Thermomechanical Properties of PbSbSn Alloys

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Resistance welding and soldering processes of parts made of PbSbSn alloys in the industry of lead-acid batteries, power engineering, electronics and chemical industry require a detailed research of thermomechanical properties of these alloys that depend on temperature. Data on thermal conductivity are acquired from experiments with a laser pulse method, and based on mathematical analysis of non-stationary one-dimensional heat conduction through an infinite flat adiabatic wall. Data on thermal conductance are determined from measurements of the temperature increase rate on one side of a sample. The melting temperature, latent heat and specific heat capacity are determined by calorimeter. The coefficient of linear expansion is determined by using a high-temperature dilatometer.

Temperature dependence of tensile testing mechanical properties is also given. The experimental results are presented for the chosen PbSbSn alloys in which the Sb content is limited to 3.5 % and the content of Sn to 0.5 %. All results of temperature dependence of thermomechanical properties are given in graphical and tabular form.

Keywords: *PbSbSn alloys, thermal conductivity, linear expansion coefficient, melting temperature, latent heat, mechanical properties.*

1. INTRODUCTION

In order to completely define the processes for resistance welding and soldering of parts made of PbSbSn alloys in the industry of lead-acid batteries, power engineering, electronics, and chemical industry [1-3], a detailed research on the thermomechanical properties of alloys that depend on temperature is carried out. This paper is aimed at presenting the results of the research for alloys of chemical contents given in Table 1.

Table 1. Chemical contents of the alloys

No.	Alloy (internal code)	Alloying elements			
		Pb	Sb	Sn	Other
1	SDS	96.12	3.28	0.43	0.17
2	SD	96.30	3.40	0.06	0.24
3	A4	96.95	2.67	0.12	0.26
4	DD	97.56	2.00	0.27	0.17

2. TEMPERATURE DEPENDENCE OF THERMAL PROPERTIES FOR PbSbSn ALLOYS

2.1 Thermal conductivity

Thermal conductivity data, λ, are acquired from experiments performed at the Institute for Nuclear Sciences in Vinča, Laboratory for Thermal Engineering and Energy.

A laser pulse method was used for experimental determination, according to the ISO standard, based on mathematical analysis of the non-stationary one-dimensional heat conduction through an infinite flat adiabatic wall. Data on thermal conductance are determined by measuring the rate of temperature increase on one side of a sample, while the other side of the sample is exposed to short duration laser pulses. Samples are in the shape of tablets, of the size Ø10 mm × 3 mm. Taking into account the geometry and the treatment of received samples, the maximal measurement uncertainty for thermal conductivity is estimated to be ± 5 %.

The acquired results are given in Table 2 and graphically depicted in Figure 1.

Table 2. Temperature dependence of thermal conductivity λ

t [°C]	λ [Wm^{-1}K^{-1}]			
	DD	A4	SDS	SD
20	30.37	30.1	31.51	28.51
40	30.17	29.76	31.12	28.22
60	29.94	29.38	30.69	27.89
80	29.68	28.97	30.24	27.54
100	29.39	28.53	29.74	27.16
120	29.07	29.06	29.21	26.75
140	28.72	27.56	28.64	26.31
160	28.35	27.02	28.04	25.84
180	27.95	26.45	27.4	25.34
200	27.52	25.85	26.73	24.81
220	27.06	25.21	26.02	24.25
240	26.57	24.54	25.26	23.66
260	25.88	23.95	24.43	23.70
280	25.01	23.32	23.73	22.83
300	24.32	22.62	23.00	22.22
320	18.1	16.8	17.2	16.4
340	18.1	16.8	17.2	16.4
360	18.1	16.8	17.2	16.4
380	18.1	16.8	17.2	16.4
400	18.1	16.8	17.2	16.4

Received: December 2009, Accepted: February 2010
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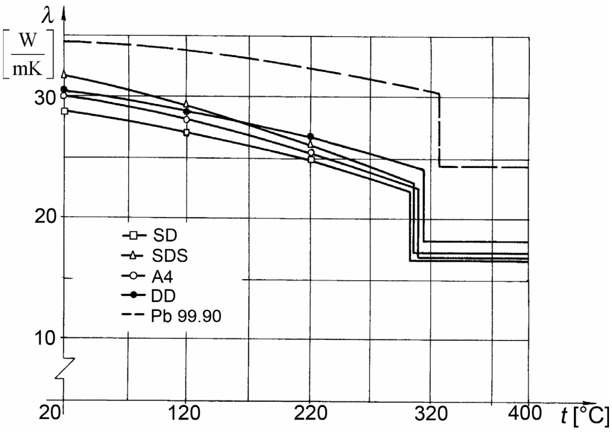

