



Influence of low melting point alloy on strength properties of epoxy resin

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ABSTRACT

Purpose: The aim of the work was to determine the effectiveness of the modification of the epoxy resin strength and elasticity by Wood's alloy particles addition.

Design/methodology/approach: Manufacture method of thermosetting polymer matrix composite materials reinforced with the Wood's alloy particles was searched. First of all mixing conditions were differentiated to obtained good dispersion of reinforcement in polymeric matrix. Microscopic examination of samples cross-sections was performed in order to search the structure of prepared composite materials. The strength and elasticity of composites were investigated using compression test.

Findings: The results of the compression tests and their analysis are presented. The paper also presents microscopic images of structure of prepared composites.

Research limitations/implications: Presented research was limited to composites in the form of small samples. The developed technology of this type of composites preparation is limited to small volumes because of sedimentation process action.

Practical implications: Materials with low melting point alloy content show many possible applications. First of all they are materials with higher thermal conductivity and electrical conductivity than standard polymeric materials. Conducted research programme showed that these materials exhibit also good mechanical properties.

Originality/value: Preparation method of thermosetting polymer matrix composite materials reinforced with the Wood's alloy particles fabricating method was developed. Composites with good mechanical properties were obtained. Microscopic examination of samples cross-sections in order to search the structure of prepared composite materials was performed. Composites with small particles evenly dispersed in epoxy matrix were achieved.

Keywords: Engineering polymers; Composites; Low-melting-point alloy; Fusible alloys; Epoxy resin

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PROPERTIES

1. Introduction

In many cases the use of a polymer material is the most proper choice. However, sometimes we need a material with

similar characteristics to pure metals or alloys but with many features of polymer materials. A typical example are housings for electronic devices. Electronic equipment without metal protection are vulnerable to an electronic noise from electric and electronic

devices in environment. The solution is the application of metallic sheets or fabrics but also polymer-metal composites, also known as high density, heavy-weight or metal-filled polymers.

Evenly dispersed in polymeric matrix fine metallic particles have found numerous industrial applications. There are many specific and unique advantages to be gained through the utilization of metallic particles in organic adhesives. The choice of a metal filler may be influenced by functional, economic or aesthetic considerations [1].

Several types of metallic fillers are being used as reinforcement in polymer composites [2-7]. The most widely used fillers are copper, aluminium, and silver particles, but metal fibres are also being introduced as a potential replacement for carbon, glass or organic fibres for some applications. Polymers with metal fibres are also applied as shielding layers in electronic devices such as mobile phones. The low cost together with electric conductivity and high mechanical properties of steel filaments compared to the traditional reinforcement systems is the main motivation to explore the potential and reliable application of polymers reinforced by steel filaments for civil engineering, automotive and electronic industries, and others applications [8].

Polymer composites with low content of a metallic filler can form materials with high thermal conductivity and mechanical strength higher than polymeric matrix.

Metals and polymers can be combined in several ways to form polymer-metal composites. Most metal surfaces are protected by polymeric materials. Polymeric layers create a corrosion protection or decorative coatings on many metallic surfaces. Another way is mixing metal fine particles with polymer materials. This can be realized in several methods but two are the most frequently applied.

Firstly, one can mix solid metal particles with liquid polymer materials and subsequently solidify polymer matrix in the way dependant on the nature of the polymer. Secondly, one can mix together fine solid metal particles and powders of polymer materials. In the second stage of this method the polymer have to be molten and then cooled, when polymer is thermoplastic, or cured when polymer is thermosetting. Low-melting alloy epoxy composites made using the last method were presented in our previous papers [9,10].

Unexpected results may arise from combinations of metals and polymeric materials. Metal-organic complexes for example may facilitate degradation processes. It is the case when small amounts of iron or zinc are present in formulations of polyvinyl halides. On the other hand metals may play positive functions at the interfaces, for example as an accelerators to enhance the curing process [1].

The use of metal particles in the polymer matrix creates three main problems:

1. The presence of rigid metal powders in molten or liquid polymer greatly decreases processing ability of the composite in comparison with the neat polymer due to viscosity increase. In highly filled systems yielding is also observed. Additionally, during the processing of the hard particles dispersed in the polymeric matrix accelerated abrasive wear of machines parts and moulds is usually observed.
2. The metal powders, especially those in nanoscale, are easily oxidized during mixing process what affects interactions

between polymer and filler and in this way changes properties of the composites. The oxide shell around pure alloy change also particle's properties, especially thermal and mechanical properties.

3. During the formation of polymer metal composites arises problems resulting from difference in densities of both materials. Density differences, of up to 8-9 times, cause sedimentation of metallic particles in polymeric matrix. Sedimentation velocity of filler particles in the slurry depend on particle and polymer densities, the polymer viscosity and particle size and shape. All other characteristics being constant, sedimentation velocity increases with the filler particle size [11]. In real systems sedimentation is also influenced by neighbouring particles due to mutual interactions. The sedimentation process not in all cases is negative. It can be utilized as driving force of graded structure formation in manufacture procedures of Polymer Graded Materials [12,13].

To solve enumerated problems a new methods of metal-polymer composite creation was developed. The new method is possible to apply in formation of polymer - low melting point alloys composites. The method of preparation of this type of composites is typical for mixing two different liquids together. This is possible because the low melting point alloys have similar melting temperature range as processing temperatures of polymer materials. Such procedures are applied in typical methods for the preparation of polymer blends but not for the production of composites. Properties of low melting point alloys (also known as fusible alloys) open new possibilities for new procedures of composites formation.

