MECHANICAL PROPERTIES OF LEAD FREE SOLDER ALLOY FOR GREEN ELECTRONICS UNDER HIGH STRAIN RATE AND THERMAL AGING

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ABSTRACT

Lead free solder (LFS) alloys have been widely acknowledged due to its good mechanical properties and no harmful effect on environment. The current work is focused on the examination of thermal aging and strain rates on mechanical properties of $Sn_{96.5}$-$Ag_{3.0}$-$Cu_{0.5}$ (SAC305) LFS alloy. The selected thermal aging temperatures are 60 °C, 100 °C and 140 °C. Strain rates are measured at 10/s, 20/s, 30/s and 40/s. The microstructure examination before and after thermal aging is carried out using scanning electron microscopy (SEM) followed by confirmation of chemical composition with energy dispersive X-ray (EDX). The microstructure is further analyzed using ImageJ to investigate the Intermetallic compounds (IMCs) particle average size at different aging temperature. Mechanical properties including Yield strength (YS) and Ultimate tensile strength (UTS) are examined before and after thermal aging and at different high strain rates from stress-strain curves using universal testing machine (UTM). Results show that LFS alloys are extremely sensitive to changes in both temperature and strain rate. The microstructure becomes coarsen after thermal aging due to growth of average IMCs particle size which significantly results in reduction in YS and UTS. Furthermore, increasing strain rates results in increasing YS and UTS due to less creep deformation. Mathematical relations are also developed to predict these properties at various levels of aging temperature and strain rate. A power law relationship exists between strain rate and mechanical properties while a reciprocal relationship is obtained between aging temperature and mechanical properties.

KEYWORDS: Lead free solder, Intermetallic compound particles, Thermal aging, Strain rate, Mechanical properties.

INTRODUCTION

Solder alloys are considered as significant materials in electronic manufacturing industries which serve as a conductive material for electrical interconnection of circuits, a mean of heat dissipation during service and for providing mechanical support to electrical components[1]. The most commonly used solder alloy in electronics assembly is the eutectic or near eutectic Sn-Pb with the most commonly referred as Sn_{63}-Pb_{37}. This is because it has low melting temperature, good wettability and wide range availability with low cost. It has also been considered as good reliable solder alloy in electronic manufacturing for many years. Further, the mechanical, metallurgical and material properties of Sn-Pb alloys are well acknowledged[2]. Besides of all these benefits of Pb in electronic solders, it has negative impact on environment as well, since it is toxic in nature and caused health related issues due to which it got restriction in its utilization through legislation worldwide. According to Environment Protection Agency (EPA), Pb and has been considered as one of the seventeen toxic substances for environment[3]. Therefore, several academic and industrial migrated towards LFSs but there are several challenges to be met for the evolution of such LFSs to be used in electronics industry. Therefore, Sn-Pb substitutes must satisfy different engineering criteria such as temperature range, reliability, manufacturability and solderability. In general, material used for LFSs must be economical, easily available and environmental friendly[4].

The most acceptable and popular is the SAC series in which SAC305 is considered to be the most potential LFS alloy for use in microelectronic manufacturing because of well acknowledged wetting properties, better mechanical properties, acceptable melting temperature, excellent fatigue resistance and solder joint reliability[5].

In SAC, the addition of Copper (Cu) improves the wettability and lowers the melting temperature but the recommended range of Cu is 0.5 - 0.9 wt% because high Cu content can increase the gap between the liquidus and solidus temperature which is not suitable for solder joint reliability[6]. The silver (Ag) results in high strength, therefore, high level of Ag content resulted in high strength but showed reasonably low ductility.

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Therefore, it is highly recommended that the amount of Ag is 2 - 3.9 wt%[7].

At elevated temperature, the microstructure of the solder joint alters constantly which results in affecting the strength of the joint and thus makes the reliability complicated. This signifies to understand the microstructure changes and its effect on mechanical properties due to thermal aging for the reliability of the solder joint[8]. Further, solder connections become under mechanical stresses and strains, when an electronic device is in use. These stresses increased due to the differences between the coefficient of thermal expansion (CTE) of the electronic components and the board on which solder joint is connected[9]. The on and off switching of the system is also responsible for cyclic thermo mechanical load. Therefore, mechanical properties are of great importance for producing reliable solder joints as these joints are not only for conducting electricity but also responsible for providing good mechanical support to electronic devices[10].

