Design and Stress Analysis of Horizontal Axis Wind Turbine Blade (1kW)

Khin Kyawt Kyawt Lin, Zin Ei Ei Win, Saw Ba Tin

***Abstract*— Wind turbine converts kinetic energy of the wind into the mechanical energy and then this energy is transformed into electrical energy. This research intends to describe design calculation and stress analysis on horizontal wind turbine (1kW). Design average wind speed, V_{avg} is 4m/sec and Reynold number, 46406 was calculated based on the viscosity, density and speed of wind. The selection of blade profile is computed by COMSOL Multiphysics software and it gave the types of blade profiles (NACA Series). Among these series, NACA 4412, blade profile was chosen because it gives the maximum lift to drag ratio. The blade setting angles, lift and drag forces acting on the airfoil were calculated by dividing the airfoil into ten divisions. Three blades were selected for this turbine. The designed rotor radius is 1.7744m. Power delivered from this turbine to the generator is 1kW. After making stress simulation, the Von-Mises stress at the blade for three different materials are compared with their respective yield strength. In Pine (Pinus strobes), Red Oak and Teak wood (Tectona grandis), the maximum Von-Mises stresses occur at the blade root and the maximum deflections occurred at the blade tip is very small. The value of maximum stress for Pine is 33.08 MPa, the value of maximum stress for Red Oak is 27.69 MPa and the value of maximum stress for Teak wood is 28.87. The Von-Mises stresses of three different materials are less than their respective yield strength. So, the designed blade is safe. The value of maximum deflection for Pine is 74.91mm, the maximum deflection for Red Oak is 91.2mm and the maximum deflection for Teak wood is 79.92mm. The deflection is not large enough to be in plastic range and so it is acceptable.**

***Index Terms*—Horizontal wind turbine, blade design, Von-Mises stress, deflection.**

1) Introduction

Among renewable energy resources, wind energy is one of clean and inexhaustible energies. Wind turbine is a device that converts kinetic energy of the wind into electrical energy that can be harnessed for use. Wind turbines can help us reducing the use of conventional resources. There are various designs of wind turbine all over the world.

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Types of wind turbines are horizontal and vertical axis wind turbines. They both have their advantages and disadvantages. The advantages of horizontal wind turbine is able to produce more electricity from a given amount of wind.

For horizontal axis wind turbine system, the efficiency of the system transformation is related to the blade shape. Therefore, it is critical to design the most efficient blade shape possible. Blade element momentum theory is widely used when designing horizontal axis wind turbine blade design.

In general, three blades are used for the wind turbine system to keep the dynamic balance. The blades are the key to the operation of the wind turbine. The rotor blade among the components of the wind turbine system transforms wind power to mechanical power.

2) Design Calculation of Horizontal Axis Wind Turbine Blade

Design Specification;

Average wind speed, $V_{avg} = 4$m/s
Cut-in speed, $V_{cut\text{-}in} = 0.7\ V_{avg} = 2.8$ m/s
Rated speed, $V_{rated} = 2\ V_{avg} = 8$ m/s
Cut-out speed, $V_{cut\text{-}out} = 3\ V_{avg} = 12$ m/s
Power coefficient, $C_p = 47.41\%$
Mechanical efficiency, $\eta_{mech} = 96\%$
Generator efficiency, $\eta_{gen} = 70\%$
Number of blade, $B = 3$
Air density, $\rho = 1.2396$ kg/m^3
Dynamic viscosity, $\mu = 1.7865\times10^{-5}$ Ns/m^2

For calculation of rotor radius for three turbine blade, the intended designed power is 1kW and the data can be put into this electrical power output equation [1].

$$\text{Power} = \tfrac{1}{2}\times\rho\times A\times(V_{rated})^3\times C_p\times\eta_{mech}\times\eta_{gen} \quad (1)$$

$A = 9.8908$ m^2

$D = 3.5487$ m

Rotor radius, $R = 1.7744$ m

Three blades were chosen for this wind turbine. The solidity, S, must be less than 5% for three bladed wind rotor. So it is set to be 4.5%. The average chord length C can be from solidity equation.

$$S = \frac{BC}{\pi D} \quad (2)$$

$C = 0.1672$ m

Reynold's number of airfoil can be calculated as follow.

$$Re = \frac{\rho V_{avg} C}{\mu} \quad (3)$$

$$Re = 46406$$

In NACA 44, the airfoil value with the maximum lift to drag ratio is calculated by using COMSOL MULTIPHYSICS for the most common airfoil shapes NACA 4412,4414 and 4415.