Metallic alloys filler particles increase polymer melt viscosity at temperatures lower than the melting point of the alloy, but decrease the viscosity at temperatures above this melting point [8]. This phenomenon allows formation of composite products with the use of conventional methods like injection moulding, extrusion or cast moulding. The viscosity during processing is lower than that for the conventional metal-polymer composites.

Mixing components in the liquid state causes the metal particles to be surrounded by the polymeric material. Thus the supply of oxygen to the surface of the alloy is very limited. The resulting alloy particles are free of oxide shell. Another reason for mixing in the liquid state is the possibility, by applying special mixers and mixing procedures, to obtain very small metal particles, what significantly restrains or even prevents sedimentation.

Mixing of the liquid phases is usually performed at low shear stresses. It results from the decreased viscosity of the polymer at higher temperatures. For these reasons, with the low-speed mixers it is only possible to prepare dispersions of mutually soluble components.

On the other hand, under conditions of high shear stresses emulsion or suspension of the mutually insoluble liquid can be formed. Unfortunately, molten metals are not soluble in polymers, they are organophobic. So, in this case, we had to use a high-speed mixer to achieve high shear stresses during mixing [15].

Low melting point alloys consist of eutectic and non-eutectic combinations of metallic elements. These elements, when not in incorporated in alloys, melt at a much higher temperature than

their alloys. They have been known for many years and have been called by many different names. Some of these have more than one name, but usually we used inventor's name - like Woods, Lipowitzs, Newtons, Roses and so on metals or alloys. On the other hand, many of these alloys are sold under their trade names or proprietary numbers - melting point value in Fahrenheit degrees.

The compositions and names of some most popular low melting point alloys are determined by national standards (see Table 1).

As it is presented in Table 1, the most traditional low melting point alloys are based on bismuth. Bismuth gives these materials the unique characteristic of expansion upon solidification. This expansion, which can continue for hours or even days after solidification, has proven to be a useful property in many processes. They are usually also alloys with high content of lead, tin and sometimes with the participation of iridium, cadmium, thallium, copper, silver or antimony [16,17,18].

The melting points of these alloys is typically less than 200°C. The melting point of some alloys with indium content are even lower than 50°C (Table 1). This is unique, especially as the parent metals in the pure state have their melting points high above alloy's. Although most of the low melting point alloys do not have high strength or hardness, they have many industrial applications.

Significant and frequent industrial applications of these alloys are [16]: anchoring of machine parts, radiation and electromagnetic shielding, tube bending, fusible safety devices, glass and other

materials blocking during grinding processes, dampening of the vibrations, fusible core technologies, proof casting of dies and moulds, lead-free waterfowl shot and etc.

Most literature describe composites of low melting point alloys and thermoplastic polymers matrixes [22,23,24]. This composites are interesting because of their easy manufacturing process and processing conditions. First step is melting of the alloy. The second one is thermoplastic material plasticisation. As a results two quasi-fluids are obtained which are mixed in different technological processes, mainly in extrusion and injection moulding. After cooling a new and ready product from metal-polymer composite material is produced.

Authors of this paper undertook an effort to create a new type of composite consisting of low melting point alloy and a curable epoxy polymer matrix.

The manufacture of parts of thermosetting polymer materials can be more difficult than fabrication parts of thermoplastic composites because cured polymers cannot be re-melted after they have been melted and formed for the first time [25]. Thermosetting polymers after curing have a three dimensional cross-linked structure and unlike thermoplastics, will not deform and flow under the action of heat [26]. Epoxy resins are the second most widely used family of curable resins for composite applications (after polyester resins). In contrast to the polyester resins, about 50% of all epoxy resins are used for non-reinforced applications. The most important of these are for coatings or adhesives. The largest market for reinforced epoxy resins is for laminate sheets, which is about 25% of the total epoxy resins production [27].

Table 1.

Examples of the low melting point alloys [19,20,21]

Inventor's name	Name according to PN-91/H-87203 standard	Name according to ASTM B774-00 standard	Example of trade names	Chemical composition	Melting point
-	-	117	Indalloy 117, CS Alloys Low 117, CERRO LOW 117 Alloy	$\text{Bi}_{44.7}\text{Pb}_{22.6}\text{In}_{19.1}\text{Sn}_{8.3}\text{Cd}_{5.3}$	47°C
-	-	136	Indalloy 136	$\text{Bi}_{49}\text{In}_{21}\text{Pb}_{18}\text{Sn}_{12}$	58°C
Field's alloy	-	-	Roto144F	$\text{Bi}_{32.5}\text{In}_{51}\text{Sn}_{16.5}$	62°C
Wood's alloy	TBC12	158	Indalloy 158, Roto158F, CERROBEND Alloy, CS Alloys Bend 158 AIM 70, AsarcoLo 158	$\text{Bi}_{50}\text{Pb}_{25}\text{Sn}_{12.5}\text{Cd}_{12.5}$	70°C
Lipowitz's alloy	TBC13	-		$\text{Bi}_{50}\text{Pb}_{27}\text{Sn}_{13}\text{Cd}_{10}$	80°C
Matrix's alloy	TBC14	-		$\text{Bi}_{53}\text{Pb}_{28.5}\text{Sn}_{14.5}$	108°C
Newton's alloy	TBC19	203	Indalloy 203 Roto203F, CERRO SHIELD Alloy, CS Alloys Shield 203	$\text{Bi}_{50}\text{Pb}_{31.2}\text{Sn}_{18.8}$	96°C
Lichtenberg's alloy	TBC20	-	-	$\text{Bi}_{50}\text{Pb}_{30}\text{Sn}_{20}$	92°C
Erman's alloy	-	-	-	$\text{Bi}_{50}\text{Pb}_{25}\text{Sn}_{25}$	93°C
Roses alloy	-	-	Indalloy 41	$\text{Bi}_{50}\text{Pb}_{28}\text{Sn}_{22}$	109°C