Metals and many other materials are strain-rate sensitive. Solder joints in electronics applications experience high strain rate deformation under conditions such as accidental drop/impact[11]. Therefore, strain rate effect on mechanical behavior of solder joint is another important issue. The effect of strain rate on mechanical properties of solder joint has been investigated and it was concluded that strain rate has great role in affecting the mechanical properties[12]. Low strain rate were normally defined at less than 1/sec and any change in strain rate to the exposed electric components altered these properties[13].

The current work is focused on the effect of thermal aging on the microstructural changes in terms of IMCs growth at different temperature. The study is expanded from as-cast samples to isothermally aged samples at an elevated temperature of 140°C for tensile testing to calculate mechanical properties. Mechanical properties at high strain rates upto 40/s are also extracted. Furthermore, precise mathematical equations having reciprocal relation with thermal aging and power law relation with strain rates in terms of mechanical properties have also been presented with small error.

EXPERIMENTAL PROCEDURE

Synthesis of Samples

The samples of Pure Sn, Ag and Cu were obtained in powder form from Beijing Gao Ye Technology Co. Ltd. The target compositions were obtained by weighing the pure metals in proportion of weights to get a good composition of sample and casted by putting them in Alumina crucible. A die used for tensile specimens has been designed in such a way that it provides high cooling rate during solidification process. Before pouring the molten metal into the die, it was heated for about 45 minutes. The crucible with the metals was then heated in the furnace to ensure complete melting. The furnace had a stirring arrangement to ensure proper mixing of the constituent metals. The molten material was then poured into the preheated die. The alloy used in this work has the following elemental composition given in Table 1.

Table 1: Selected SAC composition

Sn (wt %)	Ag (wt %)	Cu (wt %)
96.5	3.0	0.5

Characterization

For the investigation of microstructure examination, the specimen is cut in to three pieces and mounted in bakelite for proper handling and to avoid any distortion. Initial grinding is then performed to remove the oxidized layers and big scratches using metallurgical silicon carbide SiC water proof sand papers in grit size 350, 600, 800, and 1200. To avoid damage to surface when heat is generated during sand paper grinding process, tap water for lubrication purpose is used. After 1200 SiC sand paper grinding, the polishing process with polycrystalline diamond suspension as the abrasive particle size of 6 µm, 1 µm and 0.25 µm on cotton silk paper is carried out. The sample is then cleaned by distilled water to remove any residue left during polishing and finally etched with 95% ethanol and 5% hydrochloric acid solution. Subsequently, the samples are placed for two minutes in sputter coater and vacuum evaporator for gold coating to make it conductive. SEM images at different location and magnification have been taken using scanning electron microscopy. EDX analysis is also carried out to verify the chemical compositions. The SEM images are further analyzed by ImageJ software to examine the size of the IMCs particles. For thermal aging, the samples are exposed at different levels of temperatures. The microstructures of the as casted and thermally aged samples are compared for investigations.

Tensile Testing

Tensile tests were finally carried out using UTM to find out the mechanical properties from the stress- strain curve. The data has been taken at room temperature. At least 2 samples were used for each test and a custom fixture was used for gripping the specimen before loading. Rectangular tensile specimens with uniform dimension were used in this study obtained after die casting process. The dimensions of the specimens were 4 mm wide and 2 mm thick which made the specimens stronger and thus polishing quite easy. Mechanical properties were studied before and after thermal aging at different levels of temperature. Mechanical properties including YS and UTS were also investigated at different strain rates.

RESULTS AND DISCUSSION

Effect of Thermal Aging on Intermetallic Compounds Particle Size

The microstructure of SAC305 in this study is investigated using SEM images taken at various magnifications shown in Figure 1. The chemical composition confirmed by EDX is shown in Figure 2. The black zone in SEM images is composed of Sn and the white particles are the IMCs (Ag and Cu rich). The Cu based IMCs can be easily distinguished from Ag based since Cu are much darker i.e. grey in color than Ag based IMCs shown in Figure 1, which is also in consistent with[14]. The Cu based IMCs are Cu_6Sn_5 and Ag based IMCs are Ag_3Sn. The elemental peaks of these IMCs are also verified by EDX as shown in Figure 3 (a) and (b). These IMCs are hard and brittle in nature as compared to soft Sn matrix and dictate the mechanical properties of solder alloys. Therefore, the growth of these IMCs is responsible for the coarsening of the microstructure[15].

