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Quantitative Analysis for Effect of Copper on Various Mechanical Properties of Ductile Iron during Austempering

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Abstract
Aim of this study is to perform relevant quantitative analysis of the observations during austempering of with or without copper in ductile iron. Ductile iron is a group of materials having wide range of properties and possessing controlled microstructure. Austempered-Ductile-Iron (ADI) is a relatively new material having exceptional combinations of mechanical properties and having potential applications. Researchers had tried to customize its properties mainly; yield strength (YS), percentage of elongation, ultimate tensile strength (UTS) and hardness by doping materials like copper in its microstructure. The present work highlights impact of austempering temperature and time on various mechanical properties of ductile iron and further emphasis to execute quantitative analysis for uncovering the affect of copper, effectively. Next General-Regression is applied to find relation of various properties with given Austempering metrics. High R (sq) value (0.80) signifies strong relations of properties with temperature and time, respectively and demonstrated empirically in terms of linear equations for drawing necessary implications for future research. The paper does not cover the images of microstructure or change in micro structural behavior during the austempering process of ductile iron. The paper also not covers the fractural behavior of ADI.

Keywords : Austempered-Ductile-Iron (ADI), Yield Strength (YS), Percentage of Elongation, Ultimate tensile strength (UTS), hardness, quantitative analysis, General regression analysis, regression equations, Scatterplot

I. INTRODUCTION

The process of alloying is used to change the chemical composition of steel and improve its properties over carbon steel or adjust them to meet the requirements of a particular application. Every steel is truly an alloy but not all steels are called "alloy steels". Even the simplest steels are iron (Fe) (about 99%) alloyed with carbon (C) (about 0.1% to 1%, depending on type) [1] [2]. Precipitation of Cu in iron and steel is a well-known phenomenon and it might have a potential to achieve better strength-ductility balance than conventional high-strength steels because of a different nature of Cu precipitates from other precipitates like carbides and nitrides [3]. The introduction of copper into an iron–carbon melt coarsens the microstructure of the particles and increases the grain size [4]. With an increasing copper content, the elongation of steel monotonically decreases and its thermal conductivity grows [5]. The austenitizing temperature controls the carbon content of the austenite which, in turn, affects the structure and properties of the austempered casting. Austenitizing time should be the minimum required to heat the entire part to the desired austenitizing temperature and to saturate the austenite with the equilibrium level of carbon. Once the austempering temperature has been selected, the austempering time must be chosen to optimize properties through the formation of a stable structure of ausferrite [6].

II. METHODOLOGY ADOPTED

In the paper, data obtained from the previous research work [1] is further analyzed by quantitative approaches. Tests were executed by using Minitab-16 software and the effect of copper addition along with austempering temperature and time is considered.

III. RESULTS AND DISCUSSIONS

The results obtained are displayed by multi- vari chart (Fig. 1) which shows with the addition of 0.49% copper [1] percentage of elongation decreases at each stage of austenisation.

