MATHEMATICAL MODELS OF MECHANICAL PROPERTIES OF VESSEL SCREW PROPELLERS

Leszek Piaseczny

Naval Academy
ul. Śmidowicza 69, 81- 103 Gdynia 3, Poland
tel: +58 626 26 03
Gdańsk University of Technology
ul. Narutowicza 11/13 80-952 Gdańsk
tel.kom.: 0501 753 261
e-mail: piaseczny@ptnss.pl

Krzysztof Rogowski

Navy Training Centre at Ustka
Lędowo, 76-270 Ustka, Poland
tel.: 512 325 123
e-mail: hiparion_1@wp.pl

Abstract

During repairing screw propellers by welding and plastic deformation it is indispensable to know their material features and strength properties relative to the propeller part subject to repair. The authors have conducted statistical and empirical research aimed at determining those features depending on the propeller's chemical composition and blade thickness. These dependencies are presented in the form of mathematical models useful both cognitively and utilitarian-wise.

Keywords: *ship propeller, mechanical properties, regression equations, copper alloys*

Damage of screw propellers (fractures, fissure of blades) occurs above all on vessels propelled by combustion engines and is caused by unfavourable overlapping of the ship's vibrations, screw propeller and propulsion engine (Fig.1). Besides, fissures, bends and nicks of the blade rubbing edges may occur when the screw propeller strikes against floating beams or ice floes. When the screw propeller works close to the area's bottom, it is worn by the erosion of sand raised from the bottom. Screw propellers are also worn by fatigue corrosion and cavitational erosion. Depending on the kind and extent of damage, location on the propeller and the possibilities of welding or hot straightening, screw propellers are repaired or replaced.

Fig. 1. Broken blade of a screw propeller [2]

There have arisen highly resistant multicomponent copper alloys for screw propellers, among which there can be distinguished 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 screw propellers 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.

Tab. 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]
Cu1	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

Remarks:
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.

Tab. 2. Temperatures of straightening screw propeller blades made of copper alloys [3]

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).

Tab. 3. Mechanical properties dependent on the thickness of cast sections of screw propellers made of copper alloys [4]

No.	Mean section thickness [mm]	Copper alloy	Number of casts	Mean values					Source
				R_m [N/mm^2]	$R_{0.2}$ [N/mm^2]	A_5 [%]	HB	Grain diameter [mm]	
1.	25	CuAl9.5Mn1.5Ni5Fe4.5	33	679	262	22.3	163	-	[5]
2.	45		4	636	252	18.3	160	-	
3.	67.5		3	613	241	18.9	160	-	
4.	92.5		4	589	230	19.3	149	-	
5.	155		3	582	210	20.7	136	-	
6.	265		12	503	201	14.0	129	-	
7.	300		5	511	199	15.0	128	-	
8.	340		12	487	196	13.8	131	-	
9.	370		17	496	197	15.0	128	-	
10.	400		8	478	195	15.6	126	-	
11.	435		16	489	189	15.9	129	-	
12.	30	CuAl9Fe4Mn1.5Ni2	3	620	-	20.0	-	0.15	[6]
13.	175		3	580	-	22.5	-	0.30	
14.	30	CuMn8Al6Fe2Ni2	3	700	-	22.0	-	0.05	[6]
15.	175		3	627	-	22.0	-	0.12	
16.	30 1)	CuMn13Al8Zn8Fe2.5Ni2	3	650	-	19.0	-	0.04	[6]
17.	175 1)		3	610	-	21.0	-	0.08	
18.	30 2)		3	674	-	17.6	-	-	
19.	250	CuAl9.5Mn1.5Ni5Fe4.5	11	551	207	18.0	-	-	[5]
20.	90		11	582	230	17.3	-	-	

1) determined on separately cast samples
2) determined on propeller of 4.5 m diameter

