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Aging Characteristics, Dimensional Stability and Assessment of High-Temperature Performance of Cast Al-Si Alloy for Powertrain Applications

Wojciech Kasprzak[1], Zhou Tong Deng[2], Jeff Powell[3], Marek Niewczas[3]

[1] CANMET Materials Technology Laboratory, 568 Booth St., Ottawa, ON, Canada

[2] McGill University, 3610 University St., Montreal, QC, Canada

[3] McMaster University, 1280 Main St. West, Hamilton, ON, Canada

A hypoeutectic Al-Si type alloy with Cu level up to 1%, additions of transition metals as well as corresponding processing technology, is being developed for high-temperature powertrain applications such as engine blocks and cylinder heads. Alloy aging characteristics are crucial for their high-temperature performance where the retention of mechanical properties and casting dimensional stability (stability of precipitates) is required. Dilatometer analysis, together with single thermocouple thermal analysis and electrical resistivity measurements, was carried out to characterize the aging kinetic and dimensional stability of the alloy. The over-aging temperature was established for the given alloy chemistry and was correlated with the hardness distribution for various aging parameters leading to optimum T6 (peak-aging) and T7 (over-aging) conditions. High-temperature tensile testing was carried out between 25 to 400^{o}C and showed a significant drop in strength above the over-aging temperature interval of 250-300^{o}C. This indicates that the over-aging temperature established from a dilatometer analysis can be used to determine the maximum temperature the alloy could withstand without drastic loss of mechanical properties. This approach should lead to the development of a quick and reliable methodology to evaluate the alloy's high-temperature performance as a function of the alloy chemistry and heat-treatment processing. Various secondary precipitates based on Cu, Mg, Zr, and Ti elements were identified using TEM/EDX analysis and correlated with alloy chemistry and heat treatment parameters.

Keywords: *Al alloy, high-temperature performance, aging characteristics, dilatometer, electrical resistivity.*

1. Introduction

Contemporary automotive engines operate at higher temperatures reaching up to 250^{o}C and peak pressures up to 180 bar for improved gasoline consumption and reduced Greenhouse Gas (GHG) emissions. This creates demanding operating requirements for existing Al-Si-Cu and Al-Si-Mg alloy systems that typically lose strength above 150^{o}C. Current research is focused on the development of new alloy chemistries with improved high-temperature performance and, the optimization of existing 319 and 356-based chemistries with corresponding processing technology [1-4]. The alloys must exhibit better mechanical strength and ductility, better creep, fatigue, and corrosion resistance properties, particularly if bio-fuels are to be used. If these properties can be delivered using a cost-effective technology, this would represent an attractive technology for industry.

A hypoeutectic Al-Si alloy, with an increased Cu level of up to 1% and additions of transition metals such as Zr, V, and Ti, is being developed for high-temperature powertrain applications such as engine blocks and cylinder heads that require better performance at high-temperatures [3]. This alloy has a T6 UTS and a YS of approximately 360 and 320 MPa respectively. It also has a good retention of mechanical strength at elevated temperatures up to 250^{o}C for as-cast microstructure, with a secondary dendrite arm spacing (SDAS) of approximately 20μm.

High-temperature performance is a critical characteristic affecting an alloy's suitability for various automotive powertrain applications. Conventional high-temperature tensile testing provides information about mechanical properties of the material and is insufficient to develop a comprehensive understanding of the structure-property relations in this alloy system. An in-depth understanding of material microstructure and metallurgical factors responsible for the retention of mechanical properties at elevated temperatures is required for the assessment of an alloy's suitability for heat-resistant applications and selection of optimum alloy chemistry.

The objective of this paper is to evaluate the aging characteristics and dimensional stability, as well as the high-temperature performance, of a newly developed cast alloy for demanding powertrain applications.

2. Experimental procedures

2.1. Alloy chemical composition and testing methodology

A recently developed hypoeutectic Al-7% Si alloy with improved elevated-temperature properties and structural integrity was used in the present studies [3]. Alloy chemistry and corresponding melting and solidification thermal characteristics are provided in Table 1.