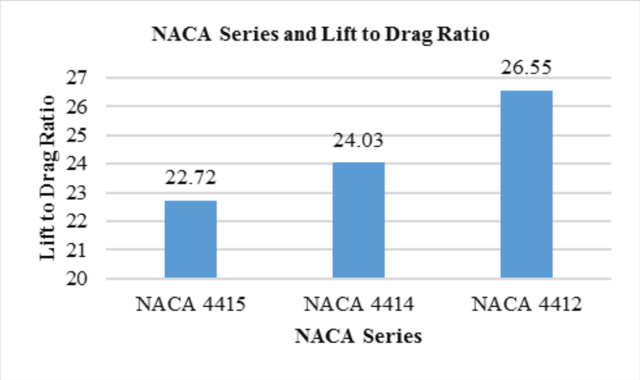

Figure 1. Compares the Lift to Drag Ratio Between NACA 4412, NACA 4414 and NACA 4415

By result, NACA 4412 is found that it has the maximum lift to drag ratio and it is selected for this design.

From Table I results, lift to drag ratio is maximum at angle of attack 6º. Lift coefficient is 1.02. Drag coefficient is 0.0384.

Table I. Numerical Results of Lift and Drag Ratios Respect to Angle of Attack for NACA 4412 (By COMSOL Multiphysics)

Angle of attack (degree)	Lift coefficient	Drag coefficient	Lift to drag ratio
-1	0.2882	0.0246	11.72
0	0.3953	0.0251	15.76
1	0.5023	0.0262	19.2
2	0.6121	0.0276	22.18
3	0.7225	0.0296	24.41
4	0.8269	0.0320	25.82
5	0.9242	0.0350	26.38
6	1.0200	0.0384	26.57
7	1.1190	0.0431	25.96
8	1.2050	0.0482	24.98
9	1.2520	0.0539	23.22
10	1.3050	0.0617	21.16

The blade is divided into 10 equal sections as shown in Fig. 2.The length 0.0744m at the root of blade is to attach the blade and hub. dr is the length of each divided section. Radius of rotor axis to each section are denoted by r_i, the subscript i refers to the section number.

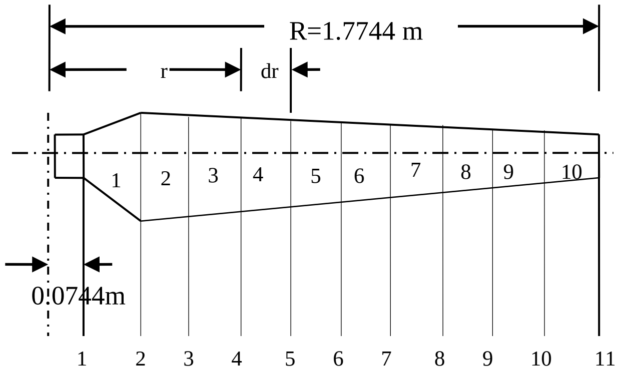

Figure 2. Elements of Blade Section

$$dr = \frac{R - 0.0744}{\text{number of section}} \tag{4}$$

$r_1 = 0.0744$m

For section 2 to 11,

$$r_i = r_{i-1} + dr \tag{5}$$

The following formula is used to calculate the speed ratio at each section and tip speed ratio λ for power coefficient (0.4741) and three blade rotor is 6 from Appendix (Fig. A).

$$\lambda_r = \lambda \times \frac{r}{R} \tag{6}$$

Table II. Calculated Results of Speed Ratio for Rotor Blade at Each Section

Cross section number	Tip speed ratio λ	Radius, r (m)	Speed ratio λ_r
1	6	0.0744	0.2516
2	6	0.2444	0.8264
3	6	0.4144	1.4013
4	6	0.5844	1.9761
5	6	0.7544	2.5509
6	6	0.9244	3.1258
7	6	1.0944	3.7006
8	6	1.2644	4.2755
9	6	1.4344	4.8503
10	6	1.6044	5.4252
11	6	1.7744	6.0000

