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RESEARCHES CONCERNING THE CUMULATIVE INFLUENCE OF THE TITANIUM AND OTHER ALLOYING ELEMENT IN ALUMINUM ALLOY 6082 ON THE PHYSICAL AND MECHANICAL CHARACTERISTICS

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Abstract: The main theme of the paper is to study the effect that have titanium and other alloying elements from aluminum alloy 6082, to the yield and tensile strength. Aluminum allies with other elements thereby improve their mechanical strength characteristics, characteristics that are influenced by the presence of impurities such as Si and Fe. Each alloying element has a positive or negative influence in the alloy that forms, aiming to be a balance and getting a high strength alloy, hardened, corrosion-resistant, with a finer grain size and toughness as well as high.
Keywords: Aluminum alloy, mechanical and physical characteristics, alloying elements

1. INTRODUCTION

Aluminum is widely used as the basis for an important series of alloys. The main alloying elements of aluminum are Si, Cu, of Mg and Zn, plus Mn, Ni, Cr and Fe. The addition of alloying elements aims to improve the mechanical properties and technological characteristics and improves casting properties [1]. The presence of the magnesium makes possible hardening heat treatments. Nickel increases resistance to high-temperature, manganese increases strength, but decreases the plasticity, and removes the negative action of iron on the corrosion resistance. Zinc improves casting properties and Ti, Zr and B finishes grain size, increasing toughness [2]. Aluminum alloy 6082 is part of the group Al-Si-Mg alloys, containing 2-14% Si, up to 2% Mg and additions of Fe, Mn and Ti. Al-Si-Mg alloys are used in the casting of strong parts required to service within important construction such as internal combustion engines or casting parts with high corrosion resistance [3].

2. EXPERIMENTAL RESEARCHES

The investigation has been carried out on the commercial 6082 aluminum alloy – appointed in accordance with the standard SR EN 573-1:2005, aiming the influence of titanium and other alloying elements on yield and tensile strength, and the results were processed in the Matlab program. Were obtained correlation equations third degree between the mechanical characteristics that are dependent parameters and alloying elements Ti, Si, Mn and Mg, grouped three together, who are independent parameters.

The experiments related to this paper were conducted at the Faculty of Engineering Hunedoara - University Politehnica Timisoara, in labs of Metal Melt, Processing Hot and Cold Material and Strength of Materials.

It will note $R^2(i)$ is the square of the correlation coefficient for the equation with the number i.Of all triple correlations that were obtained in the paper are presented only the most representative. Regression surfaces and level curves obtained from triple correlations are shown in Figure 1-12.

The equation of correlation between yield strength $Rp_{0,2}$ and the content of Si, Mn and Ti is:

$$Rp_{0,2} = 10^3 \times \begin{pmatrix} 0.0295\,Si^2 - 0.0084\,Mn^2 - 4.6558\,Ti^2 - 0.0105\,SiMn + 0.2355\,SiTi - 0.1587\,MnTi \\ -0.0570\,Si + 0.0490\,Mn + 0.5234\,Ti + 0.1566 \end{pmatrix} \quad (1)$$

Correlation coefficient is $R^2(1)$ =0.9153 for Si = Si_{med} = 1.074%; Mn = Mn_{med} = 0.737%; Ti = Ti_{med} = 0.073% and $Rp_{0,2}$= 175.01 MPa.

For Si = Si_{med}, equation correlation between $Rp_{0,2}$ and Mn and Ti content is:

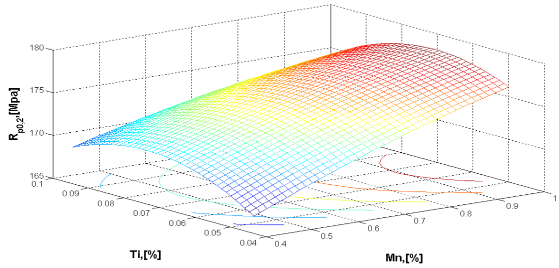
$$Rp_{0,2} = 10^3 \times \left(-0.0084\,Mn^2 - 4.6558\,Ti^2 - 0.1587\,MnTi + 0.0377\,Mn + 0.7763\,Ti + 0.1294\right) \quad (2)$$

Correlation coefficient is $R^2(2)$=0.7365. Maximum point is for Mn =1.7335%; Ti = 0.0538% and $Rp_{0,2}$= 182.9708 MPa. Stationary point is outside the limits specified in the standard (figure 1).