Figure 1. Temperature dependence of thermal conductivity *λ*

As can be seen in Figure 1, the thermal conductivity tends to drop for the lead alloys, compared to the 99.90 % Pb. The diagram depicts a gradual and almost linear drop in thermal conductivity with temperature for each alloy, with a sharp drop at melting temperature, followed by a constant value for the liquid state. As expected, the SD alloy (with the highest Sb content) has the lowest thermal conductivity value, whilst higher thermal conductivity is evident of the DD alloy (of the lowest Sb content). The somewhat faster gradual drop rate in the thermal conductivity for alloy SDS can be attributed to a relatively higher Sn content.

Table 3. Melting temperature t_r

No.	Alloy (internal code)	Temperature [°C]			
		Samples			Mean value
		1	2	3	
1	SDS	301.7	304.5	303.4	303.2
2	SD	304.1	306.1	301.7	304
3	A4	308.4	310.2	306	308.2
4	DD	313.7	311.3	314	313

Table 4. Latent heat

Latent heat [kJ/kg]	PbSb alloy (internal code)					
	SD	SDS	A4	DD	Pb	Sb
	28.2	27.9	27.1	26.2	23.4	163.8

2.2 Melting temperature point

The melting temperature is determined by using a calorimeter of the type: METTLER TA 3000 SYSTEM (at the laboratory – RMHK Trepča dd in Kosovska Mitrovica) on three samples for each alloy.

The results are given in Table 3, and a characteristic diagram for the alloy DD is shown in Figure 2.

As expected, Sb content is responsible for lowering of the melting temperature in all of the tested alloys.

2.3 Latent heat, specific heat capacity, coefficient of linear expansion

Latent heat and specific heat capacity are determined experimentally by using a DSC calorimeter of the type: METTLER TA 3000 SYSTEM, at the laboratory RMHK Trepča dd, Kosovska Mitrovica, on 3 samples for each alloy. The mean values for these quantities are given in Tables 4 and 5 and in a diagram, Fig. 3.

The linear expansion coefficient is also determined experimentally by using a high-temperature dilatometer of the type: Bähr Gerätebau GmbH, Type 702s, at the Laboratory for Metallic Materials, Centre for Multidisciplinary Studies – the Serbian Academy of Sciences and Arts (SASA), Belgrade. The temperature dependence of the linear expansion coefficient (mean values) for the tested alloys is shown graphically in Figure 4.

One concludes that latent heat is affected by the Sb content. Alloys with higher Sb have higher latent heat values. Generally, PbSb alloy mixtures with Sb have an increased latent heat.