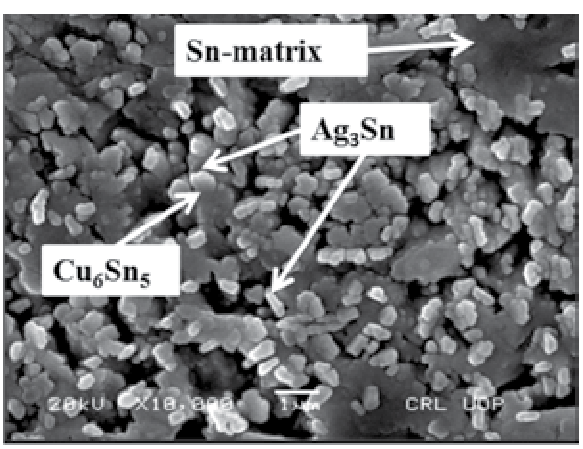

Figure 1: SEM images of SAC305.

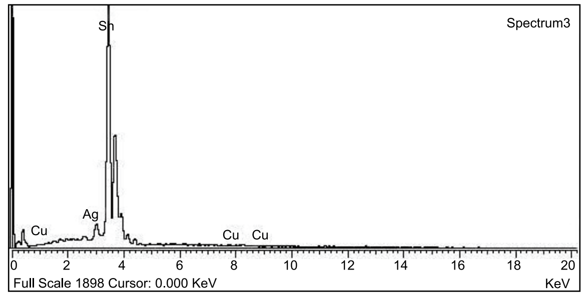

Figure 2: EDX of SAC305

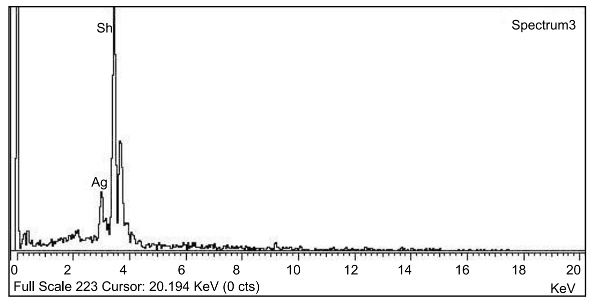

Figure 3: (a) EDX peaks for Ag3Sn

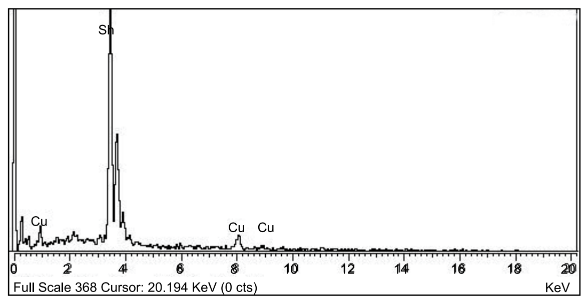

Figure 3: (b) EDX peaks for Cu_6Sn_5

Thermal aging is the prolong exposure of material at elevated temperature and responsible for coarsening of the microstructure by increasing the average IMCs particle size which ultimately results in degradation of the material properties[16]. Therefore, thermal aging is responsible for the evolution of IMCs particles average size[17]. Since aging temperature selected in this work are 60 °C, 100 °C and 140 °C for 50 hours. Therefore, the as-casted and thermally aged samples of SAC305 alloy are analyzed under SEM to investigate the effect of microstructural changes as shown in Figure 4. Since the microstructure evolution in this study is observed in terms of IMCs particle average size as function of aging temperature. Therefore, for further examination of IMCs particle size, SEM images of as-casted and thermally aged alloys at different temperatures are analyzed using ImageJ software, shown in Figure 5. The data obtained from ImageJ has been taken several times with 5% error in threshold adjustment presented in Figure 6.

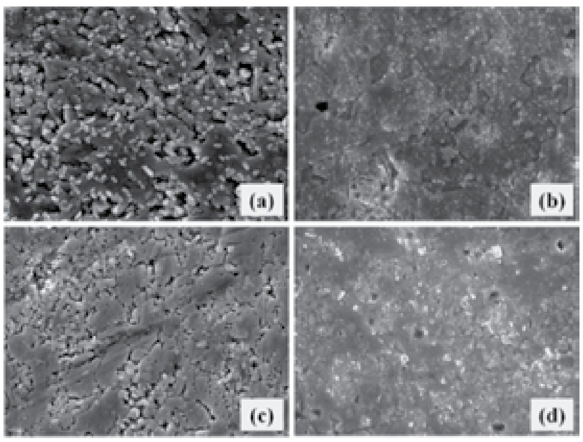

Figure 4: SEM of SAC305 (a) as-casted and thermally aged at (b) 60 °C (c) 100 °C (d) 140 °C

