Residual stresses in spot welded new generation aluminium alloys
Part A – thermophysical and thermomechanical properties of 6111 and 5754 aluminium alloys

Sanjeev K. Khanna*[1], X. Long[1], W. D. Porter[2], H. W. K. C. Liu[2], M. Radovic[2] and E. Lara-Curzio[2]

Thermophysical and thermomechanical properties of 5754 and 6111 aluminium alloys were experimentally determined between room temperature and 500°C for use as input in the numerical simulation of residual stress generated during fusion welding processes of these materials. The thermophysical properties determined included specific heat, thermal diffusivity and thermal expansion using the differential scanning calorimeter, laser flash technique and the dilatometer, respectively. Thermal conductivity was also calculated from thermal diffusivity, specific heat and density. The thermomechanical properties determined included yield strength, elastic modulus and Poisson ratio. The yield strength was determined using tensile test specimens in a heated chamber. The Poisson ratio and elastic modulus were determined using resonant ultrasound spectroscopy.

Keywords: New generation aluminium alloys, High temperature material properties, Spot welding

Introduction

Numerical simulation is being widely used to understand manufacturing processes. For simulating thermal manufacturing processes such as welding and casting, thermophysical and thermomechanical properties of the materials are required. In this investigation, the thermophysical and thermomechanical properties of 5754 and 6111 aluminium alloys have been determined. These properties have been employed to numerically simulate residual stresses generated during spot welding of sheet metals made from these aluminium alloys. These alloys are important as they are under active consideration for a future generation of automotive structures. Thermophysical properties measured include specific heat, thermal conductivity, thermal expansion and density, and can be used to simulate heat transfer and solidification of the material during a welding process. Thermomechanical properties measured included yield strength, elastic modulus and Poisson ratio, which can be used to estimate stresses and predict distortion of materials during and after welding.

It is difficult, however, to find all of the require properties in metals handbooks or other database sources. This is particularly true for new materials. Unfortunately, new materials are usually the objective for numerical studies because numerical simulation has been a powerful method to optimise or study manufacturing processes of new materials.[1–4] Some investigations have been done by previous researchers on the thermophysical and thermomechanical properties of new materials,[5,6] which show how to determine those properties for numerical simulation purposes.

For comparison purposes, some aluminium alloys, which can be found in handbooks, have been referenced in the present study. For example, 5052 and 5456 aluminium alloys can be compared to 5754 aluminium alloy, whereas 6061 and RR131D aluminium alloys can be compared to 6111 aluminium alloy. The mean chemical compositions of these alloys are listed in Table 1.[7,8]

The measured property data have been used to simulate residual stresses in a spot welded joint using thermo-electrical-mechanical finite element analysis, which is presented in Part B.[9] It should be noted that the measurement methods mentioned in the present study are not unique for determining some thermal properties of materials; some other options are also available.

Determination of thermo-physical properties as a function of temperature

The thermo-physical properties of 5754 and 6111 aluminium alloys that have been measured are thermal

[1]Department of Mechanical and Aerospace Engineering, University of Missouri - Columbia, Columbia, MO 65211, USA
[2]High Temperature Materials Laboratory, Oak Ridge National Laboratory, 1 Bethel Valley Road, P.O. Box 2008, Oak Ridge, TN 37831, USA

*Corresponding author, email khannas@missouri.edu

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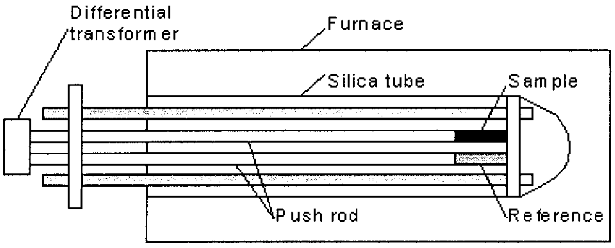


1 Schematic diagram of differential dilatometer

expansion, specific heat and thermal conductivity. Brief details of the experimental techniques used and the results are given below.