Table 1. Chemical composition and thermal analysis results of the investigated alloy.

Alloying elements (wt %)					
Si	Cu	Fe	Mg	Zr-Ti-V	
7.0	1.0	0.12	0.47	0.2	
Selected thermal analysis results					
T_{SH},(°C)	T_{LH},(°C)	T_{LC},(°C)	T_{SC},(°C)	DCP, (°C)	FS_{DCP},(%)
506.5	624.1	619.3	482.0	616.5	6.0

Note: T_{SH} (#1) - Solidus during heating, T_{LH} (#3) - Liquidus during heating, T_{LC} (#4) - Liquidus during cooling, T_{EN} (#5) - Al-Si eutectic nucleation, T_{SC} (#6) - Solidus during cooling, DCP - Dendrite Coherency Point, FS_{DCP} - Fraction Solid at DCP.

The alloy's aging characteristics were evaluated by measuring the hardness of test samples in the solution-treated and quenched conditions carried out for aging temperatures between 25 to 400°C and time periods from 15 minutes to 128 hours. The alloy's over-aging temperature was established based on the Dilatometer and Electrical Resistivity (ER) studies and was used to evaluate the alloy's suitability for high-temperature performance [3, 5]. With some precautions this temperature could be linked to casting critical-service temperature that is, once exceeded, the component mechanical properties will rapidly deteriorate. The alloy's dimensional stability was evaluated using the test sample's relative length change as a function of temperature as well as by analyzing the energy signature of aging transformation remaining after various artificial aging operations. Dilatometer and ER signals were analyzed using first derivative curves for precise aging transformation kinetic determination, and analysis. Heating rate used during thermal analysis experiments was approximately 0.1°C/s.

Tensile testing for test samples in the T7 condition (that is, solution treatment at 505°C for 9 hours followed by water-quenching and artificial aging at 250°C for 16 hrs) was carried out between 25 and 400°C using a specialized attachment in the BAHR DIL 805 quench dilatometer. Light optical and transmission electron microscopes equipped with X-Ray microanalysis systems (EDX) were used for the test samples evaluation in the over-aged condition.

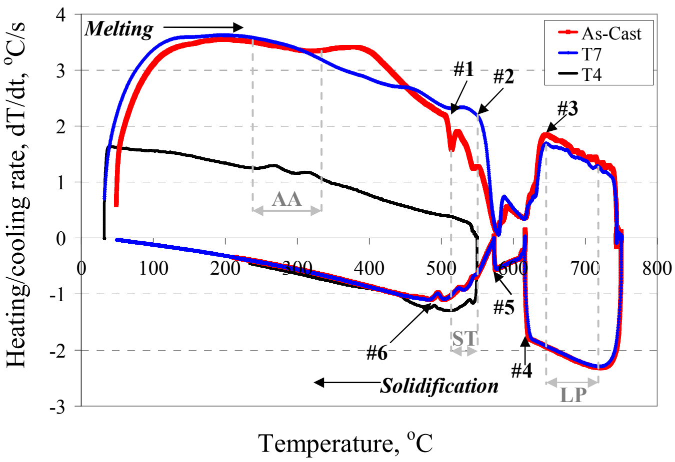

Fig. 1. Thermal analysis melting and solidification curves for the investigated alloy in the following conditions:
a) As-cast
b) T7 (ST@505°C for 9hrs+AA@250°C for 16hrs)
c) T4 (ST@500°C for 1hr+514°C for 3hrs+WQ)
Note: Operating Windows for: AA - Artificial Aging, ST - Solution Treatment, LP - Liquid Metal Processing.

