MOTROL, 2007, 9, 155–161

MATHEMATICAL MODELS OF MECHANICAL PROPERTIES OF THE HEAVY COPPER ALLOY MACHINERY CASTINGS AT THE PLACE OF THEIR REPAIR

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Summary. The elements used in many machinery exploitation systems are made as bulky copper alloy castings. When these castings work, some damages (fissures, bends and nicks etc.) can occur, and their removal requires repairing by welding. To perform an effective repair by welding it is indispensable to know the chemical composition and mechanical properties of the casting material at the place of its repair. An example of such a casting and the problems of its repair are the screw propellers, which are broadly used in shipbuilding. It seems that the proposed methods of selection of an appropriate technology of these screw propellers repair by welding can be applied for other copper alloy castings widely used in mechanical engineering

Key words: repair, mechanical properties, regression equations, copper alloys

For screw propellers there are mainly used: manganese brass (Cu1 – category alloys), aluminium brass (Cu2 – category alloys), aluminium-nickel bronze (Cu3 – category alloys) and manganese-aluminium bronze (Cu4 – category alloys).

At present, in each category several kinds of copper alloys are produced, and in the case of Cu3 category, even dozens of them, appearing under various trade names. Such a large number of copper alloys produced is the cause why before the screw propeller is repaired, the exact chemical composition of the propeller material is not known (frequently the chemical composition of propeller material is protected by patent and constitutes an industrial secret), neither the mechanical properties of the screw propeller are known, in particular the blades with variable thickness of the cylindrical section on the propeller radius; whereas such information is indispensable for selecting suitable parameters and proper repair technology for the screw propeller.

Whereas the chemical composition of the propeller material can be roughly determined without destroying the screw propeller, it is more difficult to determine the mechanical properties of the propeller in places repaired. Taking samples from the propeller blade for determining mechanical properties is out of the question.

The mechanical properties of screw propellers given in technical documentation (certificate) are determined by testing separately cast ingots of 25 mm diameter. The results of this examination are only approximate, and are not the real mechanical properties of the blades of the screw propeller cast, and these can be determined only by taking samples from the screw propeller blade places we are interested in.

The knowledge of real mechanical properties, in particular the plastic properties of propeller blades in the area of repair by hot straightening or welding, permits to select suitable repair parameters (copper alloys of categories Cu1, Cu2, Cu3 and Cu4 have different heating temperatures for the repair of screw propeller blade by hot straightening, as well as welding – Tables 1 and 2), facilitates performing the repair, permits the decrease of welding deformation and stress and to avoid possible fissures in the weld and in the SWC of the welded joint.

Table 1. Recommended welding materials and temperatures of thermal treatment at welding

Alloy category	Welding materials	Minimal preheating temperature, °C	Maximal temperature between runs, °C	Temperature of relief annealing, °C
Cu 1	Aluminium bronze[1] Manganese bronze	150	300	350–500
Cu2	Aluminium bronze Nickel-manganese bronze	150	300	350–550
Cu3	Aluminium bronze Nickel-aluminium bronze[2] Manganese-aluminium bronze	50	250	450–500
Cu4	Manganese-aluminium bronze	100	300	450–600

[1]Nickel-aluminium and manganese-aluminium bronze can be applied.
[2]Relief annealing is not required if nickel-aluminium bronze is applied as welding material.

Table 2. Temperatures of straightening screw propeller blades made of copper alloys [PRS, Przepisy 2002]

Alloy category	Temperature of hot straightening, °C
Cu1	500−800
Cu 2	500−800
Cu3	700−900
Cu4	700−850

In connection with this, the idea was conceived that the mechanical properties of the screw propeller in relevant places should be determined from the chemical composition of the propeller material.

Fragmentary research conducted in the laboratories of screw propeller manufacturers, e.g. the firm LIPS in Holland (a known producer of screw propellers), showed that the properties of screw propeller alloys spread over the propeller blade radius.

This stimulated an attempt to collect measurement data of copper alloys for screw propellers (Table 3) and subjecting them to statistical analysis which showed that the nature of changes in mechanical properties with increased thickness of the screw propeller cast is best described by regression equation, WZ_WM = a+b·lg(W).