Differential dilatometry for measurement of thermal expansion of aluminium alloys

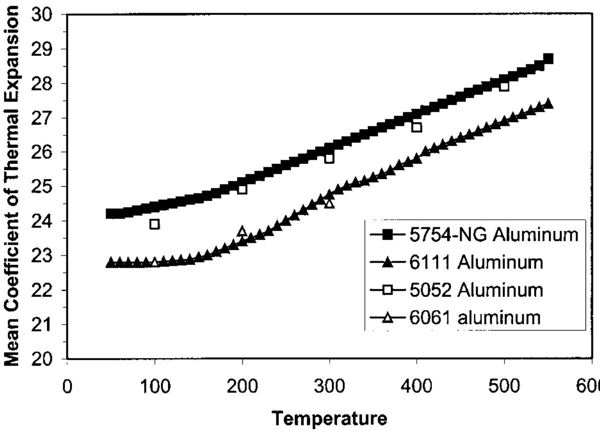
Differential dilatometry is a method in which the thermal expansion of a sample is measured relative to that of a reference material. In conventional dilatometry, the reference material is usually the measuring system itself, and this can be considered a special case of the differential method. A primary advantage of the method is that a single test can suffice to determine the difference in expansion between two materials.[10,11]

Figure 1 shows the schematic diagram of a differential dilatometer. The expansion of the sample and reference are transmitted by means of two push rods. The differential expansion is measured by means of a differential transformer. A furnace is used to heat the sample and reference. The specimen tested had the dimension of 5 mm in width, 5 mm height, and 25 mm length. Helium gas flowing at a rate of 5 mL min^{-1} was used to purge the dilatometer during testing.

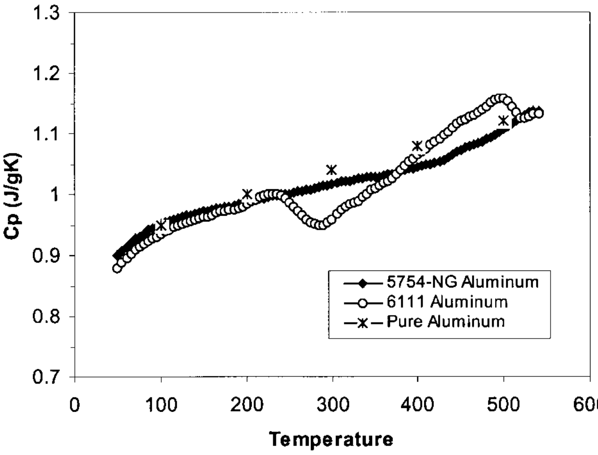
Figure 2 shows the mean coefficient of thermal expansion of 5754 and 6111 aluminium alloys. For comparison, aluminium alloys 5052 and 6061 have also been cited in Fig. 2.[12]

Differential scanning calorimetry (DSC) for measurement of specific heat

Differential scanning calorimetry (DSC) is a technique in which the difference in energy inputs into a specimen and a reference material is measured as a function of temperature while the substance and reference material are subjected to a controlled temperature program. The difference in heat flow into the test material and a reference material as a result of energy changes in the material is continually monitored and recorded. DSC measurement provides a rapid, simple method for determining the specific heat capacity of a material.[8] The ASTM standard E 1269-01 was used.[13]



2 Mean coefficient of thermal expansion of 5754 and 6111 aluminium alloys, as well as 5052 and 6061 aluminium alloys

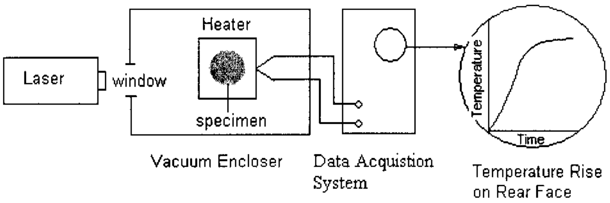


3 Specific heat of 5754 and 6111 aluminium alloys, as well as pure aluminium

The specimens used in DSC were discs of 6 mm diameter and 1·5 mm thickness. ASTM E1269-95 standard was used to determine the specific heats. Samples were heated and cooled at rates of 20 K min^{-1} in argon flowing at 50 mL min^{-1}. A sapphire disc of similar dimensions was used as the standard material. Figure 3 shows the values of specific heat of 5754 and 6111 aluminium alloys as a function of temperature. For 6111 aluminium, the dip in the specific heat around 275°C and the peak around 375°C are possibly because of precipitation and solutionising events occurring in the alloy and are not related to the heat capacity of the alloy. The specific heat of pure aluminium has been shown in Fig. 3 for comparison.[14]