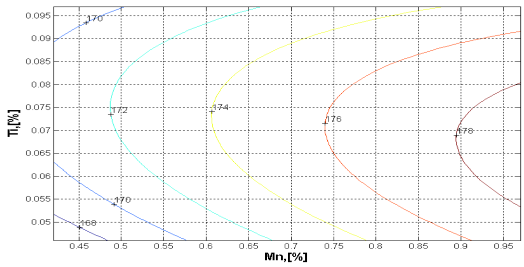
For Mn = Mn_{med}, equation correlation between $Rp_{0,2}$ and Si and Ti content is:

$$Rp_{0,2} = 10^3 \times \left(0.0295\,Si^2 - 4.6558\,Ti^2 + 0.2355\,SiTi - 0.0648\,Si + 0.4064\,Ti + 0.1882\right) \quad (3)$$

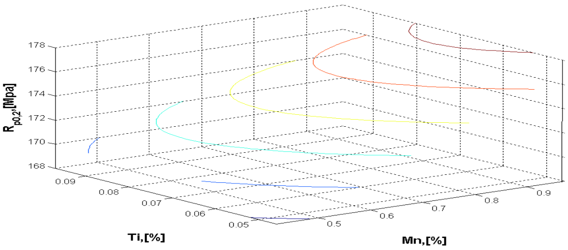
Correlation coefficient is $R^2(3)$=0.6790. Inflection point is for Si=0.8391%; Ti = 0.0649% and $Rp_{0,2}$= 174.1757 MPa. Stationary point is within the range of variation of the independent parameters (figure 2).



(a) – surface regression

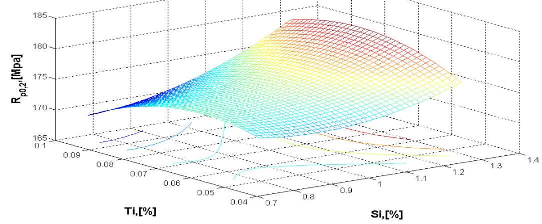


(b) – plan level lines

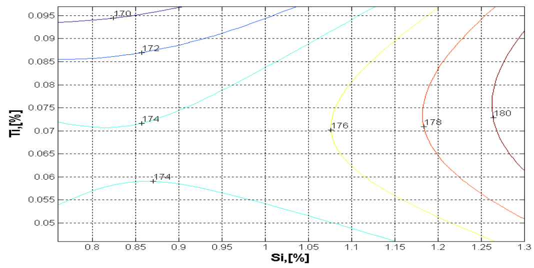


(c) –space level lines

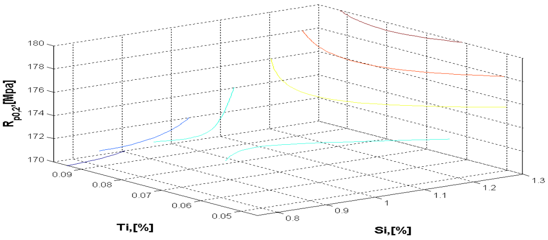
FIGURE 1. $Rp_{0,2}$ = f (*Mn, Ti*) – correlation 2nd degree, Si=Si_{med}



(a) – surface regression



(b) – plan level lines



(c) – space level lines

FIGURE 2. $Rp_{0,2}$ = f (*Si, Ti*) – correlation 2nd degree, Mn=Mn_{med}

For Ti = Ti_{med}, equation correlation between $Rp_{0,2}$ and Si and Mn content is:

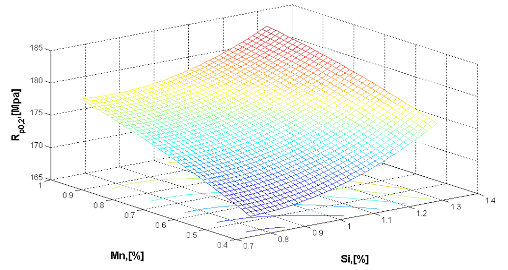
$$Rp_{0,2} = 29.4863\,Si^2 - 8.4108\,Mn^2 - 10.5072\,SiMn - 39.8111\,Si + 37.3912\,Mn + 170.0132 \quad (4)$$

Correlation coefficient is $R^2(4)$=0.8646. Inflection point is for Si=0.9638%; Mn = 1.6208% and $Rp_{0,2}$= 181.1283 MPa. Stationary point is outside the limits specified in the standard (figure 3).

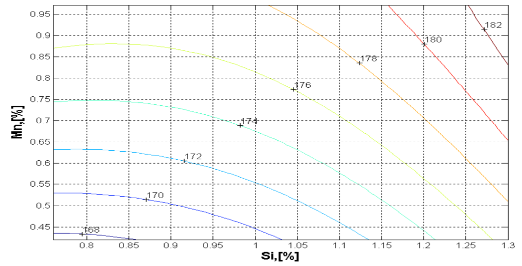
The equation of correlation between tensile strength R_m and Si, Mn ans Ti content is:

$$R_m = 10^3 \times \begin{pmatrix} -0.0610\,Si^2 - 0.1496\,Mn^2 - 5.1418\,Ti^2 + 0.1632\,SiMn - 0.8747\,SiTi + 0.7733\,MnTi \\ +0.1177\,Si - 0.0181\,Mn + 1.1669\,Ti + 0.1575 \end{pmatrix} \quad (5)$$

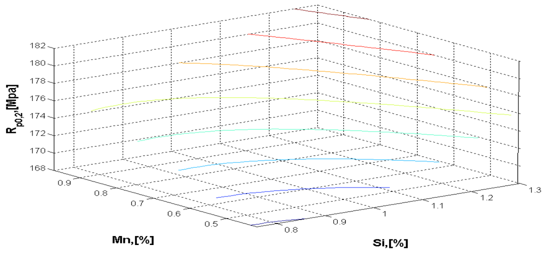
Correlation coefficient is $R^2(5)$ = 0.8676 for Si = Si_{med} = 1.074%; Mn = Mn_{med} = 0.737%; Ti = Ti_{med} = 0.073%, and R_m=273.444 MPa.