Table 3. Mechanical properties dependent on the thickness of cast sections of screw propellers made of copper alloys [Piaseczny i Rogowski 2003]

Mean section thickness, mm	Copper alloy	No. of casts	Mean values					Source
			R_m N/mm^2	$R_{0.2}$ N/mm^2	A_5 %	HB	Grain diameter mm	
25	CuAl9.5Mn1.5Ni5Fe4.5	33	679	262	22.3	163	-	[Wenschot 1986]
45		4	636	252	18.3	160	-	
67.5		3	613	241	18.9	160	-	
92.5		4	589	230	19.3	149	-	
155		3	582	210	20.7	136	-	
265		12	503	201	14.0	129	-	
300		5	511	199	15.0	128	-	
340		12	487	196	13.8	131	-	
370		17	496	197	15.0	128	-	
400		8	478	195	15.6	126	-	
435		16	489	189	15.9	129	-	
30	CuAl9Fe4Mn1.5Ni2	3	620	-	20.0	-	0.15	[Ruddeck i Koch 1972]
175		3	580	-	22.5	-	0.30	
30	CuMn8Al6Fe2Ni2	3	700	-	22.0	-	0.05	
175		3	627	-	22.0	-	0.12	
30[1)]	CuMn13Al8Zn8Fe2.5Ni2	3	650	-	19.0	-	0.04	
175[1)]		3	610	-	21.0	-	0.08	
30[2)]		3	674	-	17.6	-	-	
250	CuAl9.5Mn1.5Ni5Fe4.5	11	551	207	18.0	-	-	
90		11	582	230	17.3	-	-	

[1] Determined on separately cast samples
[2] Determined on propeller of 4.5 m diameter

The graphic distribution of measurement points in the coordinate system (relative value – blade thickness, Fig.1) and the lines obtained by way of multiple regression analysis describe fairly well the location of mean result values and suggest that when preparing statistically the measurement data in a common coordinate system – thickness, regression lines can be described by the following equations:

$$WZ(R_m, R_{0,2}, A_5, HB, D_z) = a + b\,lg(W)$$

where:

WZ – relative value of properties,
W – propeller blade thickness, mm,
a – absolute term,
b – coefficient,
D_z – grain diameter.

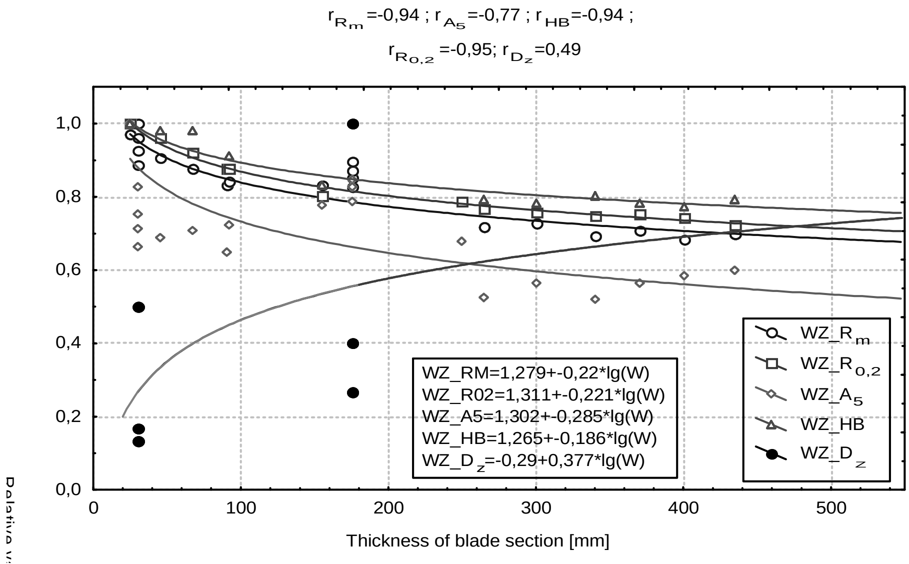

Fig. 1. Dependence of cast properties on the thickness of screw propeller section $WZ\_R_m=R_m/679$; $WZ\_R_{0.2}=R_{0.2}/262$; $WZ\_A_5=A_5/22.3$; $WZ\_HB=HB/163$; $WZ\_D_z=D_z/0.30$ [Piaseczny i Rogowski 2003]

Regression lines designated in a common coordinate system show that the changes in the properties of screw propeller cast occur mainly with increased blade thickness in the range from 25 mm to 175 mm and are close to the course of increase in grain diameter D_z; with further screw propeller blade increase, on the other hand, the changes are not very large. This permits the recognition that the deterioration of mechanical properties along with increased thickness of screw propeller blade is due to accompanying grain diameter increase of the copper alloy from which the propeller was cast.

In order to obtain regression equations, data about mechanical properties and chemical composition of copper alloys from various research centres were collected and compared according to categories. The data concerned screw propellers made by various manufacturers, in various conditions of casting. The casts within the framework of the category had different designations, different chemical compositions and different mechanical properties. Differences in the content of main alloy components in particular categories of copper alloys for screw propellers are presented in Table 4. They are generally in agreement with content differences of components in alloys given by Classification Societies.