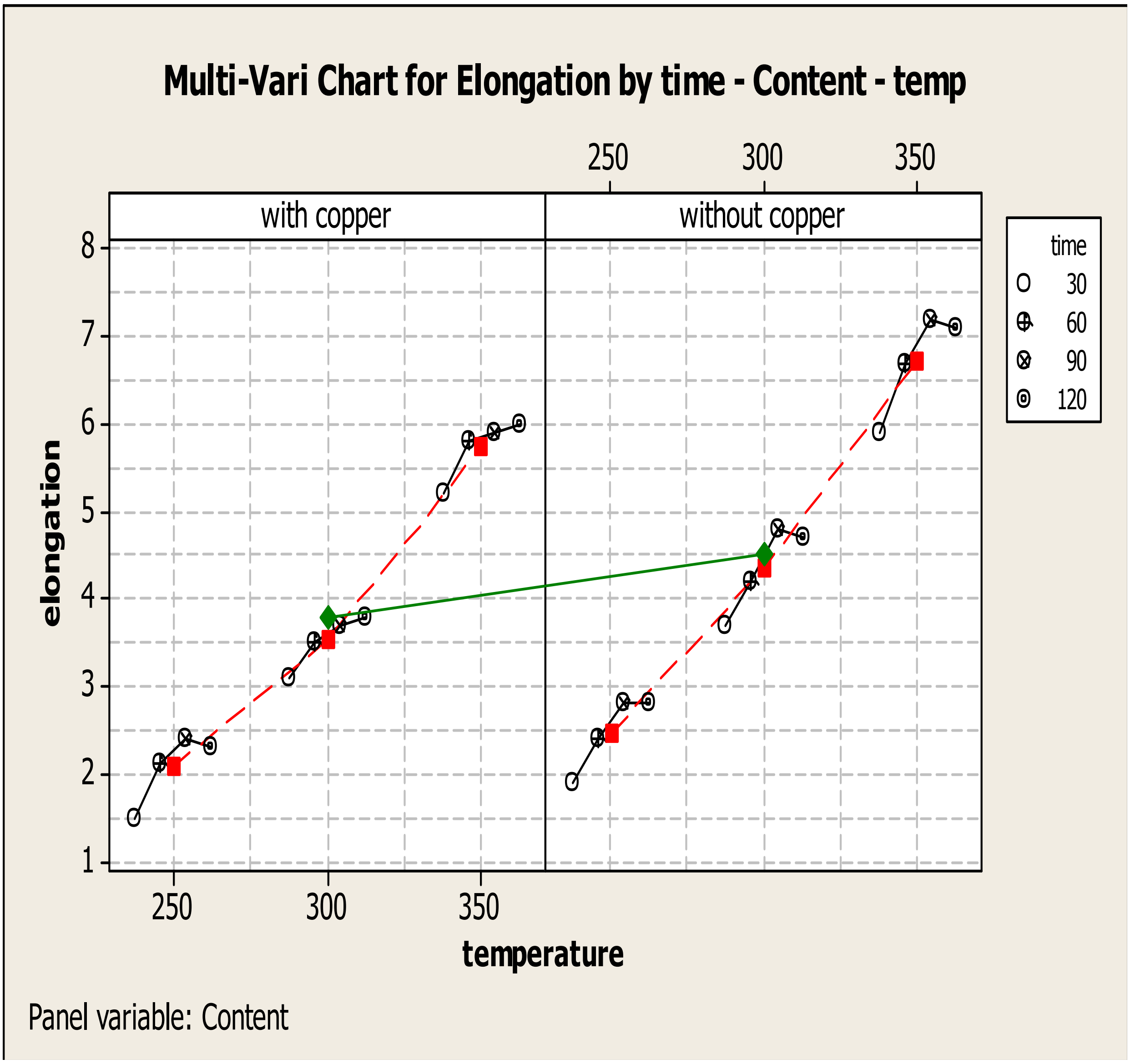

Figure 1: Effect of copper addition with different austempering temperature (°C) and time (minutes) on percentage of elongation (mm)

It is clear that elongation in both ductile irons increases with the increase in austempering temperature and time. But with the addition of copper and austempering at 250°C for 30 minutes the elongation decreases to 1.5% from 1.8% while at the same temperature with increase in austempering time up to 120 minutes elongation decreases to 2.5% from 2.8%. For the same materials at 350°C austempering temperature and 120 minutes austempering time elongation decreases to 6% with addition of copper from 7%. Based upon the results shown in Fig 1 general regression analysis has been checked out (Fig 2). For time as a variable, p value (0.000) is smaller than 0.05 and hence signifies its importance in elongation. Two separate equations are drawn to find out a linear relation between elongation and austempering temperature and austempering time.

Regression Equation

Content
with copper elongation = -8.8375 + 0.0101667 time + 0.0395 temperature

without copper elongation = -8.09583 + 0.0101667 time + 0.0395 temperature

Coefficients

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	-8.46667	0.452551	-18.7088	0.000
Content	-0.37083	0.058424	-6.3473	0.000
time	0.01017	0.001742	5.8366	0.000
temperature	0.03950	0.001431	27.6013	0.000

Summary of Model

S = 0.286218 R-Sq = 97.66% R-Sq(adj) = 97.31%
PRESS = 2.32363 R-Sq(Pred.) = 96.69%

Figure 2: General Regression Analysis: elongation versus time, temperature, Content

The regression model is well fitted (as R sq adjusted value is around 97.66%) and speaks itself the vitalness of austempering temperature and austempering time in the decrease of elongation of the material. Hardness (RA) of the materials for the same percentage addition of copper and same process parameters is also calculated (Fig 3). Results obtained define hardness of the ductile iron increases with the addition of copper as mean line indicates positive slop.