3. Results and discussion
3.1. Alloy microstructure and corresponding thermal characteristics

The investigated alloy's microstructure consisted of α-Al dendrites, Al-Si eutectic and Cu, Mg-based phases located within interdendritic regions. Thermal analysis curves from alloy melting and solidification cycles showed that in the T7 condition the investigated alloy had an incipient melting temperature at 560^{o}C (#2) which is 54^{o}C higher than the test sample in the as-cast condition, that is, 506^{o}C (#1) (Figure 1, Table 1). This indicates that the solution treatment at 506^{o}C for 9 hours was sufficient to dissolve Cu and Mg-based intermetallic phases. Re-melting of the investigated alloy in the T4 condition, that is, solution-treated and quenched, showed a visible solid state exothermic reaction in the 250-350^{o}C interval (Figure 1). This information was crucial with respect to aging optimization studies as well as in the determination of the alloy's high-temperature performance. ZrVTi-based intermetallic phases nucleated during the solidification process and, could be present in the microstructure depending on the amount of the addition of these transition metals. Nano-size secondary precipitates nucleated during heat treatment operation (Figure 2) were identified in the T7

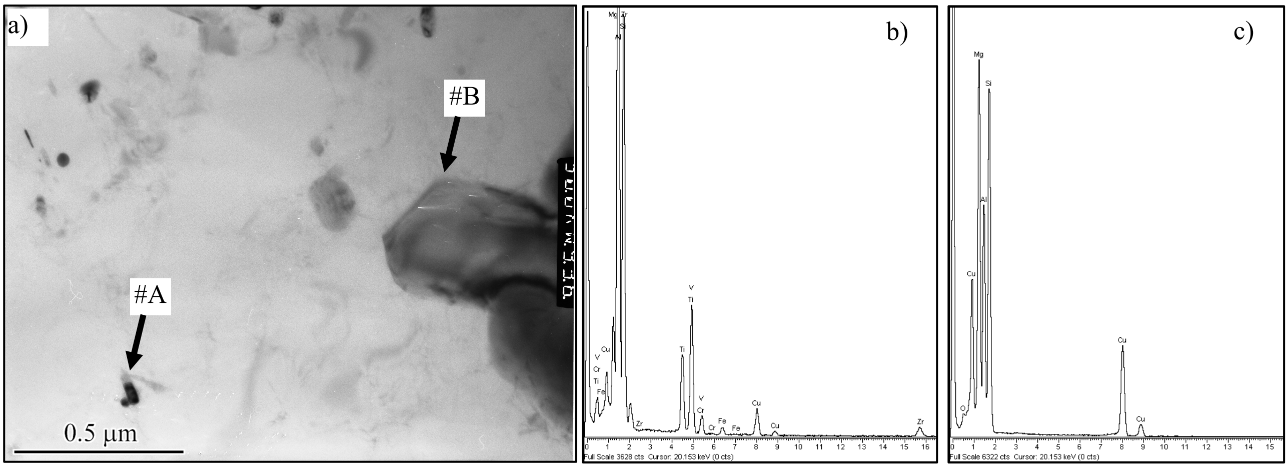

Fig. 2. Transmission Electron Microscopy (TEM) results obtained for the investigated alloy in the T7 condition, a) Bright field image (x58K) with Al-Si-Zr-Ti (#A) and Mg-Si-Cu-based (#B) precipitates, b-c) Diagrams of the energy dispersive X-Ray spectrum obtained from #A and #B.

conditions and they most likely contributed to strength retention at elevated temperatures since these phases are more thermally stable than Cu and Mg-based precipitates [1-3].

Dilatometer analysis of the investigated alloy in the solution-treated and quenched condition (T4) re-heated to 500^{o}C showed a visible over-aging reaction between 250-350^{o}C (Figure 3a). The first derivative curve (dL/dt (μm/s)) represents the transformation kinetics of the aging process, established based on isochronal experiments, that is, during the continuous heating of saturated solid solution where the precipitation (increase of sample length) and dissolution (decrease of sample length) processes are clearly visible [3, 8]. Volume fraction of precipitates can be evaluated using the first derivatives of the dL curves since it relates to an increase in sample length. The peak over-aging temperature interval was confirmed by ER measurements during the continuous heating of saturated solid solution samples (Figure 3b). The precipitation process is associated with the formation of nano-scale precipitates (Figure 2) and depletion of the solid solution with the precipitating solute. This leads to a decrease in the specific resistivity of the alloy, which is pronounced by the decrease of the rate of the resistivity increase with the temperature during continuous heating. In other words, precipitation leads to the decrease of the first derivative of resistivity versus temperature curve (dR/dT (Ω/C) in Figure 3b). On the other hand, during the dissolution process solid solution is enriched with the solute from the dissolving precipitates and this leads to an increase in the alloy's specific resistivity and an increase in the first derivative of resistivity versus temperature (dR/dT).