(a) – surface regression

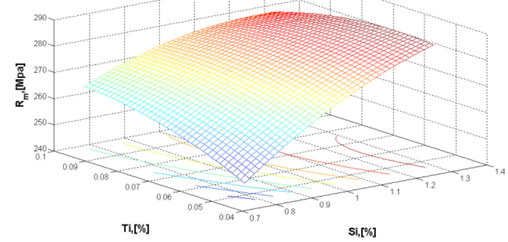


(b) – plan level lines

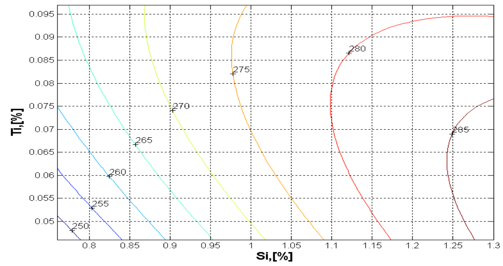


(c) –space level lines

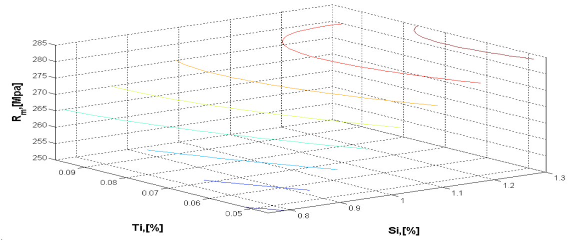
FIGURE 3. $Rp_{0,2}$ = f (*Si, Mn*) – correlation 2nd degree, Ti=Ti_{med}



(a) – surface regression



(b) – plan level lines



(c) – space level lines

FIGURE 4. R_m = f (*Si, Ti*) – correlation 2nd degree, Mn=Mn_{med}

For Si = Si $_{med}$, equation correlation between R_m and Mn and Ti content is:

$$R_m = 10^3 \times \left(-0.1496\,Mn^2 - 5.1418\,Ti^2 + 0.7733\,MnTi + 0.1571\,Mn + 0.2275\,Ti + 0.2136\right) \quad (6)$$

Correlation coefficient is $R^2(6)$=0.1900. Maximum point is for Mn=0.7226%; Ti = 0.0765% and R_m = 279.0982 MPa. Stationary point is located in technological limits.

For Mn = Mn $_{med}$, equation correlation between R_m and Si and Ti content is:

$$R_m = 10^3 \times \left(-0.0610\,Si^2 - 5.1418\,Ti^2 - 0.8747\,SiTi + 0.2380\,Si + 1.7370\,Ti + 0.0628\right) \quad (7)$$

Correlation coefficient is R^2 (7)=0.7185. Maximum point is for Si=1.8989%; Ti = 0.0074% and R_m = 295.1498 MPa. Stationary point is situated above the superior technology limit (figure 4).

For Ti = Ti $_{med}$, equation correlation between R_m and Si and Mn content is:

$$R_m = -60.9734\,Si^2 - 149.6335\,Mn^2 + 163.2142\,SiMn + 53.7975\,Si + 38.3468\,Mn + 215.3515 \quad (8)$$

Correlation coefficient is R^2 (8)=07839. Maximum point is for Si=2.2686%; Mn = 1.3654% and R_m = 302.5520 MPa. Stationary point is well above the upper limit of the range provided by standard.

The equation of correlation between yield strength $Rp_{0,2}$ and the content of Si, Mg and Ti is:

$$Rp_{0,2} = 10^3 \times \begin{pmatrix} 0.0235\,Si^2 + 0.0017\,Mg^2 - 3.0636\,Ti^2 + 0.0174\,SiMg + 0.2753\,SiTi - 0.3902\,MgTi \\ -0.0763\,Si + 0.0235\,Mg + 0.5528\,Ti + 0.1701 \end{pmatrix} \quad (9)$$

Correlation coefficient is $R^2(9)$ = 0.9040 for Si=Si_{med} = 1.074%; Mg = Mg $_{med}$ = 0.932%, Ti = Ti $_{med}$ = 0.073%, $Rp_{0,2}$=175.01 Mpa.

For Si = Si $_{med}$, equation correlation between $Rp_{0,2}$ and Mg and Ti content is:

$$Rp_{0,2} = 10^3 \times \left(0.0017\,Mg^2 - 3.0636\,Ti^2 - 0.3902\,MgTi + 0.0422\,Mg + 0.8484\,Ti + 0.1153\right) \quad (10)$$

Correlation coefficient is $R^2(10)$=0.8326. Inflection point is for Mg=0.4198%; Ti = 0.1117% and $Rp_{0,2}$=171.5263 MPa. Stationary point is situated close to the upper limit (figure 5).