One of the main advantages of epoxy resins is low tendency to emit gases in cured state even at elevated temperatures. Many other thermosetting resins emit gases being the products of free crosslinking agents, solvents or from free monomers or oligomers. Epoxy resins undergo substantially less shrinkage than polyester or vinylester resins when cured. Consequently, they are less prone to cracking under thermal loads. Epoxy resins are known to have excellent corrosion resistance. Another advantage of these resins in many applications is their thermal stability which, although not among the highest of thermosetting materials, but is much higher than that of polyester resins. Very important advantage of epoxy resin is the possibility to control many properties by proper selection of curing system. Especially thermal and chemical resistance may be changed in wide range. With some curing agents it is also possible to control hardness and flexibility. The relatively good thermal stability of epoxy resins, their excellent adhesive properties, and their good mechanical properties have led to their widespread use as the principal resin in most high-advanced composites [27,28]. Epoxy resins exhibit also some drawbacks. More precision is needed when adding curing agents because stoichiometric amounts of hardeners are demanded to achieve proper crosslinking. The second problem arises because epoxy resins are good adhesives. Preparing moulds to casting good anti-adhesion layers are needed and more carefully these layer have to be applied. Epoxy resins are also more expensive especially as polyester resins.

The mean values of tensile strength of neat cured epoxy resin, chosen epoxy resin composite filled with metal particles and strength of few low melting point alloys are presented in Fig. 1.

An epoxy resin contains one or more epoxide (or oxirane) groups that react with hydroxyl groups. Most common are the reaction products of bisphenol A and epichlorohydrin. The resins are cured (or hardened) with amines, acid anhydrides, (Lewis acids) by condensation polymerization and not, like polyester resins, by free-radical chain polymerization. The epoxy resin and the curing agent are supplied in two parts and are mixed in specific proportions (stoichiometric ratio) just prior to use to cause the curing reaction. Epoxy resins can be cured at room temperature or at higher temperatures, usually not higher than 220°C. Sometimes epoxy resin composites are postcured at elevated temperatures to raise their glass transition temperatures and to improve their physical and mechanical properties [28].

In composites under loads, applied stress is transferred from the polymer matrix to the reinforcement or fillers. Particles content, sizes and shapes have decided influence on the properties of polymer composites prepared with metal particles. Most fillers increase the modulus and the tensile yield strength and decrease the elongation at break. There are some exceptions from this general rule, namely at very low filler loadings, bad dispersion, presence of agglomerates, weak bonding to the matrix, and phase changes of the matrix (e.g., nucleation) the influence may be different [31].

Hard and stiff particles affect the strength in two ways. One is the weakening effect due to the stress concentration they cause, and another is the reinforcing effect since they may serve as barriers to crack growth. In some cases, the weakening effect is predominant and thus the composite strength is lower than that of the matrix, and in other cases, the reinforcing effect is more

significant and then the composites will have strengths higher than the polymer matrix [32]. On other hand, the particles and matrix interfacial adhesion has a prominent effect on the strength of particulate filled polymer composites. A strong interfacial bonding between particles and polymer matrix is critical for effective stress transfer leading to high composite strength. Vice-versa, a weak bonding between particles and matrix will only give low composite strength [31].

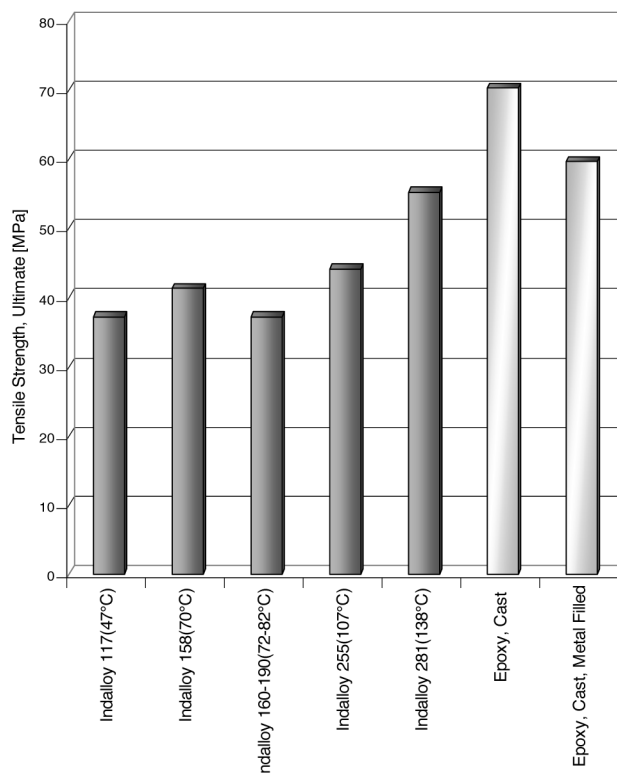


Fig. 1. Tensile strength of few low melting alloys, epoxy resin and metal filled epoxy. Values in brackets show the melting point temperatures of the alloys [29,30].

The most interesting for our research the epoxy/Wood's alloy composites should have a good adhesion between the phases. The bonding between the filler particles and the matrix should be the result mainly of mechanical adhesion. Epoxy resins shrink on curing [33] and presses the liquid or solid state of Wood's alloy particles. The bismuth, which is included in the Wood's alloy, gives these materials unique characteristic of expansion upon solidification. This expansion can continue for hours or even days after solidification [29]. As a result of the interaction between the components of the composite we get mechanical, crimp type connection between metal particles and polymer matrix.