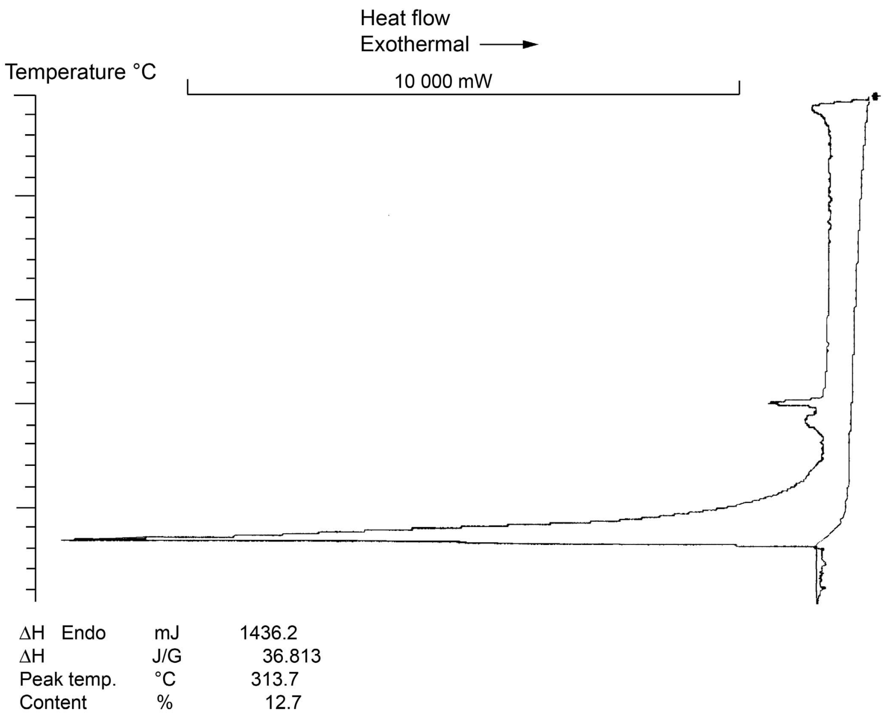

Figure 2. Diagram for the determination of melting temperature point

Table 5. Temperature dependence of the specific heat capacity *c*

No.	Alloy (internal code)	c [kJ/kgK]						
		0 °C	20 °C	100 °C	200 °C	300 °C	*t* liquid	400 °C
1	SD	0.13	0.131	0.136	0.141	0.145	0.167	0.158
2	SDS	0.13	0.131	0.136	0.141	0.145	0.167	0.158
3	A4	0.129	0.13	0.135	0.14	0.144	0.166	0.157
4	DD	0.129	0.13	0.135	0.14	0.143	0.165	0.156

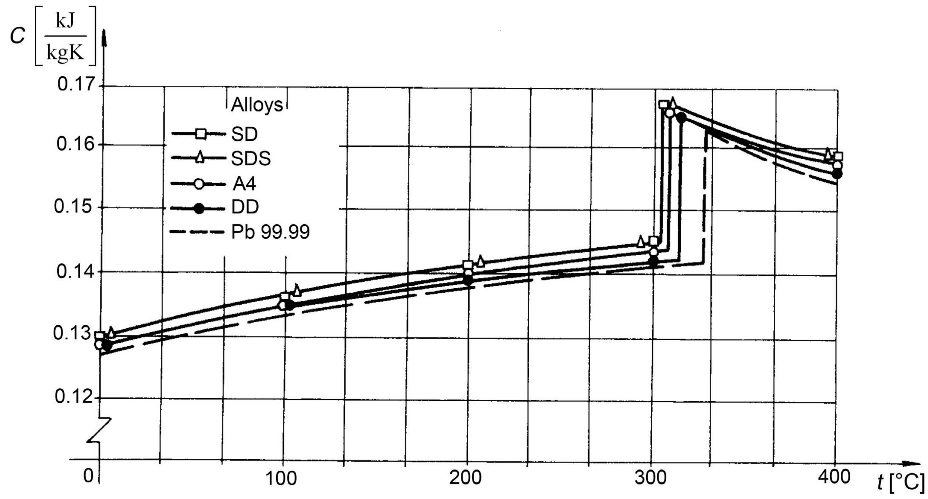

Figure 3. Temperature dependence of the specific heat capacity

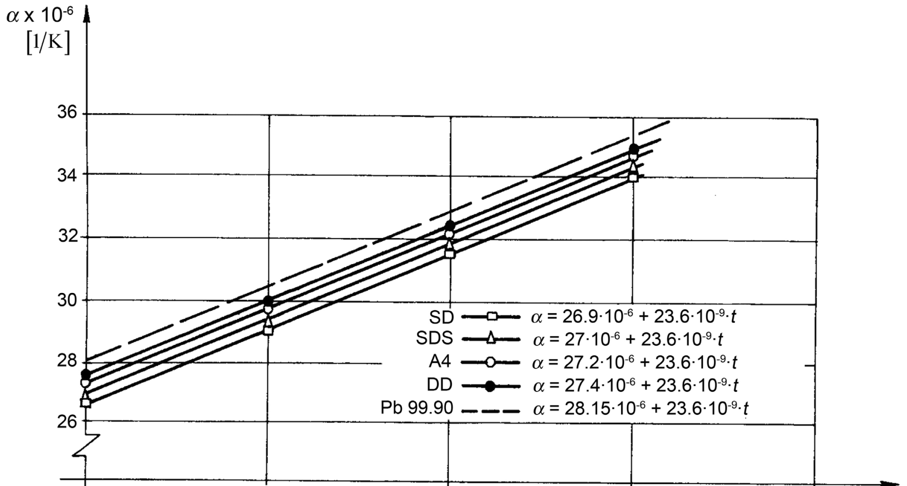

Figure 4. Temperature dependence of the coefficient of linear expansion *α*

Alloy contents practically have very little influence on the temperature dependence of specific heat capacity, as indicated in Figure 3 and Table 5, although the Sb content slightly increases heat capacity, and slightly decreases linear expansion (Fig. 4).