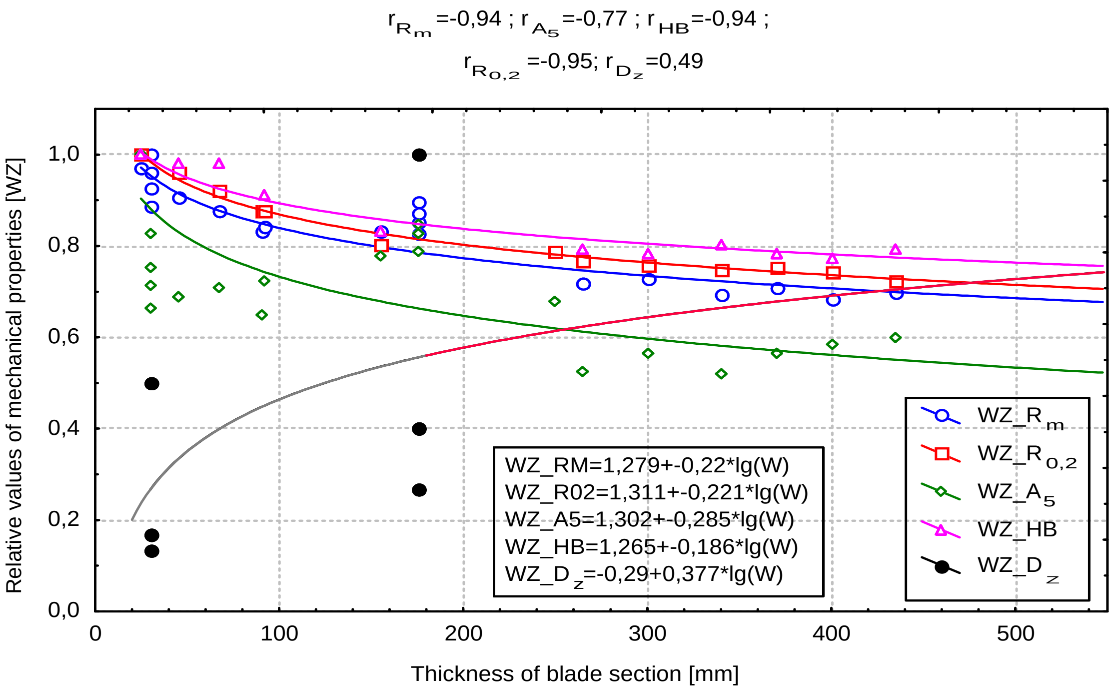

Fig. 2. Dependence of cast properties on the thickness of screw propeller section
$WZ\_R_m=R_m/679$; $WZ\_R_{0.2}=R_{0.2}/262$; $WZ\_A_5=A_5/22.3$; $WZ\_HB=HB/163$; $WZ\_D_z=D_z/0.30$ *[4]*

The graphic distribution of measurement points in the coordinate system (relative value – blade thickness, Fig.2) 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.

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.

Tab. 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):

Tab. 5. Regression equations of the model

No.	Copper alloy	Regression equations for particular categories of copper alloys for screw propellers with model parameters
1.	Cu 1	$R_m = -6.931 \cdot c_{Zn} + 61.241 \cdot c_{Al} - 18.926 \cdot c_{Mn} - 32.660 \cdot c_{Ni} - 101.284 \cdot c_{Fe} - 90.363 \cdot c_{Sn} + 907.069$ $A_5 = -0.067 \cdot c_{Zn} + 3.093 \cdot c_{Al} - 3.636 \cdot c_{Mn} - 1.170 \cdot c_{Ni} - 2.043 \cdot c_{Fe} - 5.375 \cdot c_{Sn} + 34.312$
2.	Cu 2	$R_m = 4.595 \cdot c_{Zn} + 43.680 \cdot c_{Al} + 2.154 \cdot c_{Mn} - 10.632 \cdot c_{Ni} - 21.809 \cdot c_{Fe} - 103.980 \cdot c_{Sn} + 442.035$ $A_5 = 0.090 \cdot c_{Zn} - 1.265 \cdot c_{Al} + 0.298 \cdot c_{Mn} + 0.983 \cdot c_{Ni} + 1.521 \cdot c_{Fe} + 12.339 \cdot c_{Sn} + 8.233$
3.	Cu 3 (without Zn and Sn)	$R_m = -63.538 \cdot c_{Al} + 17.021 \cdot c_{Mn} + 12.697 \cdot c_{Ni} + 42.621 \cdot c_{Fe} + 978.803$ $A_5 = -7.277 \cdot c_{Al} + 2.704 \cdot c_{Mn} - 0.977 \cdot c_{Ni} + 4.010 \cdot c_{Fe} + 71.940$
4.	Cu 4 (without Zn and Sn)	$R_m = 2.352 \cdot c_{Al} + 15.837 \cdot c_{Mn} - 27.970 \cdot c_{Ni} - 37.395 \cdot c_{Fe} + 631.727$ $A_5 = -1.331 \cdot c_{Al} + 0.308 \cdot c_{Mn} - 9.205 \cdot c_{Ni} + 17.545 \cdot c_{Fe} - 0.163$
5.	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 have been presented in Table 6.

Tab. 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 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 results obtained that the matching of the model is satisfactory and that the prognostic value of the model high and statistically.

Conclusions

In result of statistical calculations conducted, 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 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. There are no such equations in the world’s literature. Similar equations are prepared, on the other hand, for highly alloyed steel resistant to corrosion and oxidation in high temperatures, as informed by Prof. F.B. Pickering in his work “*Physical Metallurgy and the Design of Steels*”, London 1994.
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.

References

[1] Scarabello, J. M. et al., *Contribution a l’etude du systeme trenaire Cu-Al-Mn. Détermination de la coupe Cu- Mn-*Al_6 *limitée au domaine riche en cuivre*, Revue de metallurgie 1982, Vol. 79, No 12, pp. 695 - 708.

[2] Marine News, *New propeller blades in double – quick time*, 2005, N^o2, pp. 36÷37.

[3] PRS, Przepisy, Publikacja nr 7/P, *Naprawy śrub napędowych ze stopów miedzi*, Gdańsk 2002.

[4] Piaseczny, L., Rogowski, K., *Zmiana właściwości mechanicznych na promieniu (0.25 – 1)R odlewu okrętowej śruby napędowej*, Zeszyty Naukowe Akademii Marynarki Wojennej, Rok XLIV Nr 3 (154)2003.

[5] Wenschot, P., *The Properties of Ni-Al bronze sand cast ship propellers in relation to section thickness*, Naval Engineers Journal, September 1986, pp. 58 - 69.

[6] Ruddeck, P., Koch, W., *Cumanal - ein neuer Werkstoff fur hochbeanspruchte Schiffspropeller*, Seewirtschaft 1972, H. 3, ss. 196 – 199, H. 4, ss. 269 - 272.

[7] *Rogowski, K., Modelowanie właściwości mechanicznych pędników śrubowych dla doboru technologii ich napraw*, Rozprawa doktorska, AMW, Gdynia 2006.