For Mg = Mg $_{med}$, correlation equation between $Rp_{0,2}$ and Si and Ti content is:

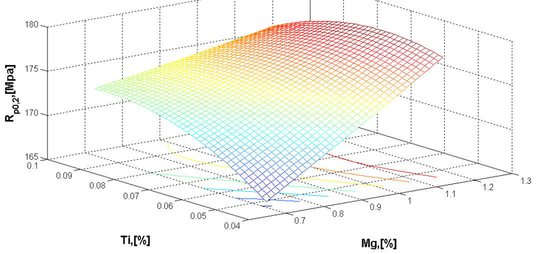
$$Rp_{0,2} = 10^3 \times \left(0.0235\,Si^2 - 3.0636\,Ti^2 + 0.2753\,SiTi - 0.0601\,Si + 0.1890\,Ti + 0.1935\right) \quad (11)$$

Correlation coefficient is $R^2(11)=0.7506$. Inflection point is for Si=0.8696%; Ti = 0.0699% and $Rp_{0,2}$= 173.9857 MPa. Stationary point is within the technological limits.

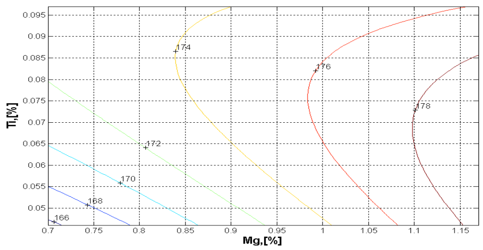
For Ti = Ti $_{med}$, correlation equation between $Rp_{0,2}$ and Si and Mg content is:

$$Rp_{0,2} = 23.4665\,Si^2 + 1.6583\,Mg^2 + 17.3965\,SiMg - 56.1645\,Si - 4.9833\,Mg + 194.1526 \qquad (12)$$

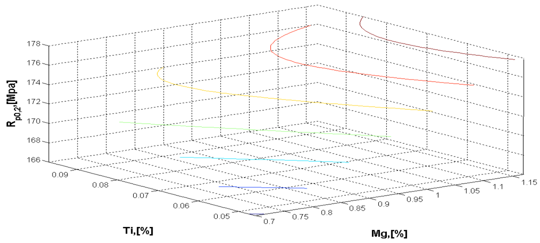
Correlation coefficient is $R^2(12)=0.8457$. Inflection point is for Si= -0.6775%; Mg= 5.0563% and $Rp_{0,2}$= 200.5802 MPa. Stationary point is well beyond the lower limit (figure 6).



(a) – surface regression

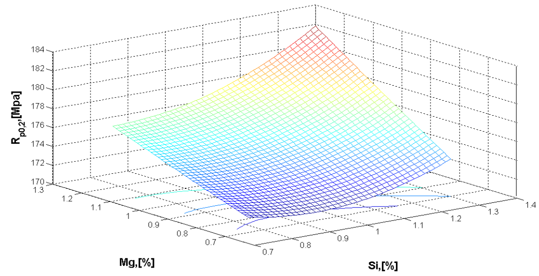


(b) – level lines

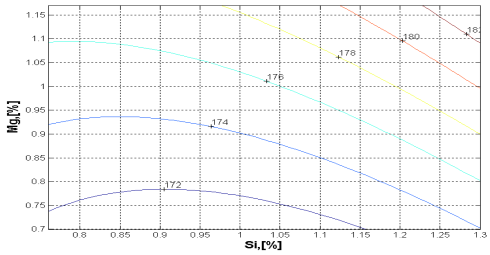


(c) - space level lines

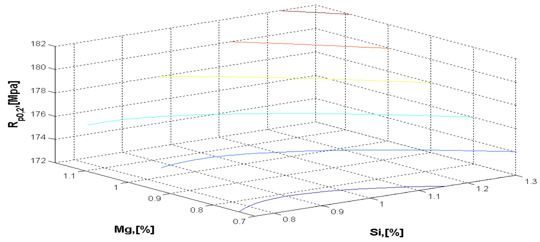
FIGURE 5. $Rp_{0,2}$ = f (*Mg, Ti*) – correlation 2nd degree, Si = Si_{med}



(a) – surface regression



(b) – level lines



(c) - space level lines

FIGURE 6. $Rp_{0,2}$ = f (*Si, Mg*) – correlation 2nd degree, Ti=Ti_{med}

Correlation equation between tensile strenght R_m and the content of Si, Mg and Ti is:

$$R_m = -89.0548\,Si^2 - 63.9940\,Mg^2 - 106.2209\,Ti^2 + 186.8086\,SiMg + 332.3718\,SiTi - 477.9972\,MgTi + 26.0743\,Si + 33.1648\,Mg + 150.6186\,Ti + 245.1113 \qquad (13)$$

Correlation coefficient is $R^2(13)$ =0.8367 for Si = Si_{med}=1.074%; Mg = Mg $_{med}$ = 0.932%, Ti = Ti $_{med}$ = 0.073%, R_m = 273.444 MPa.