3. TEMPERATURE DEPENDENCE OF MECHANICAL PROPERTIES OF PbSbSn ALLOYS

Temperature dependence of maximal load F, elongation Δl, and true cross-section area at rupture location A_K, are experimentally determined on a tensile testing machine of the type Fp 10/1 mit T250, at RMHK Trepča dd in Kosovska Mitrovica. Results are shown graphically in Figures 6-12. Based on these results and on the sample characteristics, also determined are:

- R_m – ultimate tensile strength,
- R_e – yield strength,
- E – modulus of elasticity, and
- ν – Poisson's ratio.

The testing conditions included:

- Operating load range up to 10 kN;
- Ratio of values on the diagram 5:1;
- Temperature conditions 20 °C, 120 °C, 220 °C.

Number of samples taken from each alloy: 20. The appropriate specimen type used for performing these tests is shown in Figure 5.

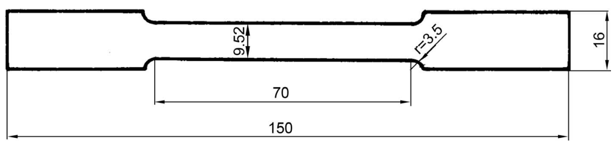

Figure 5. Tensile test specimen characteristics (*B* = 2 mm; A_o = 19.04 mm^2)

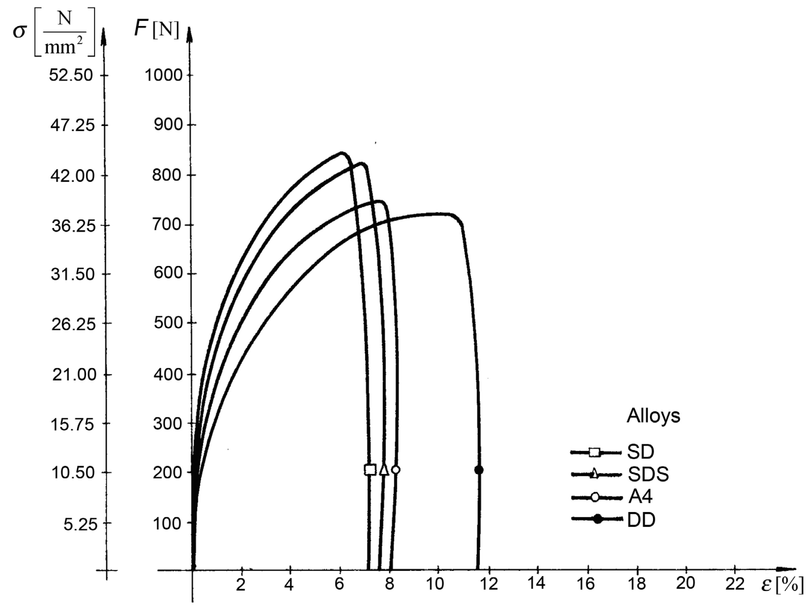

Figure 6. Tensile test diagram, load *F*, stress *σ* and percent elongation *ε*, for the PbSbSn alloy at *t* = 20 °C