The effectiveness of a filler is directly linked to the aspect ratio of particles. Generally considered that the fillers which possess a large length to diameter ratio ($l/d > 10$) increase the strength of the composite. The best reinforcement effects are achieved for fibres. However, mechanical properties are

determined also by particle size, particle size distribution, specific surface area, and shape of fillers. An optimum particle size exists for each polymer materials and processing technology. Large particles debond easily from the matrix under loading, while small particles tend to aggregate. Both processes weaken the composite properties significantly. The specific surface area determines the contact surface between the filler and the polymer [34].

S.Y. Fu, X.Q. Feng, B. Lauke, Y.W. Mai [32] clearly shown that, for a given particulate volume fraction, the composite strength increases with decreasing particle size. Smaller particles have a higher total surface area for a given particle loading. This indicates that the strength increases with increasing surface area of the filled particles through a more efficient stress transfer mechanism. Good adhesion between polymer and filler is needed of course to achieve this effect.

Commonly people expect that the presence of metal powders, such as steel powders, will impart stiffness and strength to comparatively weak polymers materials. Unfortunately, this is not necessarily true, and, quite the contrary, a loss of overall tensile strength may occur. It depends on quality of stress transfer from matrix to reinforcement. On the other hand, the denser packing of particles under compression loads usually leads to higher ultimate strengths [1].

2. Experimental

In the experimental part epoxy / Wood's alloy composite manufactured by mixing the liquid composite components was searched. Two main experiments were performed. The first was compression strength test and the second was microscopic structure investigation.

All tests were performed in the laboratories of the Department for Metals and Polymers Processing that is a part of the Institute of Engineering Materials and Biomaterials of Silesian University of Technology, Gliwice, Poland.

Low melting point Wood's alloy supplied by "Innovator" Company (Poland) was applied as a filler in the experiment. The melting point of the this alloy is 70°C. This melting temperature was the main criterion of Wood's alloy selection. The second reason of this alloy selection was its availability and low price. The other alloys which were considered were indium alloys. They exhibit even lower melting point temperatures but they are difficult to purchase and the price of these alloys is very high.

We used epoxy resin with trade name Epidian 6 and hardener with a trade name Z1. Both matrix components were produced by "Organika Sarzyna" Company (Poland). Epidian 6 is an epoxy resin obtained from bisphenol A and epichlorohydrin having an average molecular weight ≤ 700 . Z1 is triethylenetetraamine hardener. Resin with curing agent were mixed in weight proportion 100:13.

Testing samples of composites with the following weight percentage content of the Wood's alloy were prepared: 20%, 40%, 60%, 80% and 100%.

After many trials the following procedure of composites preparing was accepted:

- Defined amounts of resin Epidian 6, hardener Z1 and Wood's alloy were prepared according to the needed concentration reinforcing particles;
- The Epidian 6 and Wood's alloy were thoroughly mixed together at a temperature of 80°C at the time of 3 minutes, the rotation speed at this stage was 10 000 rpm. Linear peripheral speed of mixing blade was: 13,09 m/s. Mixtures were made with the use of dissolver mixer DISPERMAT LC30 produced by VMA-GETZMANN GMBH. Dissolver mixer fitted with a Z-blade with 25 mm diameter of disk was applied. Mixing was done in a cylinder of diameter 50 mm. The geometry of mixing system was designed to meet the manufacturer's recommendations in the case of preparing dispersions. Main manufacturer's recommendations are shown in Fig. 2.

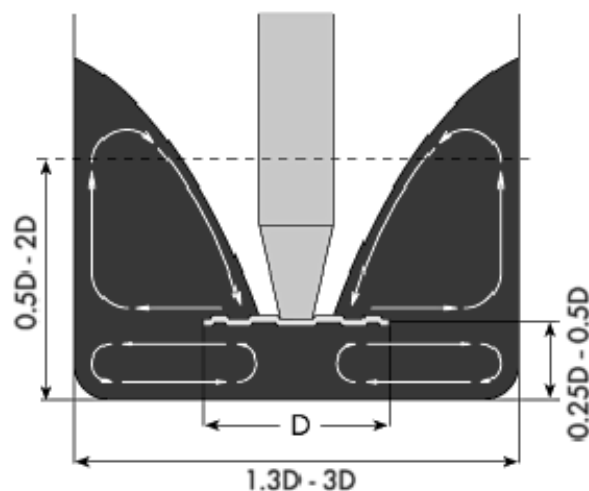


Fig. 2. Recommendations for the mixing [35], where D is diameter of the Z-blade disk.

- After cooling the mixture to the room temperature, the resin and alloy compositions were mixed with the curing agent Z1.

After preparation the compositions were cast into the glass tubes with a diameter of 10 mm and a height of 70 mm. Thin layers of ready mixtures were also spread on the top of microscopic base slides and covered with top glasses (Fig. 3.). In the next step the samples were heated in the dryer up to the temperature 25°C. In this temperature all samples were cured in 24 hours time.

The cast and cured cylinders were pulled out from the glass tubes and cut into discs 10 mm thick (Fig. 4). The discs were intended to compression tests.

Finally obtained samples of epoxy/Wood's alloy composites were compression tested using the Zwick/Roell Z020 testing machine. The research was conducted in accordance with the Polish and European standard PN-EN ISO 604 "Compression Properties of Plastics". The cross head speed of 1 mm/min. was maintained throughout the test. Testing temperature was 23°C.

Samples prepared for the microscopic investigation were observed using a confocal microscope Zeiss LSM 5 Exciter.