For Si = Si $_{med}$, correlation equation between R_m and Mg and Ti content is:

$$R_m = -63.9940\,Mg^2 - 106.2209\,Ti^2 - 477.9972\,MgTi + 167.4470\,Mg + 507.5489\,Ti + 170.4108 \qquad (14)$$

Correlation coefficient is $R^2(14)=0.6223$. Inflection point is for Mg=1.0285%; Ti = 0.0749%, R_m=275.5336 MPa. Stationary point is in the range specified in the standard (figure 7).

For Mg = Mg $_{med}$, correlation equation between R_m and Si and Ti content is:

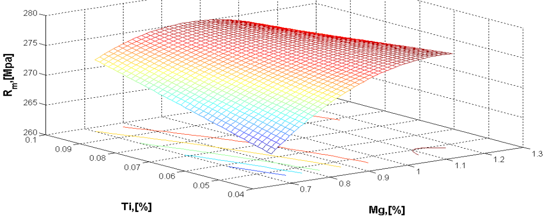
$$R_m = -89.0548\,Si^2 - 106.2209\,Ti^2 + 332.3718\,SiTi + 200.2215\,Si - 294.9810\,Ti + 158.5812 \qquad (15)$$

Correlation coefficient is $R^2(15)=0.7510$. Inflection point is for Si=0.7642%; Ti = -0.1929%, R_m=263.5353 MPa. Stationary point is well beyond the lower limit (figure 8).

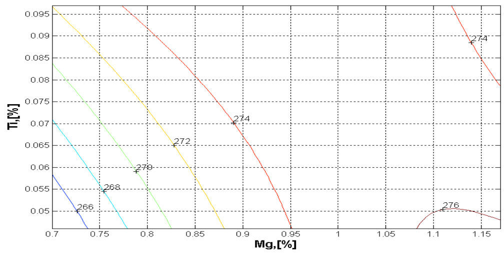
For Ti = Ti $_{med}$, correlation equation between R_m and Si and Mg content is:

$$R_m = -89.0548\,Si^2 - 63.9940\,Mg^2 + 186.8086\,SiMg + 50.3559\,Si - 68.0851\,Mg + 255.5479 \qquad (16)$$

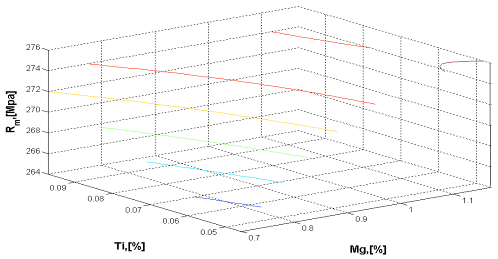
Correlation coefficient is $R^2(16)=0.8154$. Inflection point is for Si=0.5184%; Mg = 0.2247%, R_m=260.9505 MPa. Stationary point is outside the lower limit of the range of the standard (figure 9).



(a) – surface regression

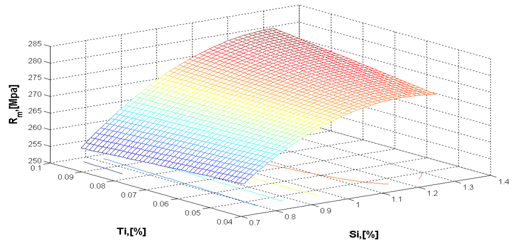


(b) – plan level lines

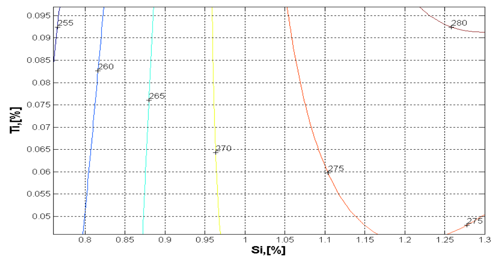


(c) – space level lines

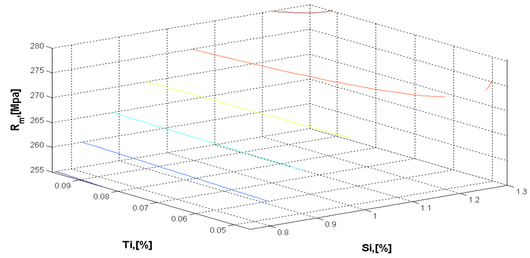
FIGURE 7. $R_m = f(Mg, Ti)$ – correlation 2nd degree, $Si = Si_{med}$