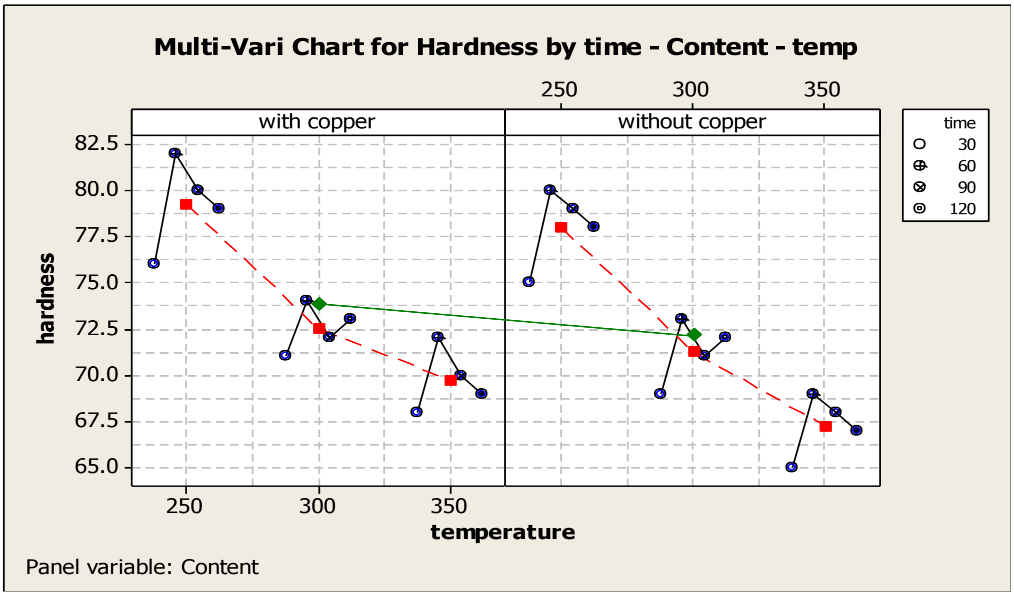

Figure 3: Effect of copper addition with different austempering temperature (°C) and time (minutes) on hardness (RA)

For both materials (with copper, without copper) at every stage of temperature hardness increases for first 60 minutes of austempering time and then starts decreasing. At austempering temperature 250°C and time 30 minutes hardness obtained is 76 RA with copper compared to 75RA without copper. While austempering at 350°C for 30 minutes hardness decreases to 68 RA with copper compared to 66 RA without copper. The general regression analysis of hardness versus austempering time and austempering temperature is also checked out (Fig 4). Two equations has been generated to find out the relation between hardness and austempering temperature and austempering time.

Regression Equation

Content
with copper hardness = 102.875 + 0.0177778 time - 0.10125 temperature

without copper hardness = 101.208 + 0.0177778 time - 0.10125 temperature

Coefficients

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	102.042	3.01533	33.8410	0.000
Content	0.833	0.38928	2.1407	0.045
time	0.018	0.01161	1.5318	0.141
temperature	-0.101	0.00954	-10.6184	0.000

Summary of Model

S = 1.90706 R-Sq = 85.68% R-Sq(adj) = 83.53%
PRESS = 102.829 R-Sq(Pred.) = 79.76%

Figure 4: General Regression Analysis: hardness versus time, temperature, Content

The regression model is well fitted as R square value is 85.68% and p value is 0.00 less the 0.5 hence significant. The regression equations show linear relation between hardness of ADI and austempering temperature and time. Negative sign in the equations show with the increase in austempering temperature hardness of the materials decrease while austempering time has small positive effect on the same. Fig 5 represents variation of Ultimate tensile strength (UTS) with austempering temperature and time. Positive slope represents UTS of the ductile iron increases with the addition of copper but with the increase of austempering temperature and austempering time UTS of ductile iron decreases.