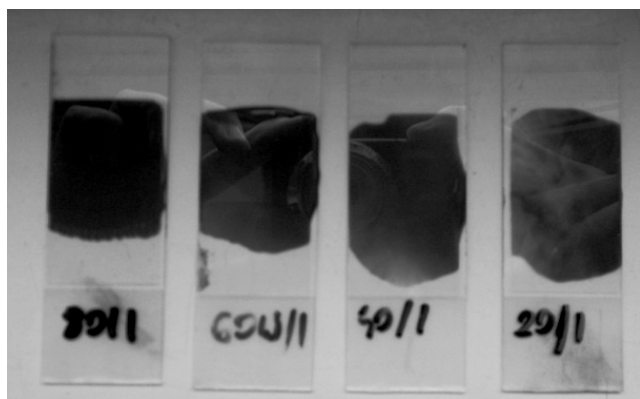


Fig. 3. Samples of the Epoxy/Wood's alloy composites prepared for microscopic investigations

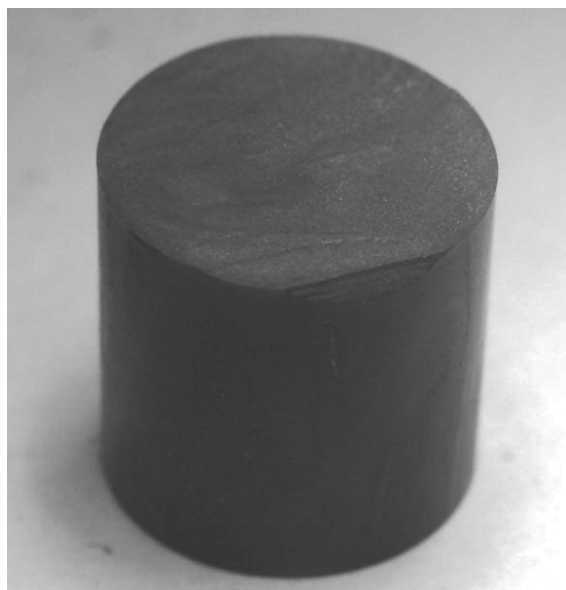


Fig. 4. The Epoxy/Wood's alloy composite sample for compression strength investigations

3. Results and discussions

Figs. 5-8 show the structure of searched composite materials. The Figs. show microscopic images of fields with $350 \times 350 \mu\text{m}$ dimensions.

The Fig. 5 shows an example of microscopic image of the composite material. The Figs. 6 to 9 show digitally processed images in such a way that particles are better visible and the images are ready for computer image analysis.

Figs. 6-9 show the structure of searched composite materials. As previously also these Figs. show microscopic images of fields with $350 \times 350 \mu\text{m}$ dimensions.

The main advantage of all composite is that sedimentation for all metal concentrations is not visible apart from that densities of

matrix material and metallic filler differ so much. It is the result of good dispersion of metal I matrix and splitting it up into small particles.



Fig. 5. Exemplary microscopic image of - Epidian 6 + Z1 (20% by weight) - Wood's alloy (80% by weight) composite

Apart from this composites with low concentration of the Wood's alloy particles have very unevenly distributed filler particles (Figs. 6 and 7). Some metallic particles are grouped into agglomerates. Because of system's low viscosity the shear stresses applied during mixing were not sufficient to disintegrate this agglomerates. Almost all metallic particles were grouped into agglomerates with different shape and size. Applied mixing procedure seems to be insufficient for this level of filling and further investigations are needed.

Most metallic particles, shown in Fig. 6, have an area less than $50 \mu\text{m}^2$. Particles of this size count approximately 83% of all particles. Particles having an area of over $100 \mu\text{m}^2$ are only 3% of all particles. Visible in the centre of the image circles are caused by interference of laser light from confocal microscope on the microscopic slide.

For the composite with a 40% by weight content of Wood's alloy (Fig. 7.) more than 96% of the particles have a surface area less than $50 \mu\text{m}^2$. The largest observed particle has an area of $136.7 \mu\text{m}^2$.

Homogeneous composite structures for the highest filler concentrations are presented in (Figs. 8 and 9). Even for 60% wt. of metallic particles good distribution of filler in polymeric matrix was achieved. Most alloy particles, shown in Fig. 8, have an area less than $50 \mu\text{m}^2$. Particles having an area of over $100 \mu\text{m}^2$ are only 0.4%. For a composite with a 80% wt. content of Wood's alloy (Fig. 7.) almost all particles have a surface area less than $50 \mu\text{m}^2$.

Vary satisfactory is that no air bubbles and voids are visible in these composites. It proves that this amount of polymeric matrix is sufficient to wet and join all metallic particles and to form homogeneous composite. The images suggest that it is possible to introduce more metallic particles into the epoxy matrix. Before this microscopic observations with higher magnifications are planned to verify this conclusion. Also adhesion between metallic particles and polymeric matrix have to be checked.

In our previous research [9] we concluded that it is probably possible to disperse metallic particles in polymeric matrix in such a way that small particles are homogeneously distributed in all volume of surrounding polymer. The microscopic images (Figs. 5 to 9) show that applied compounds preparing procedure enables it, especially for higher low melting point alloys concentrations.