(a) – surface regression

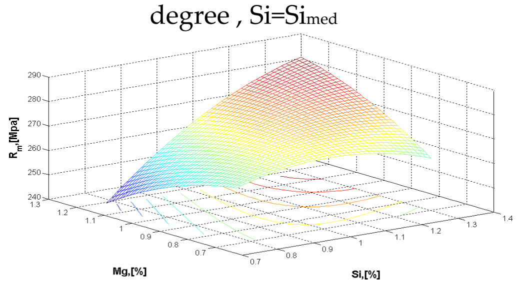


(b) – level lines

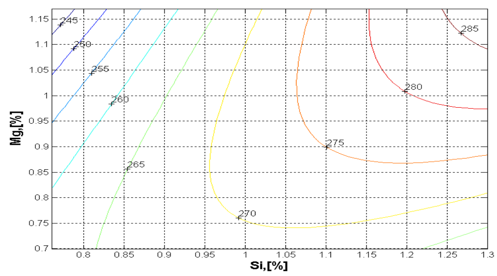


(c) – space level lines

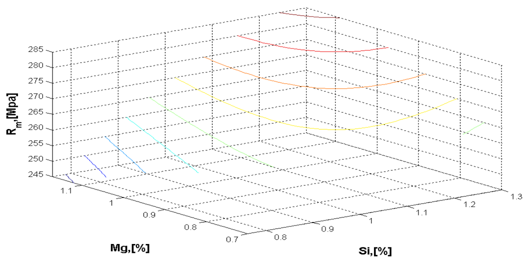
FIGURE 8. $R_m = f(Si, Ti)$ – correlation 2nd degree, $Mg = Mg_{med}$



(a) – surface regression

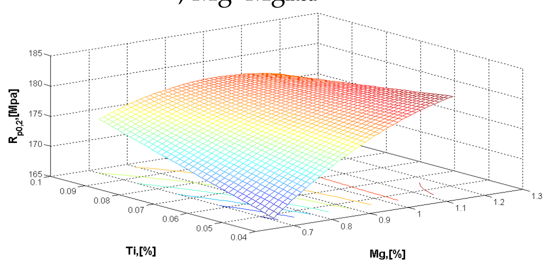


(b) – plan level lines

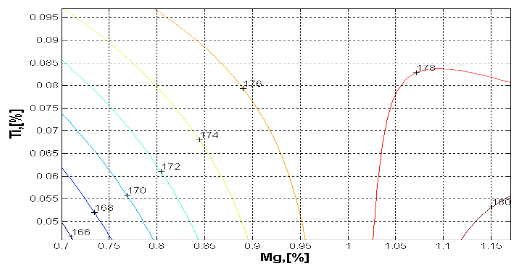


(c) – space level lines

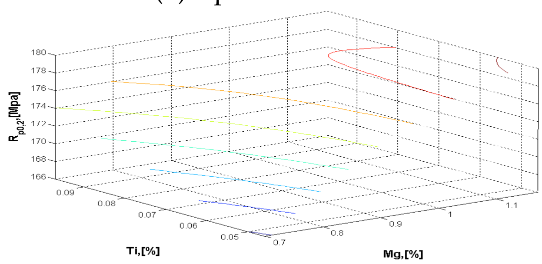
FIGURE 9. $R_m = f(Si, Mg)$ – correlation 2nd degree, $Ti = Ti_{med}$



(a) – surface regression



(b) – plan level lines



(c) – space level lines

FIGURE 10. $Rp_{0,2} = f(Mg, Ti)$ - correlation 2nd degree, $Mn = Mn_{med}$

Correlation equation between yield strenght $Rp_{0,2}$ and the content of Mn, Mg and Ti is:

$$Rp_{0,2} = -51.9118\,Mn^2 - 40{,}7802\,Mg^2 + 103.8402\,Ti^2 + 90.2381\,MnMg - 92.0092\,MnTi - 526.6073\,MgTi - 1.8211\,Mn + 66.7990\,Mg + 589.6681\,Ti + 114.3222 \quad (17)$$

Correlation coefficient is $R^2(17)^*$ =0,8720 for Mn = Mn_{med} =0.737%; Mg = Mg_{med} = 0.932%; Ti = Ti_{med} = 0.073%, $Rp_{0,2}$ = 175.01 MPa.

Pentru Mn = Mn_{med}, correlation equation between $Rp_{0,2}$ and Mg and Ti content is:

$$Rp_{0,2} = -40.7802\,Mg^2 + 103.8402\,Ti^2 - 526.6073\,MgTi + 133.3245\,Mg + 521.8369\,Ti + 84.7657 \quad (18)$$

Correlation coefficient is $R^2(18)$=0.8006. Inflection point is for Mg = 1.0280%, Ti = 0.0940, $Rp_{0,2}$= 177.8105 MPa. Stationary point is within the range of variation of the independent parameters (figure 10).