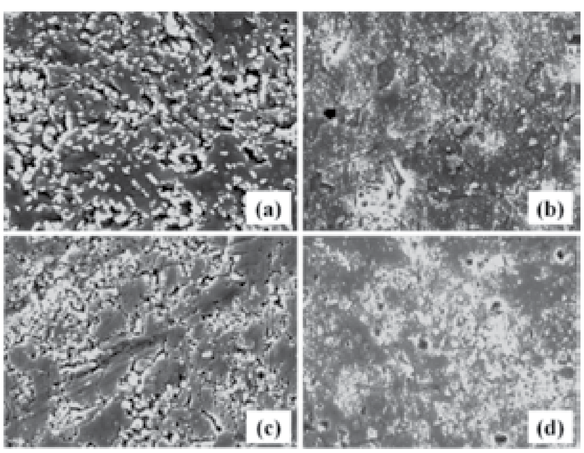

Figure 5: SEM images analyzed in ImageJ (a) as-casted and thermally aged at (b) 60 °C (c) 100 °C (d) 140 °C

It has been observed that the average IMCs particle size increase from the as-casted to thermal aging samples at 60 °C, 100 °C and 140 °C and small difference is obtained between circularity and other parameters which show that there is uniform distribution of the particles in the solder alloy. This also shows that LFS alloys are highly microstructure dependent which changes considerably during its life time. Therefore, it is reasonably expected that after thermal aging the IMCs particle size increases which results in coarsening of the

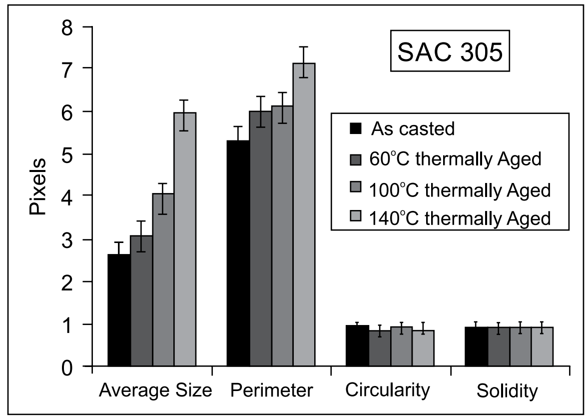

Figure 6: Details of ImageJ analysis

microstructure. To justify this investigation, tensile tests have been performed on tensile specimen for as casted and thermally aged specimens to link microstructure changes with mechanical properties.

Effect of Thermal Aging on Mechanical Properties

Solder assemblies when exposed to high temperature during services are also subjected to tensile loading. Therefore, mechanical properties like YS, UTS and ductility becomes very important in determining the maximum extend of tensile deformation which the solder joint can sustain before failure[18]. These mechanical properties are also affected by the microstructure evolution[19]. In this study, the tensile specimens were tested to extract YS and UTS from tensile testing. The stress-strain curve for the as-casted and thermally aged specimen is shown in Figure 7 and all values are summarized in Table 2.

A significant decrease in the YS and UTS has been observed from the as-casted to the thermally aged samples. This means that as the aging temperature increases, the mechanical properties degrades. This reduction in YS and UTS is due to the coarsening of the microstructure as a result of IMCs growth which causes less number of grain boundaries for blocking of dislocation movement which results an early failure, thus reduces the solder joint reliability and hence a decrease in strength is occurred which was also reported in[20]. In order to further discuss these properties, mathematical relations based on experimental values is developed between aging temperature and mechanical properties. Eqs (1) – (2) are valid for satisfying and predicting values of YS and UTS for the given values of aging