The two stages of precipitation and dissolution reactions are clearly visible in Figure 3b and correspond well to the stages of the increase followed by the decrease of dL/dt characteristic as observed in Figure 3a.

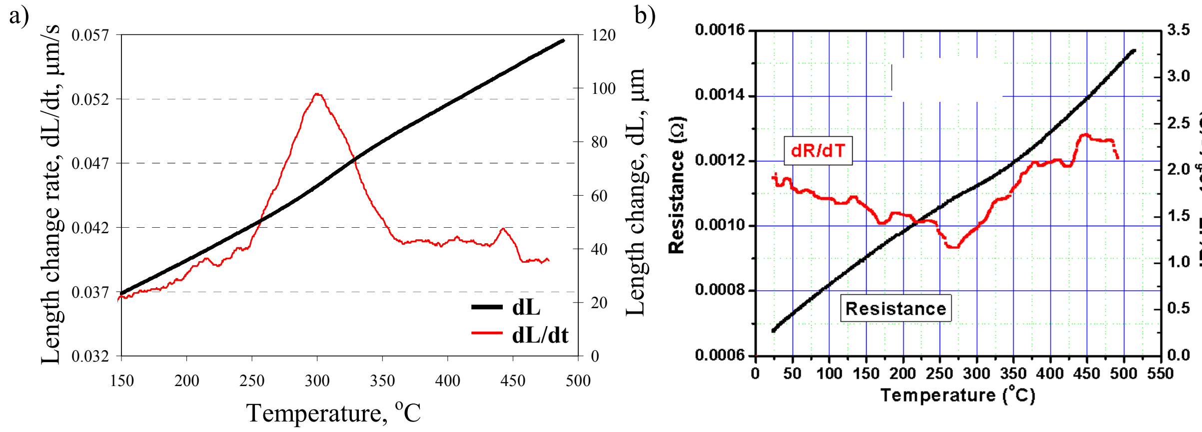

Fig. 3. Aging kinetics obtained during continuous heating (isochronal) of the investigated alloy solution-treated at 500°C for 1 hr and 514°C for 0.5 hr followed by gas quenching at 30°C/s rate using the following techniques: a) Dilatometer analysis, b) Electrical resistivity. Note the over-aging peak interval between 250 to 300°C.

Typically, the majority of aging kinetics studies are performed using calorimetric techniques such as Differential Scanning Calorimetry (DSC) [6, 7] where, besides transformation temperatures, the information about the volume fraction of precipitates is obtained from the stored energy data, which is proportional to the area under the peaks. The described method, combining dilatometer and ER measurements, represents a new approach in the study of precipitation-dissolution reactions in age-hardenable alloys and provides valuable insight on the structure-property relations in the alloy studied.

The over-aging temperature range from dilatometer analysis corresponded well with aging curves established based on hardness measurements carried out for various aging temperatures (between 100-400°C) and times (between 15 minutes to 128 hours). Peak hardness values decreased from approximately 68 to 52 HRB once the aging temperature approached 250°C and decreased below the as-cast value of 36 HRB when the aging temperature reached 300°C (Figure 4). No hardness increase was observed for aging temperatures higher than 300°C. Based on the hardness characteristics as presented on Figure 4, it was determined that T6 (peak-hardness) condition corresponds to artificial aging at 150°C for 100 hours while T7 (over-aging) condition corresponds to artificial aging at 250°C for 16 hours for the test samples solution-treated at 505°C for 9 hours.