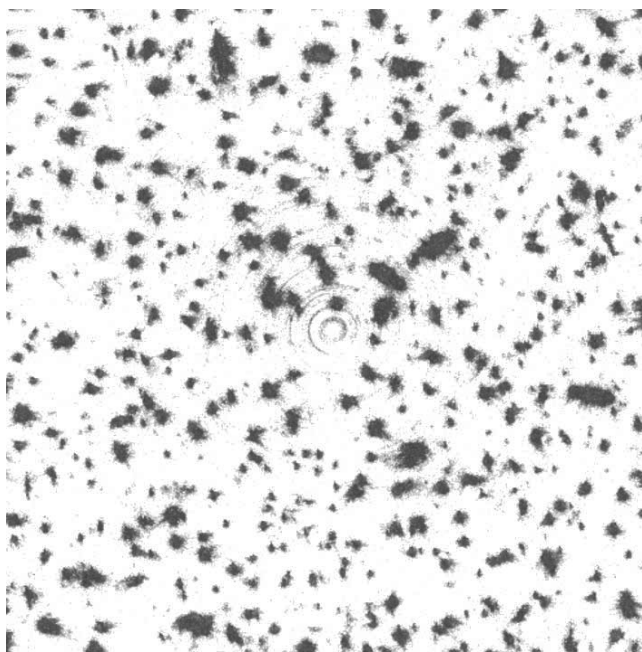


Fig. 6. Exemplary image of Epidian 6 + Z1 (80% wt.) - Wood's alloy (20% wt.) composite

In presented research proves that it is possible for epoxy-Wood's alloy composites. For prepared systems also low level of typical composites imperfections was observed. Such composites may be applied in many different industry fields such as electrical, electronic and mechanical engineering. Further research is needed to confirm it for other thermosetting polymer-low melting point alloy systems and to better recognize crucial properties of tested and other composites. The proper research projects are planned in near future.

The mechanical properties of the composites were identified in the compression test. The compression strength test is easy to perform, but its interpretation is difficult, especially for high strain values, because complex stress state arises as tension and shear forces act concurrently inside the material. Some authors [36] suggest the correctness of the compression test only for stiff

and brittle materials and only for small range of deformation. The problem with compression strength tests is that the specimens of some materials, among them also polymers, may compress to barrel shapes during the test. This and interpretation of test curve may be a reason of overestimation of tested materials compression strength. For most materials, compression strength is much greater than tensile strength [37]. In spite of this compression test was applied in this research. The main reason was that it was not possible using casting technology to prepare samples with the dumbbell shape demanded in tensile test. A special mould have to be constructed to enable it.

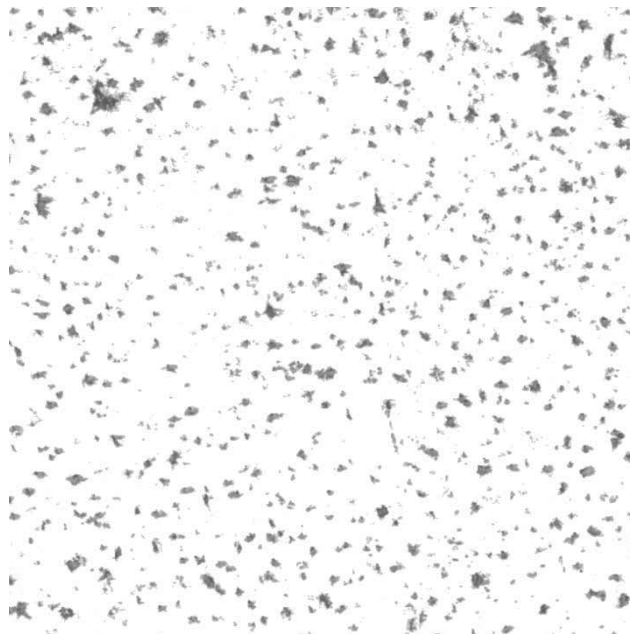


Fig. 7. Exemplary image of Epidian 6 + Z1 (60% wt.) - Wood's alloy (40% wt.) composite

The basic strength characteristic, namely compression strength and Young's modulus were calculated using compression force - strain curves. An example of the achieved testing curve is presented in Fig. 10.

An interesting shape of the curve was obtained for the sample of pure Wood's alloy (Fig. 11). The curve shows peculiarity at the point corresponding to force about 4200 N. The probably reason for this phenomenon is temperature rise above the alloy's recrystallization temperature due to energy dissipation. Recrystallization temperature is in the range of 0.4 to 0.6 this melting point of the metal alloy. The research was carried out at 24°C but temperature significantly increase during plastic deformation so proposed explanation seems to be legitimate. Nevertheless it is planned to continue further experiments to confirm this hypothesis.

Cylindrical test samples cracked and were damaged with a different intensity. Samples with low content of the Wood's alloy showed higher tendency to cracking with brittle fracture but it was not a strictly fulfilled rule (Fig. 12).

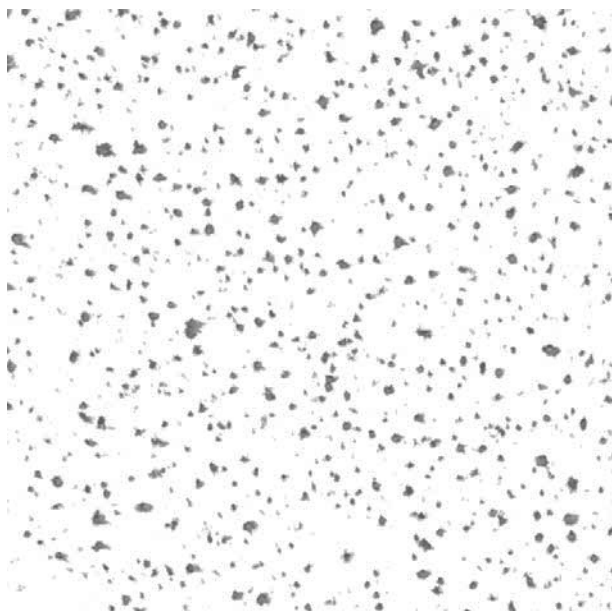


Fig. 8. Exemplary image of Epidian 6 + Z1 (40% wt.) - Wood's alloy (60% wt.) composite

