalizations. This technique also allows the simple modification of the AlTAP for different metal casting conditions and for inclusion of other chemical compositions.

The CBR system was validated using the methodology of Gonzales et al. [23] showing retrieval and adaptation functions that met the established criteria. However, the domain currently covered by the case base can be expanded to provide solutions throughout a wider range of chemical composition, such as different levels of modifier, grain refiner, tramp elements and hydrogen content, as well as other elements like silicon and copper. Mechanical properties could also be included in the solution part of the cases.

Acknowledgements

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