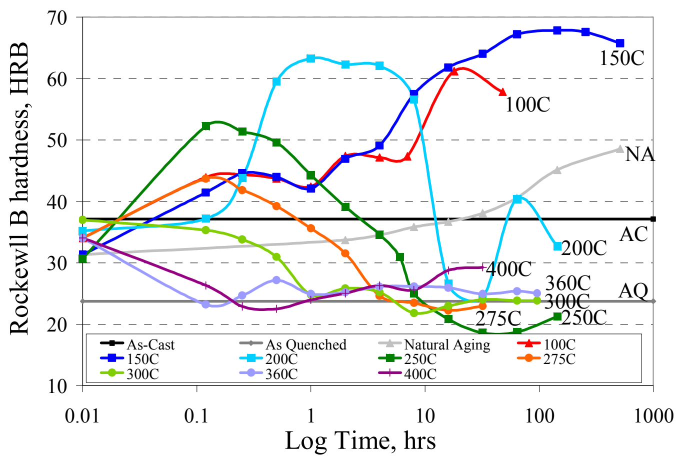

Fig. 4. The effect of artificial aging temperature varied between 100 to 400°C and time between 15 mins to 128 hrs on hardness development. Prior to aging experiments the investigated alloy was solution-treated at 505°C for 9 hrs and water-quenched with 100°C/s rate. The T6 (peak aging) and T7 (over-aging) conditions were defined as AA at 150°C for 100 hrs and AA at 250°C for 16 hrs respectively. Note that as-cast (AC) and as quenched (AQ) hardness was 35 and 25 HRB.

Cast components are heat-treated to ensure satisfactory strength and dimensional stability during in-service operation. This is required to determine heat-treatment parameters, specifically the artificial aging

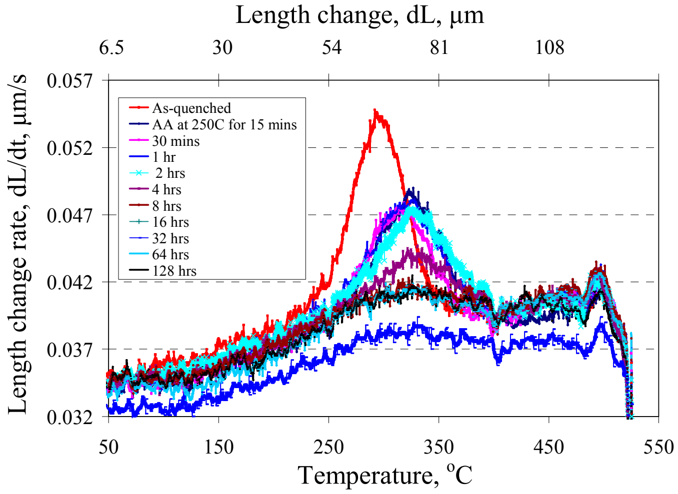

Fig. 5. The kinetic of the "remaining" aging transformation during re-heating of the investigated alloy from 50 to 500°C in the following conditions: solution-treated, quenched and aged at 250°C within times that varied between 15 mins to 128 hrs. Note that the highest peak corresponds to the alloy in its as-quenched condition. Its height diminishes with increasing aging time to 128 hrs, where no further transformation occurs.

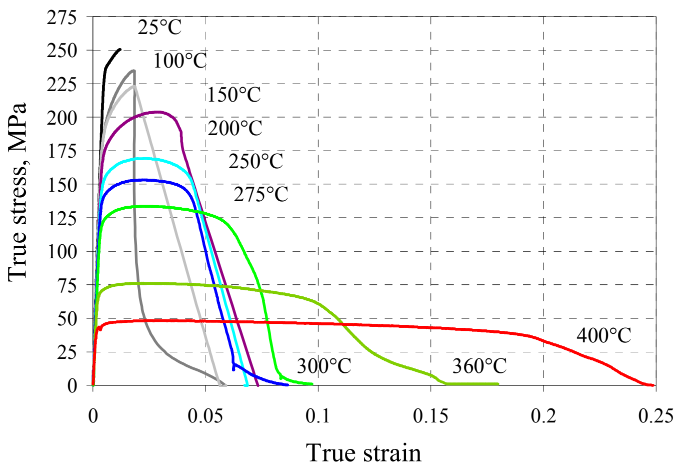

Fig. 6. True stress vs. strain curves for the investigated alloy in the T7 condition tested at temperatures between 25 to 400°C. Note that T7 consisted of solution treatment at 505°C for 9 hrs followed by water-quenching and aging at 250°C for 16 hrs.