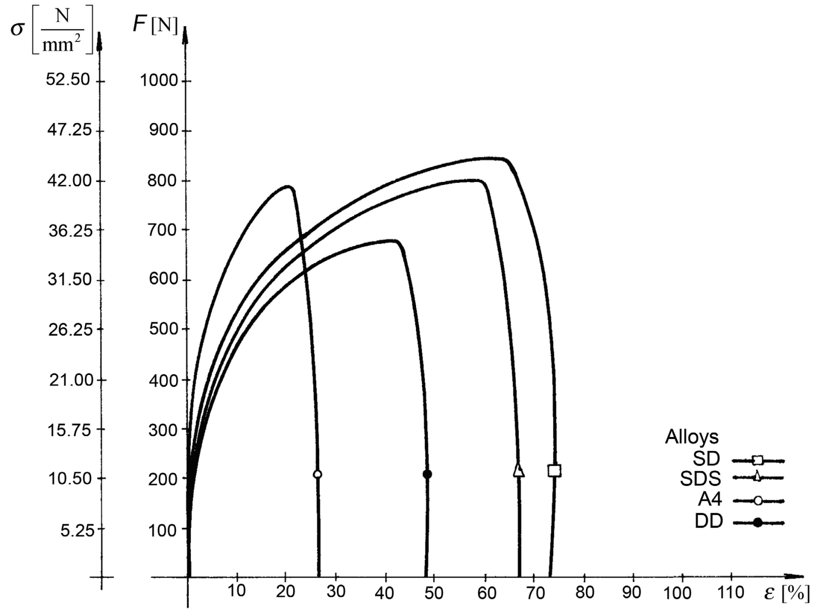

Figure 7. Tensile test diagram, load *F*, stress *σ*, and percent elongation *ε*, for the PbSbSn alloy at *t* = 120 °C

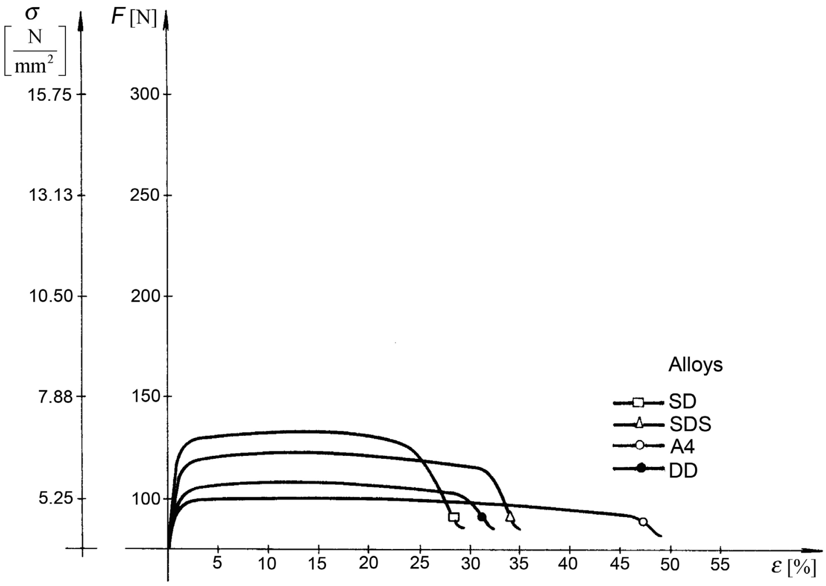

Figure 8. Tensile test diagram, load *F*, stress *σ*, and percent elongation *ε*, for the PbSbSn alloy at *t* = 220 °C

Results of the tested mechanical properties are depicted in Figures 6-8, showing the alloys' stress-strain diagrams (σ-ε) for testing temperatures of 20 °C, 120 °C, and 220 °C, in respect. The diagrams have the load (F) axis added for sake of comparison.

Apparently, the Sb content in the tested alloys influences the stress-strain curves such that higher Sb content increase the ultimate strength level, while the material plasticity (depicted by strain, ε) is decreased (Fig. 6).

Owing to the tested thermal properties and how they are affected by Sb content, alloy stress-strain material behaviour at elevated temperatures of 120 °C and 220 °C is shown in Figures 7 and 8, in respect. Material plasticity is highly affected at 120 °C due to the Sb content in contrast to ultimate strength (Fig. 7). At a higher temperature of 220 °C softening mechanisms are dominant in the material structure of alloy A4, with a high increase in plasticity and a rapidly diminishing material strength.