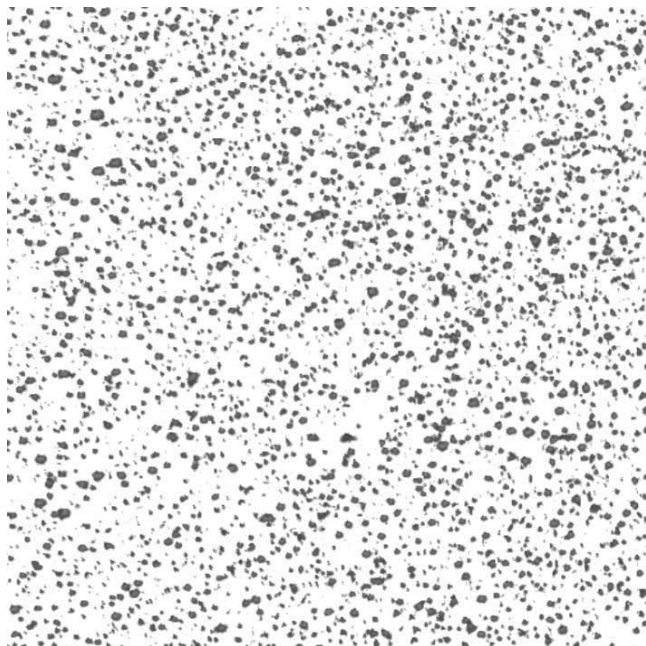


Fig. 9. Exemplary image of Epidian 6 + Z1 (20% wt.) - Wood's alloy (80% wt.) composite

All results of the compression strength and Young's modulus are shown in Table 2.

The largest scatter of results was observed for values of Young's modulus. For composite materials scatter of the values was larger than for pure Epidian 6 or pure Wood's alloy.

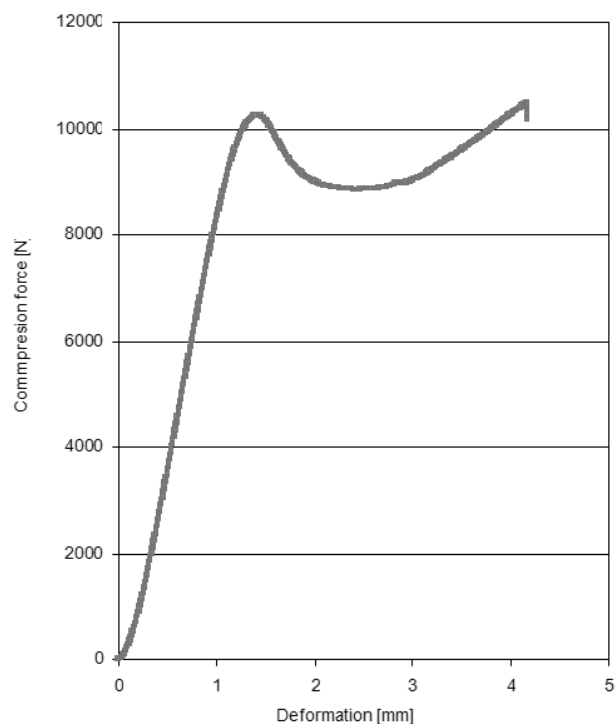


Fig. 10. Exemplary compression testing curve for Epidian 6 + Z1 (20% wt.) - Wood's alloy (80% wt.) composite

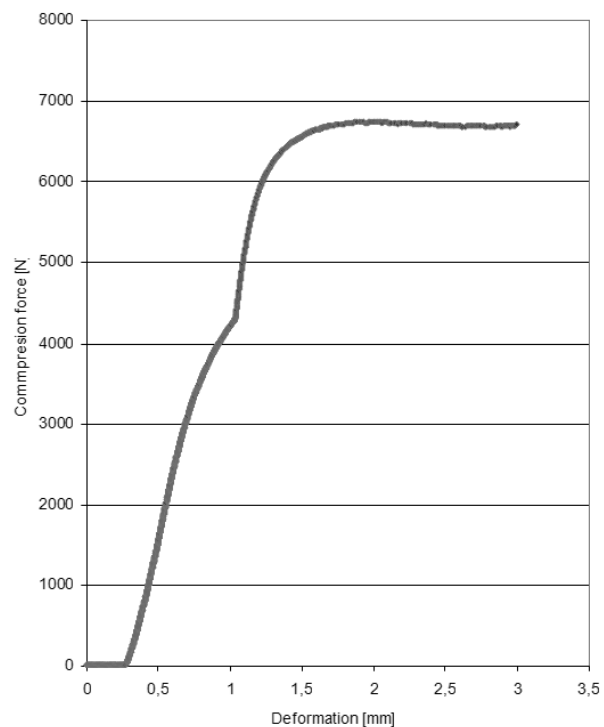


Fig. 11. The testing curve of Wood's alloy

In the next step dependency of compression strength on filler content was analysed. Fig. 13 shows results of this analysis in graphical form. Polynomial dependence was used to approximate experimental results with mathematical model. The least squares method was applied to find coefficients of the model. The following polynomial model was achieved:

$$y = -0.0148x^2 + 0.2538x + 120.47 \quad (1)$$

where:

y is compression strength [MPa],

x is a Wood's alloy mass content in the composite [%].

This equation has a high squared correlation coefficient (R^2), which is 0.912.