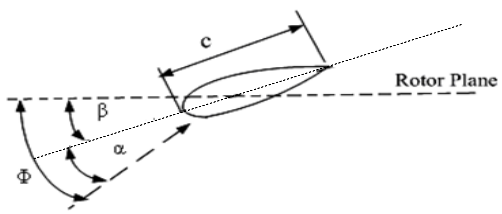

Figure 3. Blade Setting Angles

The shape parameters for each speed ratio λ_{r1} to λ_{r11}, from Appendix (Fig. B) are 3.2, 3.2, 1.8, 1.2, 0.8, 0.6, 0.45, 0.32, 0.25, 0.19 and 0.17.

Chord length,
$$c = \frac{r \times SP}{C_L \times B} \tag{7}$$

Twist angle,
$$\phi = \tan^{-1}\left[\frac{2}{3} \times \frac{1}{\lambda_r}\right] \tag{8}$$

Blade setting angle ,
$$\beta = \phi - \alpha \tag{9}$$

Airfoil maximum thickness,
$$t = c \times 0.12 \tag{10}$$

Table III. Calculated Results of Blade Parameters

Cross section number	α (degree)	c (m)	Φ (degree)	β (degree)	t (m)
1	6	0.0778	69	63	0.0093
2	6	0.2556	39	33	0.0307
3	6	0.2438	25	19	0.0293
4	6	0.2292	19	13	0.0275
5	6	0.1972	15	9	0.0237
6	6	0.1813	12	6	0.0218
7	6	0.1609	10	4	0.0193
8	6	0.1322	9	3	0.0159
9	6	0.1172	8	2	0.0141
10	6	0.0996	7	1	0.0120
11	6	0.0986	6	0	0.0118

Lift and drag forces for each section can be calculated by using the following equation [4].

$$dF_L = \frac{1}{2}\rho dA_b v^2 C_L \tag{11}$$

$$dF_d = \frac{1}{2}\rho dA_b v^2 C_D \tag{12}$$

The elemental areas dA_b for each section can be calculated. For element one, dA_{b1} can be calculated as follow:

$$dA_{b1} = \frac{1}{2} \times (c_1 \cos\beta_1 + c_2 \cos\beta_2) \times dr \tag{13}$$

Relative wind velocity for each element one,

$$v_1 = \sqrt{u^2 + (-\omega_1)^2} \tag{14}$$

Where, ω_1 = linear velocity of element one equal to $r_{e1}\Omega$. r_{e1} is radius at the center of element one equal to 0.0774 + dr/2.

Angular velocity of rotor,

$$\Omega = \frac{2\pi N}{60} \tag{15}$$

The rotor speed,

$$N = \frac{\lambda \times V_{rated} \times 60}{\pi D} \tag{16}$$

Table IV. Calculated Results Of Lift And Drag Forces On Each Section Of The Blade

Blade section number	Section area (m^2)	Relative velocity (m/s)	Section lift force (N)	Section drag force (N)
1	0.0206	9.0881	1.0756	0.0405
2	0.0362	11.9752	3.2819	0.1236
3	0.0363	15.7009	5.6573	0.2130
4	0.0344	19.7972	8.5235	0.3209
5	0.0319	24.0756	11.6895	0.4401
6	0.0293	28.4543	14.9974	0.5646
7	0.0265	32.8931	18.1262	0.6824
8	0.0238	37.3705	21.0129	0.7911
9	0.0210	41.8744	23.2792	0.8764
10	0.0182	46.3970	24.7687	0.9325

Thrust and moment forces for each section can be calculated by using the following equation.

$$dF_T = dF_L \cos\phi + dF_D \sin\phi \tag{17}$$
$$dF_M = dF_L \sin\phi - dF_D \cos\phi \tag{18}$$

Moment and power of each element can be calculated as follows.

$$dM = r_e \times dF_M \tag{19}$$

$$dP = \Omega \times dM \tag{20}$$

Table V. Thrust Force, Moment Force, Moment and Power Acting On Each Section of the Blade