Table 4. Differences in the content of main alloy components in particular categories of copper alloys for screw propellers

Copper alloys of category Cu1						
Difference between main alloy components, %						
Cu	Zn	Al	Mn	Ni	Fe	Sn
58±4.0	37.5±2.5	1.75±1.25	2.25±1.75	0.5±0.5	1.5±1.0	0.75±0.75
Copper alloys of category Cu2						
Difference between main alloy components, %						
Cu	Zn	Al	Mn	Ni	Fe	Sn
59±9.0	35.5±2.5	3.03±2.55	2.5±1.5	4.25±3.75	2.75±2.25	0.77±0.72
Copper alloys of category Cu3						
Difference between main alloy components, %						
Cu	Zn	Al	Mn	Ni	Fe	Sn
81.80±4.8	0.62±0.37	9.0±2.0	3.25±2.75	2.92±2.67	4.0±2.0	0.2±0.15
Copper alloys of category Cu4						
Difference between main alloy components, %						
Cu	Zn	Al	Mn	Ni	Fe	Sn
73.0±10.5	4.35±3.85	7.5±1.5	13.5±6.5	2.0±1.0	4.5±2.5	0.55±0.45

The following regression equations were assumed for preparing statistical data:

– for copper alloys category Cu1:

$$R_m = a_1 \cdot c_{Zn} + b_1 \cdot c_{Al} + c_1 \cdot c_{Mn} + d_1 \cdot c_{Ni} + e_1 \cdot c_{Fe} + f_1 \cdot c_{Sn} + g_1\,; \quad \%,$$
$$A_5 = a_2 \cdot c_{Zn} + b_2 \cdot c_{Al} + c_2 \cdot c_{Mn} + d_2 \cdot c_{Ni} + e_2 \cdot c_{Fe} + f_2 \cdot c_{Sn} + g_2\,; \quad \%,$$

– for copper alloys category Cu2:

$$R_m = a_1 \cdot c_{Zn} + b_1 \cdot c_{Al} + c_1 \cdot c_{Mn} + d_1 \cdot c_{Ni} + e_1 \cdot c_{Fe} + f_1 \cdot c_{Sn} + g_1\,; \quad \%,$$
$$A_5 = a_2 \cdot c_{Zn} + b_2 \cdot c_{Al} + c_2 \cdot c_{Mn} + d_2 \cdot c_{Ni} + e_2 \cdot c_{Fe} + f_2 \cdot c_{Sn} + g_2\,; \quad \%,$$

– for copper alloys category Cu3 without Zn and Sn:

$$R_m = a_1 \cdot c_{Al} + b_1 \cdot c_{Mn} + c_1 \cdot c_{Ni} + d_1 \cdot c_{Fe} + e_1\,; \quad \%,$$
$$A_5 = a_2 \cdot c_{Al} + b_2 \cdot c_{Mn} + c_2 \cdot c_{Ni} + d_2 \cdot c_{Fe} + e_2\,; \quad \%,$$

– for copper alloys category Cu4 without Zn and Sn:

$$R_m = a_1 \cdot c_{Al} + b_1 \cdot c_{Mn} + c_1 \cdot c_{Ni} + d_1 \cdot c_{Fe} + e_1\,; \quad \%,$$
$$A_5 = a_2 \cdot c_{Al} + b_2 \cdot c_{Mn} + c_2 \cdot c_{Ni} + d_2 \cdot c_{Fe} + e_2\,; \quad \%,$$

– for copper alloys category Cu4 with Zn, but without Sn:

$$R_m = a_1 \cdot c_{Zn} + b_1 \cdot c_{Al} + c_1 \cdot c_{Mn} + d_1 \cdot c_{Ni} + e_1 \cdot c_{Fe} + f_1\,; \quad \%,$$
$$A_5 = a_2 \cdot c_{Zn} + b_2 \cdot c_{Al} + c_2 \cdot c_{Mn} + d_2 \cdot c_{Ni} + e_2 \cdot c_{Fe} + f_2\,; \quad \%.$$

as a result of which the following model parameters have been obtained (Table 5):