The range 80% to 100% of the Wood's alloy particles content

was excluded from the domain of this experimental model. This was done due to the difficulty of determining the correct value of the Wood's alloy strength because of earlier mentioned recrystallization phenomena.

The Fig. 13. shows the strength of Wood's alloy (+), and the value of stress measured at the hold on the compression curve (x). These results significantly differ from all the other that form regular curve. Forced incorporation of these values into the scope of experimental results caused the correlation coefficient to fall to about 0.6.

The same approximation procedure was applied to results of the Young's modulus and for the strain at break. The correlation coefficients were very low so that there was no statistical evidence that any dependences existed between these characteristics and Wood's alloy content.

Table 2.

Mechanical properties of tested materials

Composites	Sample No	Compression strength [MPa]		Relative strain [%]		Young's Modulus [MPa]	
		sample	average	sample	average	sample	average
100% Epidian 6 + Z1	1E	125.23		1.91		950	
	2E	117.20		1.47		1080	
	3E	125.58	125.66	1.40	1.52	1050	1045.00
	4E	130.62		1.42		1100	
	5E	129.69		1.41		1045	
20% Wood's alloy 80% Epidian 6 + Z1	1A	111.68		2.13		986	
	2A	106.30		1.85		911	
	3A	110.93	110.28	1.65	1.76	1230	1093.40
	4A	110.31		1.59		1310	
	5A	112.18		1.61		1030	
40% Wood's alloy 60% Epidian 6 + Z1	1B	103.23		1.56		441	
	2B	102.54		1.61		1170	
	3B	102.02	103.68	1.50	1.52	839	902.00
	4B	102.30		1.46		1010	
	5B	108.33		1.46		1050	
60% Wood's alloy 40% Epidian 6 + Z1	1C	94.94		1.47		816	
	2C	97.44		1.99		786	
	3C	96.88	95.84	1.69	1.67	946	915.80
	4C	96.45		1.57		941	
	5C	93.51		1.65		1090	
80% Wood's alloy 20% Epidian 6 + Z1	1D	40.77		0.83		280	
	2D	37.02		1.12		684	
	3D	39.82	39.53	1.37	1.20	491	517.60
	4D	39.43		1.28		532	
	5D	40.59		1.41		601	
100% Wood's alloy	1W	77.57		2.45		841	
	2W	77.66		1.83		865	
	3W	85.78	80.31	2.47	2.26	945	914.80
	4W	77.70		2.48		950	
	5W	82.87		2.06		973	



Fig. 12. Photograph of damaged test sample - Epidian 6 + Z1 (40% wt.) - Wood's alloy (60% wt.) composite

4. Conclusions

Results show that using elaborated procedure of compounds mixing it is possible to manufacture homogeneous epoxy / Wood's alloy composites with low level of typical composites imperfections. No air bubbles and no voids were observed. Macroscopic images proved that good wetting of metal surfaces by polymeric matrix was achieved.

Such composites may be interesting for many industry branches where high thermal and electrical conductivity is important.

Analyses of microscopic photographs showed that with increasing content of the alloy particles, the filler particles are smaller and have a more repeatable shape. Also all the composite became more homogenous.

The research has shown that the compression strength of composites decreases with increasing concentration of Wood's alloy. It is surprising that the composite with 80% of Wood's alloy has a lower strength than pure alloy. The probable reason for the decrease in the strength can be near spherical shape of alloy particles. Such fillers may weaken the polymer composite. The significant improvement in strength could be expected for the fillers of elongated shape. Also the adhesion between metallic particles and polymeric matrix may be not so high.

The changes of Young's modulus with increased content of Wood's alloy were not so unambiguous as strength changes. The scatter of modulus was very high so no statistically significant relationship was found.

This work gives valuable insight into the behaviour of epoxy composite materials reinforced with Wood's alloy in mixing and curing processes.

Presented research was preliminary. In the future, researches with a smaller alloy particles are planned. Smaller particles of

filler will be received by the higher shear forces during mixing. In the next step tribological, electrical and thermal properties will be tested. Further research is also needed to confirm some of presented results and to find explanations of stated hypothesis.

In the future we also plan experiments with other low-melting alloys.

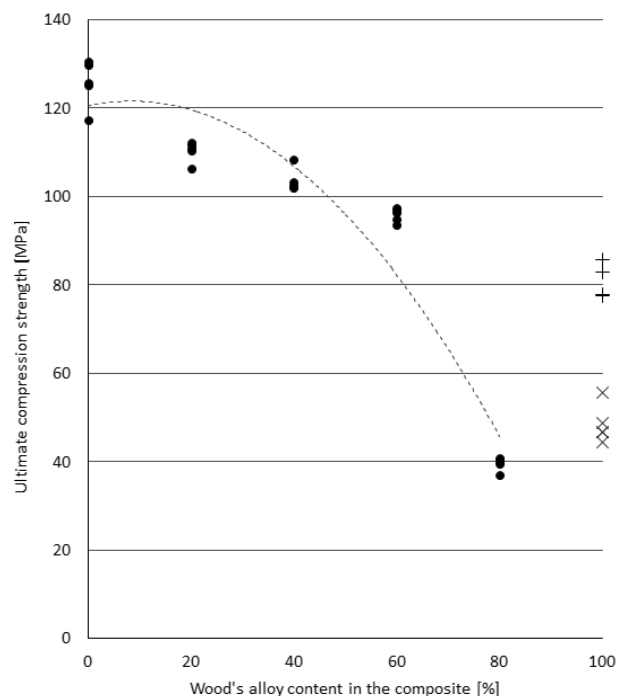


Fig. 13. Graph of strength changes depending on the content of Wood's alloy in the composite

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