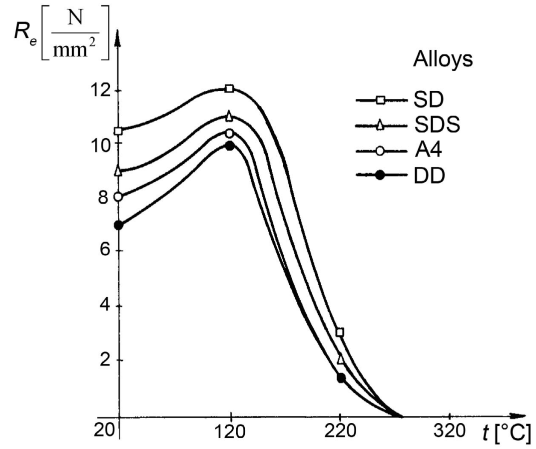

Figure 9. Temperature dependence of yield stress, R_e

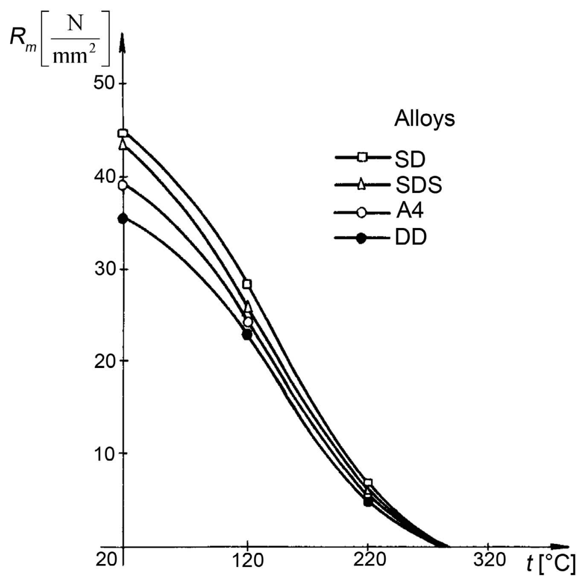

Figure 10. Temperature dependence of ultimate tensile strength, R_m

Figures 9-12 show the diagrams of the temperature dependence of yield stress (R_e), ultimate tensile strength (R_m), modulus of elasticity (E), and Poisson's ratio (v), in respect. Analysing these diagrams one concludes that all of these mechanical properties are in consistence with alloy content levels of Sb, except for Poisson's ratio (Fig. 12). The temperature dependence of Poisson's ratio for alloy A4, in this case, noticeably deviates compared the other tested alloys. Interestingly, Poisson ratios for all of the tested alloys have a minimum at 120 °C, where alloys SD, DD, and SDS acquire Poisson ratio values i.e. approximately to that of steel (0.3).

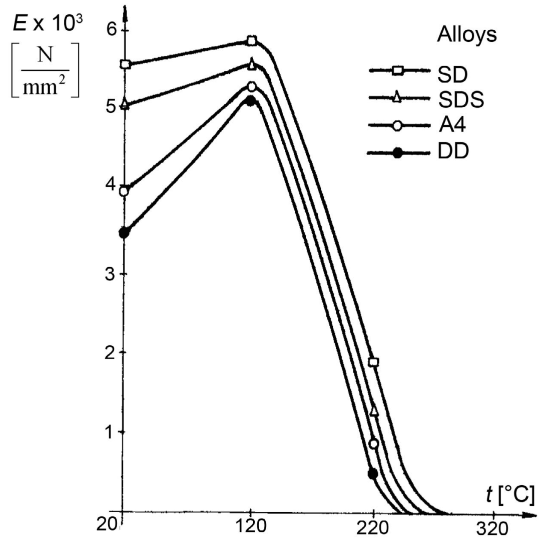

Figure 11. Temperature dependence of elasticity modulus, E

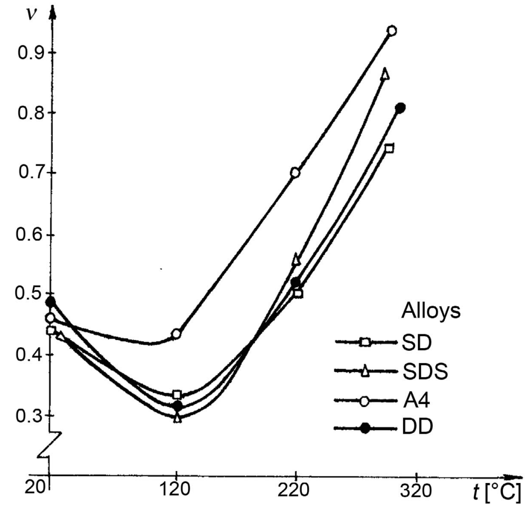

Figure 12. Temperature dependence of Poisson's ratio, v

3.1 Hardness

Tests are performed on 10 samples from each of the alloy types at temperatures 20 °C, 120 °C and 220 °C, according to the Shore D hardness test, and the results are given in Tables 6, 7 and 8.