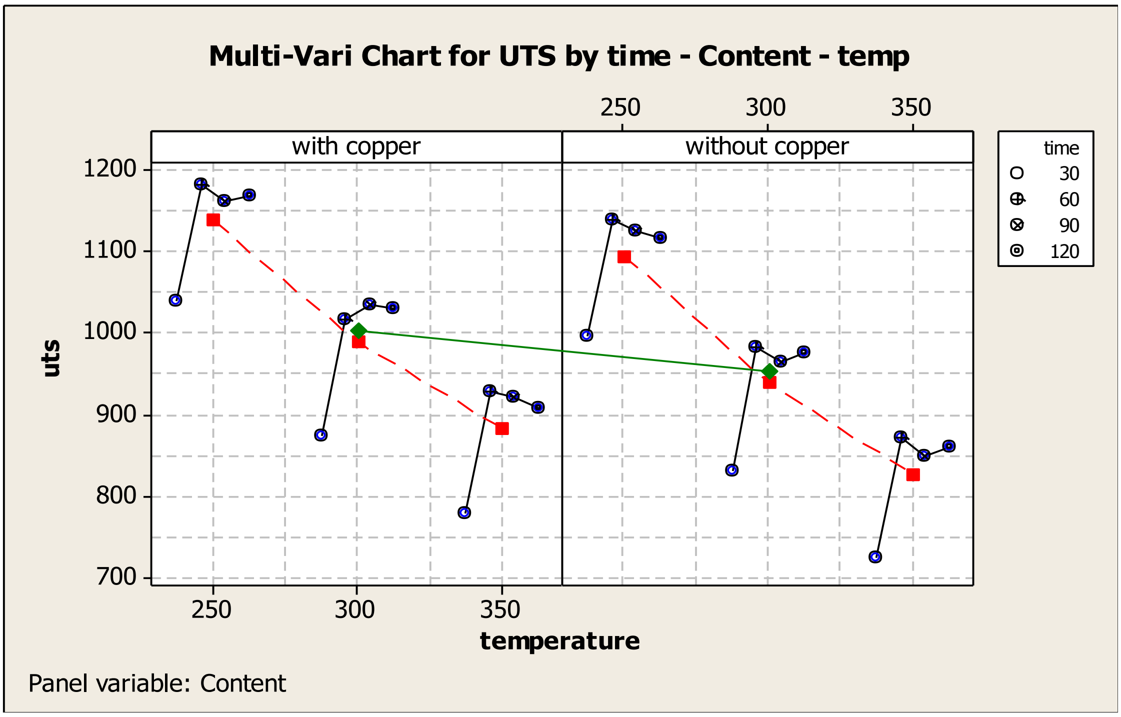

Figure 5: Effect of copper addition with different austempering temperature (°C) and time (minutes) on ultimate tensile strength (MPa)

From the observations maximum UTS achieved is around 1200 MPa with the addition of copper and austempering at 250°C for 60 minutes compared to 1150 MPa without copper for the same process variables. UTS of the materials shows same trend as observed in hardness. With the increase in austempering temperature from 250°C to 350°C UTS of the ADI decreases in both cases. The above shown results are further analyzed by general regression analysis shown in Fig 6. Again two separate equations have been formed to find out the linear relation of UTS with austempering temperature and time with confidence level.

Regression Equation

Content
with copper UTS = 1686.46 + 1.32444 time - 2.60875 temperature

without copper UTS = 1636.29 + 1.32444 time - 2.60875 temperature

Coefficients

Term	Coef	SE Coef	T	P
Constant	1661.38	74.2634	22.3714	0.000
Content	25.08	9.5874	2.6163	0.017
time	1.32	0.2858	4.6335	0.000
temperature	-2.61	0.2348	-11.1086	0.000

Summary of Model

S = 46.9683	R-Sq = 88.35%	R-Sq(adj) = 86.61%
PRESS = 62903.7	R-Sq(Pred.) = 83.39%	

Figure 6: General Regression Analysis: ultimate tensile strength versus time, temperature

The regression model is well fitted as R square value is 88.35% and P value is 0.00 less than 0.5. Negative sign in the equation show decrease of UTS with the increase of austempering temperature. Fig 7 represents variation of Yield strength (YS) with austempering temperature and time. Positive slope represents YS of the ductile iron increases with the addition of copper but with the increase of austempering temperature and austempering time YS of ductile iron decreases.