Blade section number	Thrust Force (N)	Moment Force (N)	Moment (N-m)	Power (W)
1	0.8614	0.6454	0.1029	2.7837
2	3.0266	1.2750	0.4200	11.3619
3	5.4184	1.6404	0.8192	22.1612
4	8.3161	1.8961	1.2692	34.3347
5	11.5256	1.9999	1.6787	45.4125
6	14.8676	2.0482	2.0675	55.9304
7	18.0098	2.1616	2.5494	68.9669
8	20.9185	2.1410	2.8891	78.1565
9	23.2125	1.9672	2.9890	80.8590
10	24.7305	1.6616	2.8071	75.9382
Total	130.887	17.4346	17.594	475.905

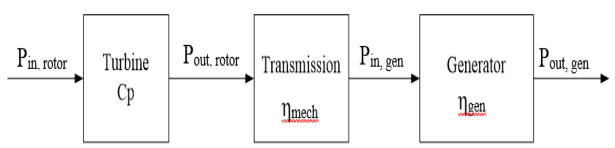

Figure 4. Power transmission Diagram from Rotor Input Power to Generator Output Power

$P_{in,\ rotor} = \frac{1}{2} \times \rho\ A\ (V_{rated})^3 = 3.139$ kW
$P_{out,\ rotor} = P_{in,\ rotor} \times C_p = 1.488$ kW
$P_{in,\ gen} = P_{out,\ rotor} \times \eta_{mech} = 1.428$ kW
$P_{out,\ gen} = P_{in,\ gen} \times \eta_{gen} = 1$kW

3) Stress Analysis On The Blade

To make the stress analysis, the loading conditions must be known and so it is essential to know how the aerodynamic and centrifugal forces are acting on the blade. In the simulation test, the thrust and moment forces which are the components of lift and drag forces are implied on each blade section. The values of aerodynamic forces acting on each blade are described in Table V. The following relation for centrifugal force can be used for centrifugal force.

$$F_C = mr\omega^2 \qquad (21)$$

Where, F_c is centrifugal force (N), m is mass of element (kg), ω is angular velocity (27.0522rad/sec) and r is distance between the rotor center and blade C.G (m).

Stress analysis can be performed by using failure theories. Von-Mises's failure theory will be used to check the strength of the blade. Von Mises stress, also known as Huber stress, is a measure that accounts for all six stress components of a general 3-D state of stress. The Von Mises equivalent stress is computed as:

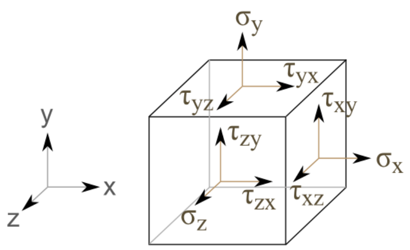

Figure 5. 3D state of stress

$$\sigma_{VM}=[0.5\{(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2\}+3(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)]^{0.5} \qquad (22)$$

Where, σ_x = direct stress in the x direction,
σ_y = direct stress in the y direction,
σ_z = direct stress in the z direction,
τ_{xy} = shear stress on the x-y plane,
τ_{yz} = shear stress on the y-z plane,
τ_{zx} = shear stress on the z-x plane,

$$\sigma_x = \frac{E_x}{h}\left[1-(v_{yz})^2\frac{E_z}{E_y}\right](\varepsilon_x - \alpha_x\Delta T) + \frac{E_y}{h}(v_{xy}) + v_{xz}v_{yz}\frac{E_z}{E_y}(\varepsilon_y - \alpha_y\Delta T) + \frac{E_z}{h}(v_{xz}+v_{yz}v_{xy})(\varepsilon_z - \alpha_z\Delta T) \qquad (23)$$

Where, ε_x = direct strain in the x direction
ε_y = direct strain in the y direction
ε_z = direct strain in the z direction
E_x = Young's modulus in the x direction
v_{xy} = major Poisson's ratio
v_{yx} = minor Poisson's ratio
G_{xy} = shear modulus in the xy plane
α_x= thermal expansion coefficient

The value of h can be determined from the following equation.

$$h = 1-(v_{xy})^2\frac{E_y}{E_x} - (v_{yz})^2\frac{E_z}{E_y} - (v_{xz})^2\frac{E_z}{E_x} - 2v_{xy}v_{yz}v_{xz}\frac{E_z}{E_x} \qquad (24)$$