Table 6. Hardness of PbSbSn alloy at t = 20 °C

Alloy type		Shore D hardness										Mean value
No.	Internal code	Specimens										
		1	2	3	4	5	6	7	8	9	10	
1	SD	77	80	79	77	80	77	75	79	79	79	78.5
2	SDS	75	80	74	76	76	76	75	77	78	78	76.5
3	A4	75	75	75	79	77	75	76	79	76	78	76.5
4	DD	76	77	75	77	77	77	77	76	76	76	76.4

Table 7. Hardness of PbSbSn alloy at t = 120 °C

Alloy type		Shore D hardness										Mean value
No.	Internal code	Specimens										
		1	2	3	4	5	6	7	8	9	10	
1	SD	75	77	76	76	75	77	75	78	76	74	75.9
2	SDS	76	75	75	78	77	77	76	78	76	78	75.1
3	A4	75	76	75	72	72	74	75	76	74	74	74.3
4	DD	70	71	73	73	73	73	76	73	74	75	73.1

Table 8. Hardness of PbSbSn alloy at t = 220 °C

Alloy type		Shore D hardness										Mean value
No.	Internal code	Specimens										
		1	2	3	4	5	6	7	8	9	10	
1	SD	70	70	70	70	71	71	70	72	72	73	70.9
2	SDS	72	74	73	72	74	72	69	60	71	72	70.8
3	A4	66	66	67	71	74	73	71	73	70	68	69.9
4	DD	68	72	69	67	69	71	70	68	71	72	69.7

4. CONCLUSION

The level of knowledge and understanding of phenomena in processes such as thermal, mechanical and electrical that define the resistance spot welding process, as well as the mechanical and metallurgical characteristics of high temperature techniques, are essential for the manufacturing process and mathematical modelling description. The increase in quantity and quality of data on physical and mechanical properties of metals at temperatures near to melting, or within the solidus and liquidus temperature interval, is of particular importance.

Experimental testing of thermal and mechanical properties of PbSbSn alloys, usually joined by resistance welding, have lead to certain conclusions.

Generally, most thermal properties (thermal conductivity, melting temperature and linear expansion) decrease with small additions of the Sb alloy content.

All effects of increased mechanical properties of the tested alloys by adding small Sb amounts are totally lost as the liquidus temperature is approached.

At room temperature, added Sb content strengthens the alloy on the account of a lowered plasticity. Softening mechanisms become evident at 120 °C without any noticeable loss in material strength, and much more pronounced at 220 °C, with the exception of alloy A4.

As can be concluded here, and according to some data in literature [1], the group of PbSbSn alloys containing about 2.5 % Sb seem to be less affected by both thermal and mechanical treatment at temperatures of 120 °C or higher.

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ТЕРМОМЕХАНИЧКЕ ОСОБИНЕ НЕКИХ PbSbSn ЛЕГУРА

Драган Калаба, Дејан Чикара, Зоран Радаковић

Процеси електроотпорног заваривања и лемљења делова израђених од легура PbSbSn у индустрији акумулатора типа олово-киселина, у енергетици, електроници и хемијској индустрији захтевају детаљна истраживања термомеханичких особина ових легура, које зависе од температуре. Експериментални резултати коефицијента провођења топлоте, добијени су употребом методе ласерског импулса, заснованој на математичкој анализи нестационарног једнодимензијског провођења топлоте кроз бесконачан раван адијабатски зид. Резултати топлотне проводљивости добијени су из мерења брзине пораста температуре на једној страни епрувете. Температура топљења, латентна топлота и специфични топлотни капацитет одређени су коришћењем калориметра. Коефицијент линеарног ширења је одређен коришћењем високо температурног дилатометра.

Дата је температурска зависност испитиваних механичких особина. Експериментални резултати су представљени за дате PbSbSn легуре, у којима је садржај Sb ограничен до 3,5 %, а садржај Sn до 0,5 %. Сви добијени резултати температурске зависности термомеханичких особина су представљени графички и табеларно.