For Mg = Mg_{med}, correlation equation between $Rp_{0,2}$ and Mn and Ti content is:

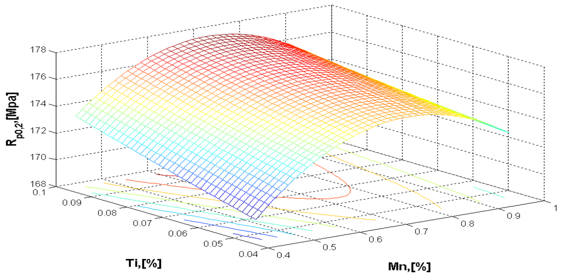
$$Rp_{0,2} = -51.9118Mn^2 + 103.8402Ti^2 - 92.0092MnTi + 82.3009Mn + 98.7530Ti + 141.1541 \quad (19)$$

Correlation coefficient is $R^2(19)$=0.4765. Inflection point is for Mn = 0.8718%, Ti = -0.0893, $Rp_{0,2}$=172.6217 MPa. Stationary point is well beyond the lower limit (figure 11).

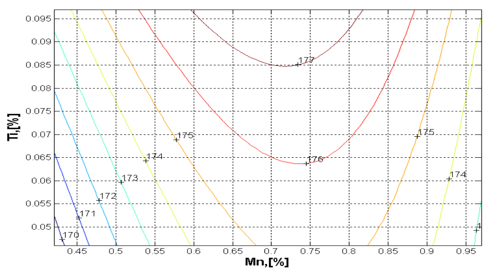
For Ti = Ti_{med}, correlation equation between $Rp_{0,2}$ and Mn and Mg content is:

$$Rp_{0,2} = -51.9118Mn^2 - 40.7802Mg^2 + 90.2381MnMg - 8.5429Mn + 28.3274Mg + 157.9549 \quad (20)$$

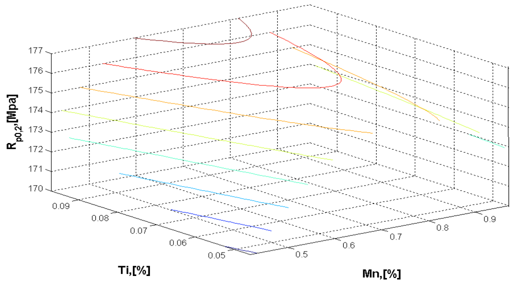
Correlation coefficient is $R^2(20)$=0.7936. Maximum point is for Mn = 5.7216%, Mg = 6.6777, $Rp_{0,2}$=228.0964 MPa. Stationary point is well above the upper limit of the range of the standard.



(a) – surface regression

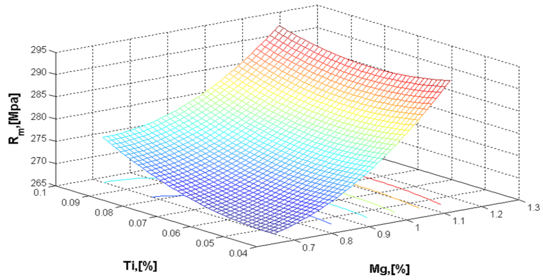


(b) – plan level lines

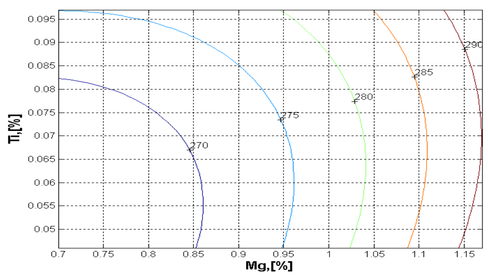


(c) – space level lines

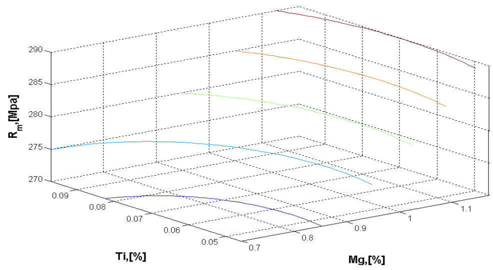
FIGURE 11 . $Rp_{0,2}$ = f (Mn, Ti) - correlation 2[nd] degree , Mg=Mg_{med}



(a) – surface regression



(b) – plan level lines



(c) – space level lines

FIGURE 12 . Rm = f (Mg, Ti) - correlation 2[nd] degree , Mn=Mn_{med}

Correlation equation between tensile strength R_m and the content of Mn, Mg and Ti is:

$$R_m = 10^3 \times \begin{pmatrix} 0.0084\,Mn^2 + 0.0821\,Mg^2 + 4.1534\,Ti^2 - 0.1056\,MnMg - 0.7859\,MnTi - 0.3873\,MgTi \\ + 0.1217\,Mn + 0.0003\,Mg + 0.4523\,Ti + 0.1944 \end{pmatrix} \quad (21)$$

Correlation coefficient is $R^2(21)$ =0.7723 for Mn = Mn_{med} =0.737%; Mg = Mg_{med} = 0.932%; Ti = Ti_{med} = 0.073%, R_m =273.444 MPa

For Mn = Mn_{med}, correlation equation between R_m and Mg and Ti content is:

$$R_m = 10^3 \times \left(0.0821\,Mg^2 + 4.1534\,Ti^2 - 0.3873\,MgTi - 0.0775\,Mg - 0.1271\,Ti + 0.2887\right) \quad (22)$$

Correlation coefficient is $R^2(22)$=0.6917. Minimum point is for Mg = 0.5714%; Ti = 0.0419%, R_m = 263.8780 MPa. Stationary point is within the range of variation of the independent parameters (figure 12).