Table 5. Regression equations of the model

Copper alloy	Regression equations for particular categories of copper alloys for screw propellers with model parameters
Cu 1	$R_m = -6.931 \cdot c_{Zn} + 61.241 \cdot c_{Al} - 18.926 \cdot c_{Mn} - 32.660 \cdot c_{Ni} - 101.284 \cdot c_{Fe} - 90.363 \cdot c_{Sn} + 907.069$ $A_5 = -0.067 \cdot c_{Zn} + 3.093 \cdot c_{Al} - 3.636 \cdot c_{Mn} - 1.170 \cdot c_{Ni} - 2.043 \cdot c_{Fe} - 5.375 \cdot c_{Sn} + 34.312$
Cu 2	$R_m = 4.595 \cdot c_{Zn} + 43.680 \cdot c_{Al} + 2.154 \cdot c_{Mn} - 10.632 \cdot c_{Ni} - 21.809 \cdot c_{Fe} - 103.980 \cdot c_{Sn} + 442.035$ $A_5 = 0.090 \cdot c_{Zn} - 1.265 \cdot c_{Al} + 0.298 \cdot c_{Mn} + 0.983 \cdot c_{Ni} + 1.521 \cdot c_{Fe} + 12.339 \cdot c_{Sn} + 8.233$
Cu 3 (without Zn and Sn)	$R_m = -63.538 \cdot c_{Al} + 17.021 \cdot c_{Mn} + 12.697 \cdot c_{Ni} + 42.621 \cdot c_{Fe} + 978.803$ $A_5 = -7.277 \cdot c_{Al} + 2.704 \cdot c_{Mn} - 0.977 \cdot c_{Ni} + 4.010 \cdot c_{Fe} + 71.940$
Cu 4 (without Zn and Sn)	$R_m = 2.352 \cdot c_{Al} + 15.837 \cdot c_{Mn} - 27.970 \cdot c_{Ni} - 37.395 \cdot c_{Fe} + 631.727$ $A_5 = -1.331 \cdot c_{Al} + 0.308 \cdot c_{Mn} - 9.205 \cdot c_{Ni} + 17.545 \cdot c_{Fe} - 0.163$
Cu 4 (with Zn but without Sn)	$R_m = -1.612 \cdot c_{Zn} - 2.804 \cdot c_{Al} + 1.383 \cdot c_{Mn} + 14.214 \cdot c_{Ni} - 8.111 \cdot c_{Fe} + 704.306$ $A_5 = -0.037 \cdot c_{Zn} - 1.296 \cdot c_{Al} - 0.444 \cdot c_{Mn} + 1.639 \cdot c_{Ni} + 0.608 \cdot c_{Fe} + 31.704$

In spite of certain differences in the contents of the main alloy components (Table 4), essential regression equations have been obtained for most cases. Correlation coefficients and the results of Fisher test for checking the essentiality of regression calculated for dependent variables R_m and A_5 are presented in Table 6.

Table 6. Assessment of regression equations

Copper alloy	Dependent variables	Correlation coefficient	Value of Fisher test	Assessment of regression
Cu1	R_m A_5	0.937 0.909	5.989 3.982	essential essential
Cu2	R_m A_5	0.966 0.906	16.247 5.376	essential essential
Cu3 (without Zn and Sn)	R_m A_5	0.836 0.631	12.179 3.483	essential essential
Cu4 (without Zn and Sn)	R_m A_5	0.870 0.933	7.780 16.903	essential essential
Cu4 (with Zn but without Sn)	R_m A_5	0.806 0.997	0.370 32.597	non-essential incidental

Correlation coefficients indicate which of the mechanical properties correlate better with the chemical composition of copper alloy for screw propellers, and which ones correlate worse. The fact that R_m correlates better (Table 6) with the chemical composition than A_5 results from the measurement technique of results. The determination of value A_5 depends on the accuracy of comparing both parts of the culled sample.

As shown by Table 6, only regression equations for alloys of category Cu4 with the addition of zinc proved to be non-essential for the value R_m, and possibly incidental for the value A_5. This was probably decided by the overly large discrepancy of zinc content in those alloys ranging from 3.0 to 8.2%, whereas in alloys of other categories the content of particular components is kept within narrower bounds.

It can be stated on the basis of obtained results that the matching of the model is satisfactory and that the prognostic value of the model is high and statistically significant.

CONCLUSIONS

As a result of the conducted statistical calculations, the following conclusions can be drawn:

1. Regression equations of mechanical properties and chemical composition of marine screw propeller casts made of Cu1, Cu2, Cu3 and Cu4 alloys may be essential and permit the modelling of the mechanical properties of the propeller with an accuracy sufficient for repair technology.
2. There has been formulated a new, original shape of regression equations of mechanical properties and chemical composition values of screw propeller casts made of copper alloys of categories Cu1, Cu2, Cu3 and Cu4.
3. Vessel repair technologies have been given a method of modelling the mechanical properties of screw propeller in the blade section being repaired, which will facilitate the preparation of an effective technology (without shrinkage cracks) of repairing the screw propeller by welding or hot straightening of blades.
4. The given method of modelling can be useful for other than screw propellers copper alloy castings, especially for the ones that are of complex shape and big dimensions.

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