Shear stress equation can be described as follow:

$$\sigma_{xy} = G_{xy}\,\varepsilon_{xy} \qquad (25)$$

Where, ε_{xy} = shear strain in the x-y plane
G_{xy}= shear modulus

Then according to von Mises's failure criterion, the material under multi-axial loading will yield when the von Mises stress is equal to or greater than the critical value for the material.

$$\sigma_{VM} \geq \sigma_Y \qquad (26)$$

Table VI. Mechanical Properties of Material [5]

Type	Pine (Pinus strobes)	Red Oak	Teak wood (Tectona grandis)
Elastic modulus(MN/m^2)	11500	8100	9400
Poisson's ratio	0.328	0.154	0.341
Mass density (kg/m^3)	470	560	630
Yield strength (MN/m^2)	11500	47	10830

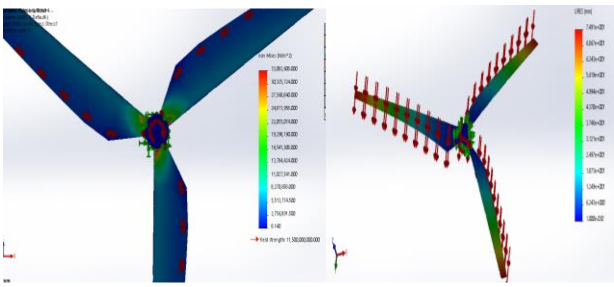

Figure 6. Stress and Deflection Induced in the Blade (Pine)

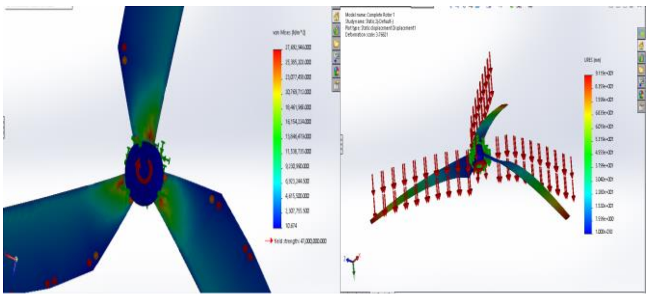

Figure 7. Stress and Deflection Induced in the Blade (Red Oak)

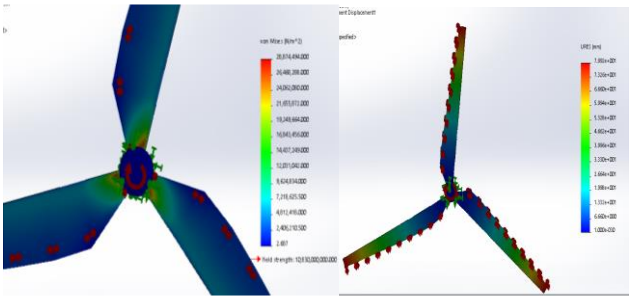

Figure 8. Stress and Deflection Induced in the Blade (Teak wood)

4) Results And Discussions

After making stress simulation, the Von-Mises stress at the blade for three different materials are compared with their respective yield strength. In Red Oak, Teak wood and Pine, the maximum Von-Mises stresses occur at the blade root and the maximum deflections occurred at the blade tip is very small.