operation that will ensure the component's minimal dimensional change within the temperature range typically observed during component operation. From a physical metallurgy point of view aging transformation must be completed, that is, no further precipitation can occur during the in-service operation. Figure 5 presents the kinetics of aging transformations recorded using dilatometer analysis for the investigated alloy in the solution-treated and quenched condition followed by aging at 250°C for time between 15 minutes to 128 hours. All investigated test samples after completion of these heat-treatment cycles were re-heated to 500°C. The highest peak (see Figure 5) corresponds to the test sample in the solution-treated and quenched condition. It can be seen that the peak height diminishes with increasing aging time at 250°C. A test sample that spent more than 32 hours at 250°C did not show any remaining aging transformation and should experience minimum dimensional change if re-heated after completion of the heat-treatment cycle. This approach clearly shows the applicability of this type of dilatometer analysis for proper selection of artificial aging parameters. Relative length change during heating of the investigated alloy from 50 to 450°C was from 6.5 to 108µm (Figure 5).

High-temperature tensile testing was carried out between 25 and 400°C for the alloy in the T7 condition and was correlated with over-aging temperature. True stress decreased from approximately 250 MPa at room temperature to approximately 50 MPa at 400°C (Figure 6). The corresponding true strain increased from 0.012 to 0.25.

Figure 7 summarizes the effect of testing temperature on UTS/YS/E for the investigated alloy in the T7 condition. The dilatometer isochronal aging curve (dL/dt) is superimposed to show its correlation with the alloy's high-temperature performance. It was found that a significant drop in strength occurred when the testing temperature reached the 250-300°C interval. This was accompanied by an increase in sample elongation. This interval corresponded to the over-aging peak beginning at 250°C and reaching 300°C. This indicates that the over-aging temperature established from a dilatometer analysis can be used to determine the maximum temperature the alloy can withstand without drastic loss of mechanical properties.

4. Conclusions

Based on the presented metallurgical analysis carried out for the new hypoeutectic Al-Si alloy with 1% Cu and additions of transition metals the following was concluded:

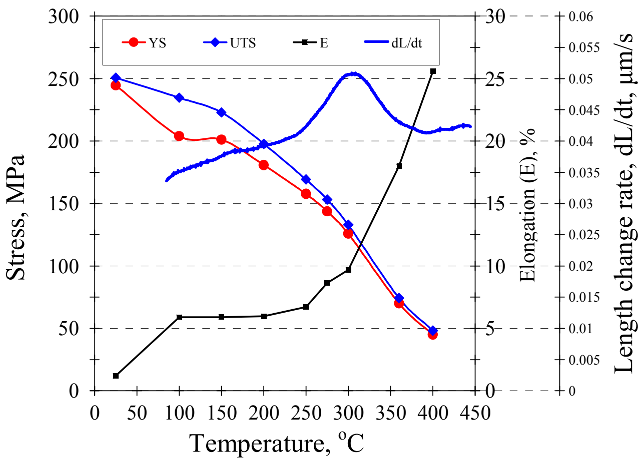

Fig. 7. The effect of tensile testing temperature on UTS/YS/E for the investigated alloy in the T7 condition. The dilatometer isochronal aging curve (dL/dt) is superimposed to show its correlation with alloy's high-temperature performance. The beginning of the over-aging peak at 250°C corresponds to the rapid increase in sample elongation and transition drop in alloy strength.

a) Dilatometer and ER analysis of the alloy in the solution-treated and quenched condition show visible over-aging reactions between 250-300°C.
b) This over-aging temperature interval corresponds well with hardness measurements where peak hardness values decreased from approximately 68 to 52 HRB once the aging temperature approaches 250°C and a further decrease below the as-cast value of 36 HRB, when the aging temperature reaches 300°C.
c) High-temperature tensile testing carried out up to 400°C shows a significant drop in strength above the over-aging temperature interval of 250-300°C.
d) Over-aging temperature determined based on a dilatometer analysis can be used to establish the maximum temperature the alloy can withstand without drastic loss of mechanical properties.

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