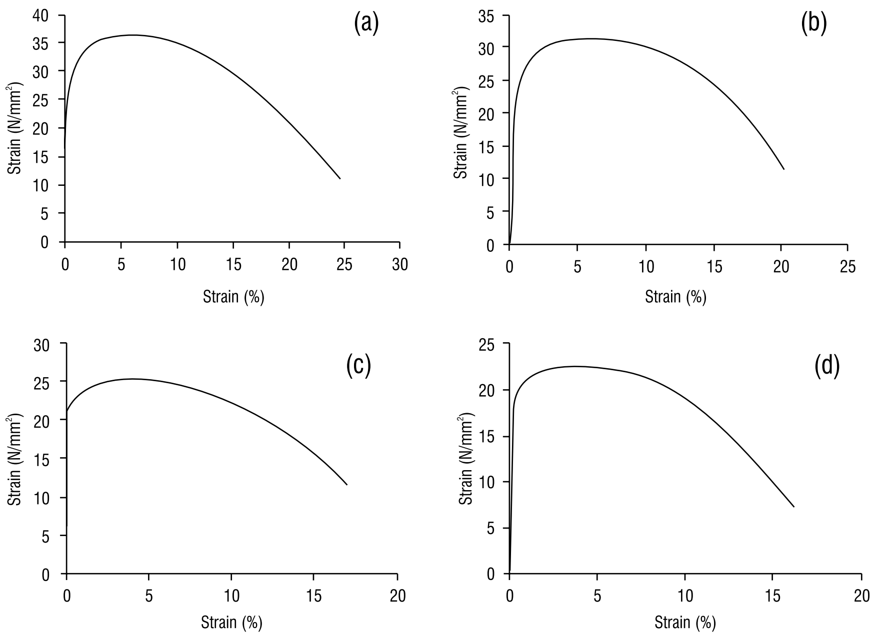

Figure 7: Stress strain curves of SAC305 (a) as-casted and thermally aged at (b) 60 °C (c) 100 °C (d) 140 °C

Table 2: YS and UTS at different aging temperature

Solder Alloy	Condition	YS (N/mm2)	UTS (N/mm2)
SAC305	as casted	31.080	36.240
	60◦C aged at 50 h	24.478	31.670
	100◦C aged at 50 h	22.530	25.070
	140◦C aged at 50 h	19.850	22.740

temperature.

$$YS_{(SAC)} = 1/(A_1 + A_2 * T_g) \quad (1)$$

$$UTS_{(SAC)} = 1/(B_1 + B_2 * T_g) \quad (2)$$

Eqs (1) - (2), satisfied that on increasing aging temperature, the level of YS and UTS decreases which is in consistent with our experimental results. Where T_g is the aging temperature and A_1, A_2, B_1, B_2, are the constants for the YS and UTS. The details of these constants are given in Table 3. It is cleared in Table 4 that the experimental data are closely linked with the predicted values obtained from Eqs (1) - (2) with minimum error. The predicted values of mechanical properties are accurate with experimental data with maximum 5.89 % and minimum 1.59 % for YS and 3.60 % maximum and 0.86 % minimum for UTS.

Table 3: Mathematical constants

Solder Alloy	YS		UTS	
SAC305	A1	A2	B1	B2
	2.88 x 10-2	1.63 x 10-4	2.36 x 10-2	1.49 x 10-4

Table 4. Predicted data at different aging temperature

Solder Alloy	Condition	Calculated values		% Errors	
		YS (N/mm2)	UTS (N/mm2)	YS	UTS
SAC305	as casted	30.42	36.55	2.13%	-0.86%
	60°C aged at 50 h	25.92	30.71	-5.89%	3.02%
	100°C aged at 50 h	22.17	25.97	1.59%	-3.60%
	140°C aged at 50 h	19.37	22.50	2.41%	1.06%

Effect of Strain Rate on Mechanical Properties

Electronic components when subjected to shock and vibration experienced strain rate of 1 to 100/s. Also, there is little data available in literature for commonly used SAC305 solders in the strain rate range of 1/s to 100/s[21]. Therefore, experimental works on strain rates greater than 1/s is mainly aimed in this work to investigate the related behaviors of solders. Therefore, similar tensile specimens were also used to study the effect of strain rate on mechanical properties at 10/s, 20/s, 30/s and 40/s. The stress-strain curves under different strain rates are shown in figure 8 and the extracted data is summarized in Table 5.