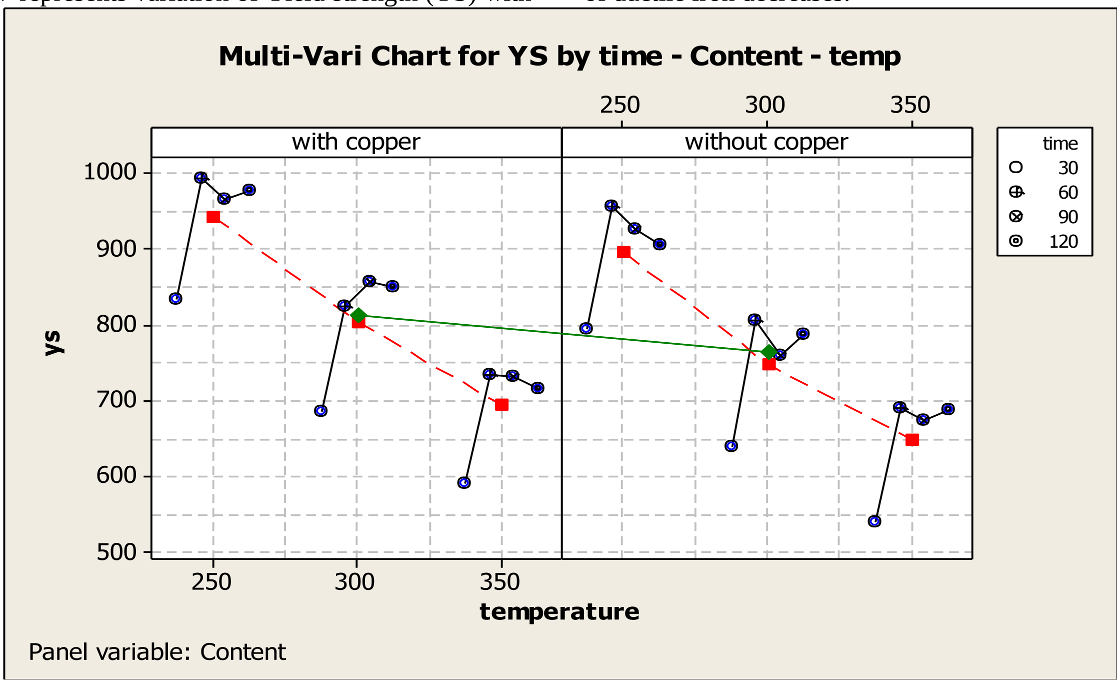

Figure 7: Effect of copper addition with different austempering temperature (°C) and time (minutes) on yield strength (MPa)

YS of the ADI also show the same trend shown by UTS. With the addition of copper yield strength of the ADI decreases from 1000 MPa to 600 MPa compared to 950 MPa to 550 MPa with increase of austempering temperature from 250°C to 350°C .

The above shown results are further analyzed by general regression analysis shown in Fig 8. Again two separate equations have been formed to find out the linear relation of YS with austempering temperature and time with confidence level.

Regression Equation

Content

with copper YS = 1460.21 + 1.35389 time - 2.4925 temperature

without copper YS = 1410.12 + 1.35389 time - 2.4925 temperature

Coefficients

Term	Coef	SE Coef	T	P
Constant	1435.17	79.6643	18.0152	0.000
Content	25.04	10.2846	2.4349	0.024
time	1.35	0.3066	4.4154	0.000
temperature	-2.49	0.2519	-9.8940	0.000

Summary of Model

S = 50.3842 R-Sq = 86.04% R-Sq(adj) = 83.95%
PRESS = 72388.1 R-Sq(pred.) = 80.10%

Figure 8: General Regression Analysis: Yield strength versus time, temperature

The regression model is well fitted as R square value is 86.04% and P value is 0.00 less than 0.5. Negative sign in the equation show decrease of YS with the increase of austempering temperature.

IV. CONCLUSION

Quantitative analysis of the observations represents elongation is the only property that decreases with the addition of copper in ADI while hardness, YS and UTS increases. In both materials with and without copper at every stage of temperature with increase in austempering time elongation increases. Hardness, UTS and YS shows common behavior as with increase in austempering time the values obtained first increase for 60 minutes and then start decreasing. General regression models are well fitted as R square values obtained always greater than 80%.

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