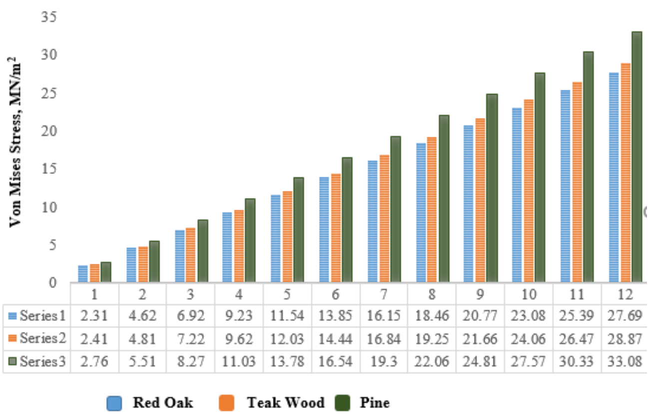

Figure 9. Results of Von Mises Stress of Pine, Red Oak and Teak Wood

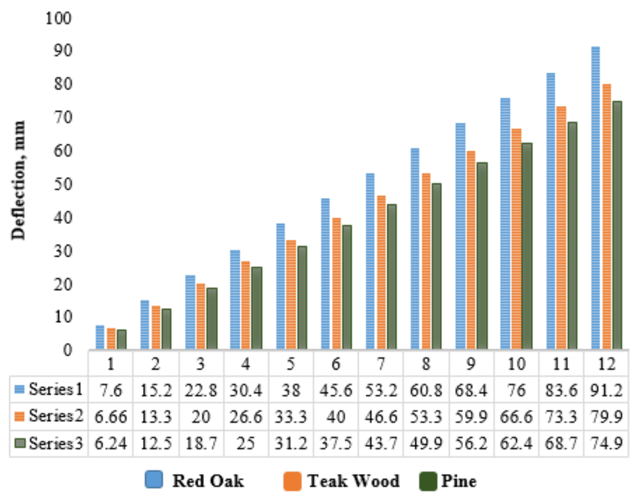

Figure 10. Results of deflection of Pine, Red Oak and Teak Wood

Table VII. Comparison with Simulation Results of Pine, Red Oak and Teak Wood

Material	Maximum Von Mises Stress (MN/m^2)	Maximum Deflection (mm)
Pine (Pinus strobes)	33.08	74.91
Red Oak	27.69	91.2
Teak wood (Tectona grandis)	28.87	79.92

The Von-Mises stresses of three different materials are less than their respective yield strength. So, the designed blade is safe.

By the simulation result, Von Mises stress and deflection that occur at the blade (Teak wood) is medium than the other two materials. So, Teak wood is the suitable material for this design.

5) Conclusion

This research present blade design and stress analysis for horizontal axis wind turbine (1kW). Design average wind speed, V_{avg} is 4m/sec, the number of blade is 3, rotor diameter, D is 3.5487m and the value of Reynold number (Re) is 46406. One of the commercial software, COMSOL Multiphysics is used for NACA optimization. According to the result of optimization, the blade profile for HAWT blade is selected as NACA 4412 for the designed blade. In this research, the blade is divided into 10 equal sections and chord length, twist angle, blade setting angle, airfoil thickness, tip speed ratio, velocity components, lift force, drag force, thrust force, moment force and power acting on each blade section were calculated. Power input to rotor is 3.139kW and power output from rotor is 1.488kW. Power input to generator is 1.428kW and power output from generator is 1kW. Finally, the designed wind generator can generate 1 kW power.

In this research, Pine, Red Oak and Teak wood are simulated for Von-Mises stress. The Von-Mises stress at the blade for three different materials are compared with their respective yield strength. The Von-Mises stresses of three different materials are less than their respective yield strength. So, the designed blade is safe. By the simulation result, Von Mises stress and deflection that occur at the blade (Teak wood) is medium than the other two materials. So, Teak wood is the suitable material for this design.

Appendix

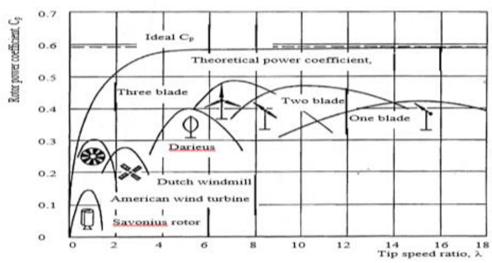

Figure A. Tip speed ratio Vs performance coefficient [2]

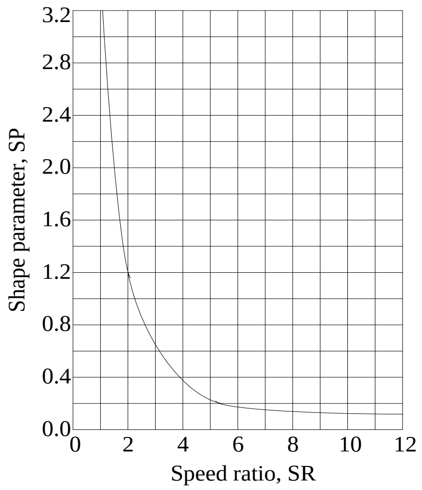

Figure B. Tip Speed Ratio Vs Shape Parameter [3]

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[5] www.matwed.com (Material property data)

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