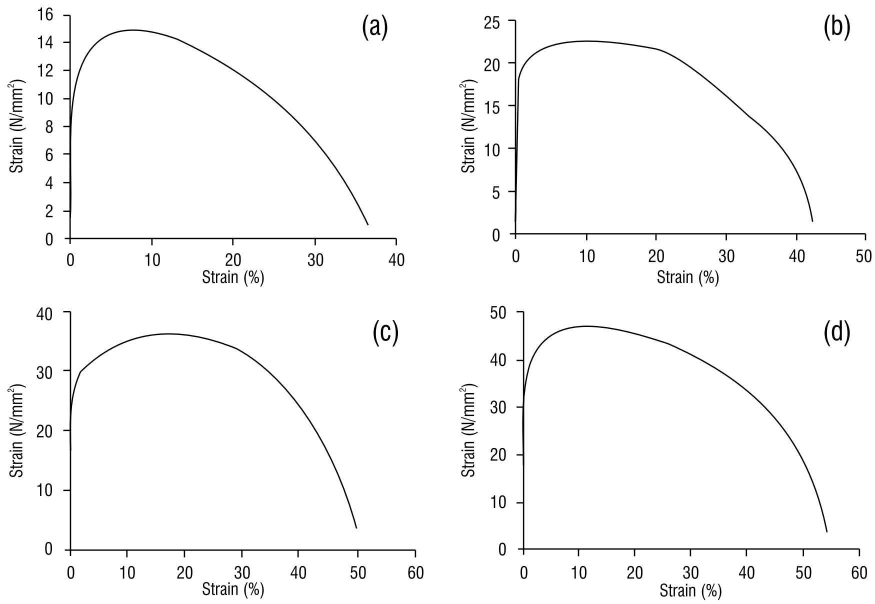

Figure 8: Stress strain curves of SAC305 under high strain rate (a) 10/s (b) 20/s (c) 30/s (d) 40/s

Table 5: YS and UTS at different strain rates

Solder Alloy	Condition	YS (N/mm2)	UTS (N/mm2)
SAC305	10/s	10.52	15.05
	20/s	20.17	23.12
	30/s	30.77	36.54
	40/s	41.02	46.51

It has been observed from the experimental values that strain rate has direct relation with mechanical properties because a significant increase in YS and UTS has been observed as the strain rate increases. This increase at high strain rates is due to less creep deformation which increases the strength of the solder joint since at lower strain rates creep deformation is more and ultimately strength reduces which was also reported in[22]. From the above experimental data, a mathematical relationship between strain rate and mechanical properties is developed. These mathematical relations will help in predicting the mechanical properties with different strain rates. The strain rate dependent mechanical properties for YS and UTS are given in Eqs (3) – (4) as follows:

$$YS_{(SAC)} = C_1 \ (\varepsilon - C_2)C_3 \qquad (3)$$

$$UTS_{(SAC)} = D_1 \ (\varepsilon - D_2)D_3 \qquad (4)$$

The above equations satisfy the values of YS and UTS for the different strain rates obtained from the experimental work, where ε is the strain rate and C_1, C_2, C_3, D_1, D_2, D_3 are constants of equations. The details of these constants are shown in Table 6. These mechanical relations can be used for predicting material properties of the LFS under different strain rates. It can be seen that the data obtained from mathematical equations are accurate with available experimental data with maximum 0.8% and minimum 0.2% error for the predicted YS and maximum 5.6% and minimum 0.9% for the predicted UTS. The calculated values and errors obtained from mathematical Eqs. (3) - (4) are presented in Table 7.

Table 6. Mathematical constants

Solder Alloy	YS			UTS		
	C1	C2	C3	D1	D2	D3
SAC305	7.3474 x 10-1	-1.7482	1.0783	2.7212 x 10-1	-1.0890 x 101	1.3107

Table 7: Predicted data and errors under various strain rates

Solder Alloy	Condition	Calculated values		% Errors	
		YS (N/mm2)	UTS (N/mm2)	YS	UTS
SAC305	10/s	10.47	14.62	0.5%	2.9%
	20/s	20.34	24.40	-0.8%	-5.6%
	30/s	30.58	35.25	0.6%	3.5%
	40/s	41.09	46.95	-0.2%	-0.9%

CONCLUSIONS

In this study, the evolution of microstructure analysis of SAC305 LFS alloy in association with mechanical properties has been performed at various thermal aging temperatures and high strain rates. In addition to experimental study, mathematical relations for the prediction of mechanical properties at various aging temperatures and strain rates have also been presented. From the study, it is investigated that there are variations in the mechanical properties due to different thermal aging temperatures and strain rates. The microstructure of SAC305 becomes coarsen as the aging temperatures increase due to the growth of IMCs particle size which ultimately results in degradation of YS and UTS. The YS and UTS are highly strain rate dependent and increased linearly with increasing strain rate due to less creep deformation. The aging temperature dependent and strain rate dependent mathematical relations are developed with minimum errors which can be used to predict the mechanical properties and a good fit of the predicted values with the experimental results is observed.

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