Table 1 Chemical compositions of 5754, 6111 and some reference aluminium alloys

Alloy	Mg	Si	Cu	Fe	Mn	Cr	Zn	Ti
5754	2·6–3·6	0·4	0·1	0·4	0·5	0·3	0·2	0·15
6111	0·5–1·0	0·7–1·1	0·5–0·9	0·4	0·15–0·45	0·1	0·15	0·1
5052	2·2–2·8	0·25	0·1	0·4	0·1	0·15–0·35	0·1	…
6061	0·8–1·2	0·4–0·8	0·15–0·4	0·7	0·15	0·04–0·35	0·25	0·15
5456	4·7–5·5	0·25	0·1	0·4	0·5–1·0	0·02–0·2	0·25	0·2
RR131D	1·4	0·5	0·3	0·3	0·1	0·2	0·45	0·12



4 Schematic diagram of laser flash apparatus for measuring thermal diffusivity of material

Laser flash for measurement of thermal diffusivity and thermal conductivity

Thermal diffusivity α is a measure of transient heat flow and is defined by the equation

$$\alpha = k/(\rho C_p) \tag{1}$$

where k is thermal conductivity, ρ is density, and C_p is specific heat. However, thermal diffusivity α has been measured independently using the 'Laser Flash' method, and not using the above equation as it is very difficult to measure thermal conductivity.

In the laser flash method, the front face of a small disc shaped specimen is subjected to a very short burst of radiant energy coming from a laser or a xenon flash lamp, with the irradiation time being of the order of 1 ms or less. The resulting temperature rise of the rear surface of the specimen is recorded and measured and thermal diffusivity values are computed from temperature rise versus time data using the expression

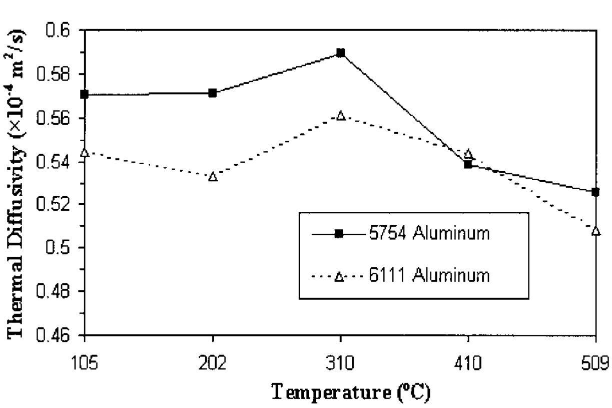
$$\alpha = 1{\cdot}37 L^2/(\pi^2 t_{1/2}) \tag{2}$$

where L is the thickness of the specimen, and $t_{1/2}$ is a specific time at which the rear surface temperature reaches half its maximum value. The above equation is the Parker equation that assumes no heat loss; however, the Clark and Taylor correction to the Parker values was used in the data analysis.

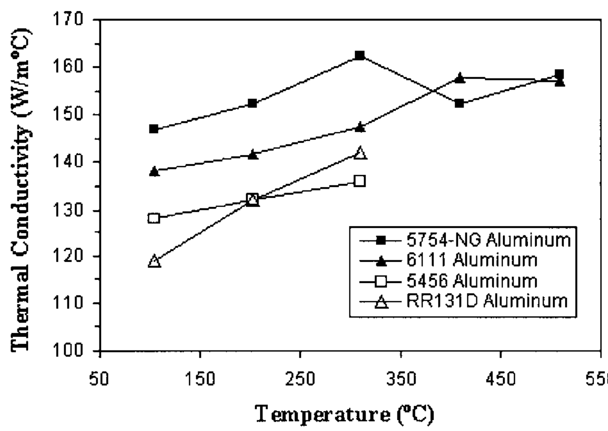
Figure 4 schematically shows the instrument for measuring diffusivity of a material using the laser flash method. The specimens used in the laser flash method are discs of 6 mm diameter and 1·5 mm thickness. The test temperatures ranged from room temperature to 500°C. Figure 5 shows the thermal diffusivity of 5754 and 6111 aluminium alloys as a function of temperature.