For Mg = Mg_{med}, correlation equation between R_m and Mn and Ti content is:

$$R_m = 10^3 \times \left(0.0084\,Mn^2 + 4.1534\,Ti^2 - 0.7859\,MnTi + 0.0233\,Mn + 0.0912\,Ti + 0.2660\right) \quad (23)$$

Correlation coefficient is $R^2(23)$=0.2034. Inflection point is for Mn = 0.5550 %, Ti = 0.0415 %, R_m = 274.3461 MPa. Stationary point is within the technological limits.

For Ti = Ti_{med}, correlation equation between R_m and Mn and Mg content is:

$$R_m = 8.3849\,Mn^2 + 82.0734\,Mg^2 - 105.5702\,MnMg + 64.3275\,Mn - 28.0090\,Mg + 249.5956 \quad (24)$$

Correlation coefficient is $R^2(24)$=0.6547. Inflection point is for Mn = 0.9059%, Ti = 0.7532%, R_m = 268.1826 MPa. Stationary point is within the range of variation of the independent parameters.

3. INTERPRETATION OF THE RESULTS

From the results obtained from processing data can be considered as were obtained triple correlation equations between resistance characteristics and key elements of chemical composition: Si, Mn, Mg and Ti. Of triple correlation equations, the most significant (high correlation coefficient) were represented in graphical form. For the representation in three-dimensional space, we gave an independent parameter the average value. By permutation, from a correlation equation of the third degree, resulting three equations correlation of the second degree for each triple correlation, therefore, graphic, three correlation surfaces.

In terms of cumulative influence by elements Si, Mn and Ti, it was found:

- for content of Si = Si_{med}, increasing Mn content leads to increased yield strength, regardless of the content of Ti, higher values obtaining for Ti = 0.065 to 0.085%. Also, an increase of Ti leads to increased yield strength, particularly to 0.085% Ti (figure 1);
- for content of Mn = Mn_{med} the influence of Ti is similar as described above, and also increasing silicon content leads to increased yield strength (figure 2);
- for content of Ti equal to the medium value, both the increase of the Si, and the one of Mn, leading to increased yield strenght values, the highest values obtaining when the two elements are at the upper limit (figure 3);
- in terms of the influence of Si, Mn and Ti (Mn = Mn_{med}) influences on tensile strength (figure 4) are similar to those on the yield strength (figure 2), confirming the relationship between yield strength and tensile strength.

Regarding the cumulative influence of the elements Si, Mg and Ti, it was found:

- for content of Si = Si_{med}, increasing the content of Ti and Mg leads to an increase in yield strenght values, are significantly increases for the content of Ti to 0.090% (figure 5);
- the simultaneous growth of Si and Mg content when Ti = Ti_{med}, cause an increase for the yield strength values obtaining its maximum when Mg and Si stands for the upper limit. This increase can be considered to be caused by grain finishing through the Mg_2Si compound (figure 6);
- for values of Si = Si_{med}, the simultaneous increase of Mg and Ti content (0.090%) lead to increasing tensile strength values. These increases are caused by both grain finishing and the formation of solid solution allied (figure 7);
- Ti content increases, respectively, Si, in the range from 0.85 to 1.3% when Mg = Mg_{med} lead to increasing values for tensile strength, yielding higher values when these elements are situated at the upper limit (figure 8);

- simultaneous, growth of Si and Mg content for a constant content of Ti, determine each increase tensile strength values, so when these elements are situated at the upper limit for R_m highest values are obtained. Just like in the previous cases, the explanation lies in the formation of Mg2 Si compound leading to grain finishing (figure 9);

Regarding the cumulative influence of the elements Mn, Mg and Ti it was found:

- for content of Mn = Mn_{med}, increasing Ti content leads to increased yield strength values and in terms of Mg content, these values increase, especially up to 1.05% Mg (figure 10);
- in terms of the cumulative influence of Ti and Mn (for Mg = Mg_{med}) Ti content increases lead to higher values for yield strength, and also Mn has the same influence, especially for high Ti content (figure 11);
- concerning the cumulative influence of Ti and Mg on tensile strength (Mn = Mn_{med}), it is found that the highest values for this feature are obtained when the two elements lie at the upper limit provided in the standard (figure 12).

4. CONCLUSION

Following the analysis of experimental results, we can conclude the following:

- Alloying elements Si, Mn, Mg and Ti significantly influence (positively) the quality of the alloy, ie, characteristics $Rp_{0,2}$ and R_m;
- Influences upon those two characteristics, $Rp_{0,2}$ and R_m are similar, which shows a good correlation between the two mechanical characteristics;
- Values of the mechanical characteristics are influenced by compounds that finishing grain size, as well as those that form solid solutions allied;
- knowing the correlations allow a better match between the alloying elements.

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