Since it is very difficult to measure thermal conductivity, it was calculated using the expression

$$k = \rho \alpha C_p \tag{3}$$



5 Thermal diffusivity of 5754 and 6111 aluminium alloys



6 Thermal conductivity of 5754 and 6111 aluminium alloys, as well as 5456 and RR131D aluminium alloys

The density has been assumed constant at 2700 kg m^{-3} for both aluminium alloys. Substituting density, measured specific heat and thermal diffusivity into equation (3), thermal conductivity can be obtained. Figure 6 shows the calculated thermal conductivity as a function of temperature.

Determination of thermo-mechanical properties as a function of temperature

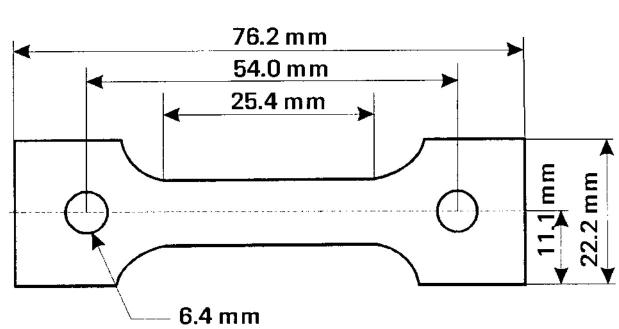
The following thermo-mechanical properties of 5754 and 6111 aluminium alloys were measured: yield strength, elastic modulus, tangent modulus and Poisson ratio. All of these properties were determined as a function of temperature.

High temperature tensile test for measurement of yield strength and elastic modulus

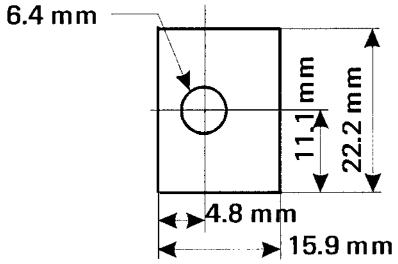
High temperature tensile tests were performed on a 200 kN Instron Model 4507 testing machine. ASTM standard E-21 was followed for the elevated temperature tension tests on the two aluminium alloys.

The dimensions of the specimen are shown in Fig. 7. The specimen thickness was 3·24 mm for 5754 aluminium and 2·0 mm for 6111 aluminium (6111 was not available in thicker stock). End tabs, which are schematically shown in Fig. 8, were welded to test specimens to strengthen the region where the mechanical load is transferred to the specimen by pin loading.

Figure 9 shows typical tensile stress–strain curves of 5754 and 6111 alloys as a function of temperature.



7 Schematic diagram of tensile specimen



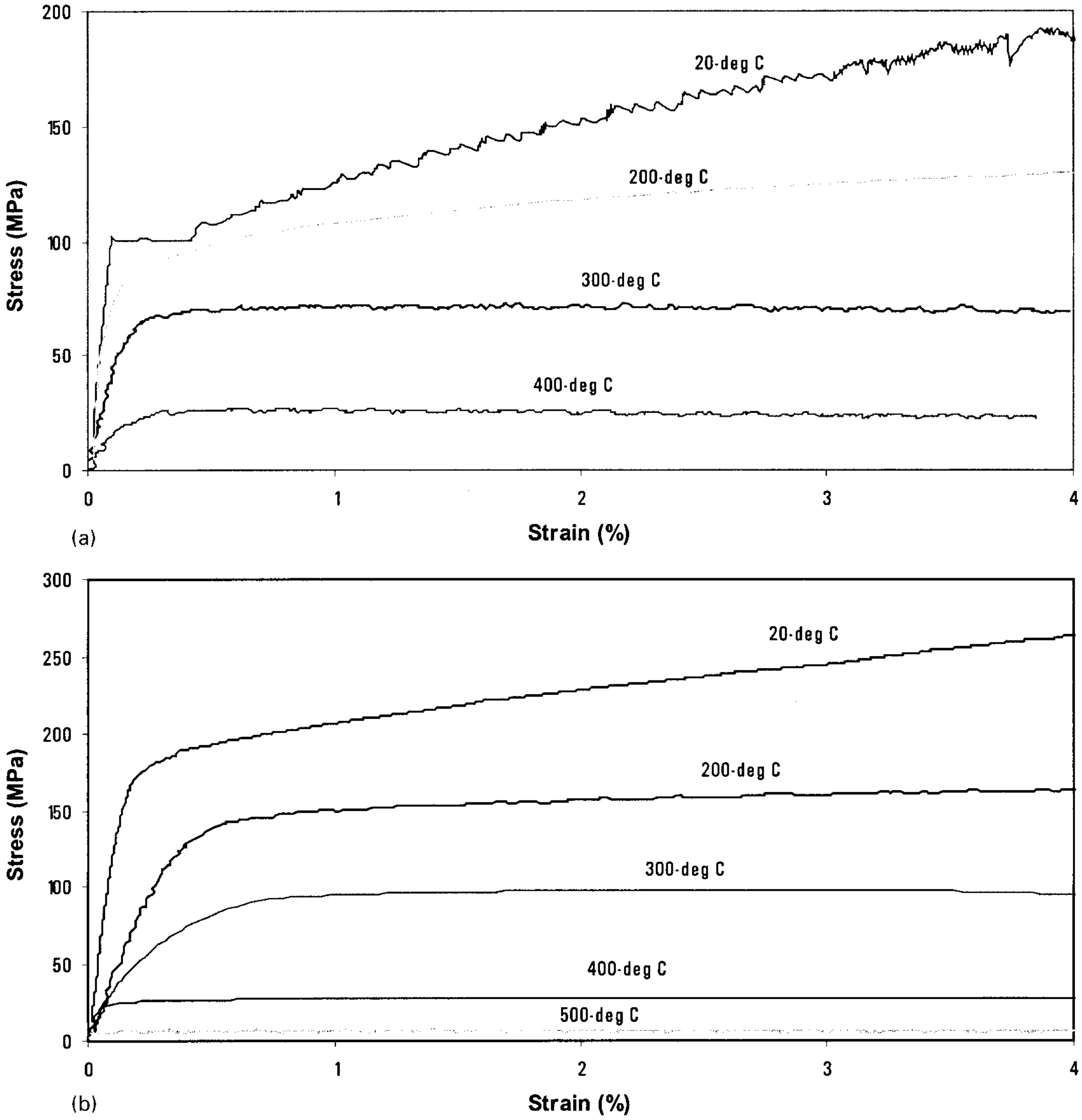
8 Schematic diagram of tab welded to end of tensile specimen

Table 2 lists the mechanical properties obtained from the tensile tests on 5754 and 6111 alloys. It should be noted that the slope of an apparently linear region was used to estimate the value of the yield strength corresponding to 0·2% strain. The elastic moduli listed in Table 2 are average values obtained by approximating the stress–strain region over 0·2% strain with a linear region. The tangential modulus was obtained corresponding to 2% strain for a simplified linear hardening stress–strain curve, which will be used in numerical simulation of spot welding process.

Resonant ultrasound spectroscopy (RUS) techniques for measurement of elastic modulus and Poisson ratio

Principle of RUS

The RUS technique is based on measuring the spectrum of mechanical resonances for a sample of known shape. An approximate spectrum is previously calculated from the known sample dimensions, its mass, and a set of assumed elastic constants. The measured spectra of mechanical resonances are compared with the theoretically calculated spectrum. The true set of elastic constants is then calculated by a recursive regression method that varies the assumed elastic constants until the calculated resonant spectrum is matched with the experimental one. A multidimensional minimisation of the error between the measured and calculated spectra enables deduction of all the elastic constants of the solid from a single frequency scan. More details of this technique can be found elsewhere.[15–19] Over the last 10 years, RUS has become a versatile laboratory technique for measuring elastic constants, ultrasonic attenuation, thermodynamic properties, structure phase transitions, etc. in solids. The available results demonstrate that RUS can be used on small samples with high precision.[18]



9 Typical tensile stress–strain curves of *a* 5754 and *b* 6111 aluminium alloys as a function of temperature