

Dependence of hardness to the applied load of the 42CrMo4 steel manufactured by MIM process

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Abstract

For the purposes of this article the hardness of material 42CrMo4 steel which is manufactured by metal injection molding (MIM) process was measured by Vickers method. When determining hardness the following loads: 196,1; 294,1; 392,2; 490,2; and 980,4 N were used. The objective was to determine the unknown relationship between applied load and hardness. A numerical processing of the experimental data was performed in the software package MATLAB (v.R2012.a, The MathWorks, Inc., Natick, MA, USA). The impact of the load on the hardness was determined by regression analysis. In calculating the undetermined coefficients two mathematical models were used, Meyer's law and a model of resistance proportional to the properties of the sample (PSR). The results show that used mathematical models very well describe the effect of the load on the measured hardness.

Keywords: steel 42CrMo4, hardness, metal injection molding

1. Introduction

Metal injection molding (MIM) combines two technologies, plastic injection molding and powder metallurgy. MIM process is ideal for small production of complex parts with excellent mechanical properties. Compared to traditional manufacturing process MIM offers greater freedom of designing parts made from stainless steel, nickel-iron, copper, titanium and other metals [1]. A very important step in the MIM process is the production of raw materials which will be used. In order to achieve good flow, which is required in the metal injection molding process, the powder is mixed with thermoplastic polymers (also known as a binder) in a hot state to form a mixture in which all metal particles are equally coated with the binder. The result is a non-united sample which is then subjected to a binder removal process. Mixing metal or ceramic powders with organic binders in the production process is a critical step to ensure a quality product [2]. Research has shown that MIM improves product quality, reduces production time and achieves cost savings of up to 50%. Although new technology, MIM

process is becoming widely accepted as a standard procedure in the number of industrial sectors including medical, military applications, precision engineering and automotive industry.

2. Hypothesis

Numerous studies show that the hardness depends on the load. For most materials hardness reduces with increased load (normal impact load hardness), while some material hardness increases with load (reverse impact load for the hardness) [3]. In our case dependence of load to hardness is not defined because the properties of parts manufactured by MIM process are unknown. So, the main objective of this study is to determine the relationship between load and hardness of material manufactured by MIM process.

For the purposes of this paper material samples of 42CrMo4 steel hardness were measured by Vickers method. Hardness testing is probably the most commonly used test of mechanical properties. Despite the mechanical properties are determined by testing, the hardness is not physically unambiguously defined

size, and is correlated with other mechanical properties. This primarily refers to the tensile strength, resistance to abrasive wear and so on. For the test it is not required to make a special tube, but it is only appropriate to prepare the sample surfaces or mechanical parts. The most commonly applied method for measuring the hardness of metal materials are methods of Vickers (HV) and Brinell (HB).

For each of five specified loads 15 samples were measured (every load three prints), which resulted in total of 225 prints measured. The prints were taken on the random places of the samples. The dimensions of samples are 6x4x44 mm. The samples were hardened on 850°C for 30 minutes and cooled in oil. Prior to measuring, the surface of samples was prepared with 80 gritt sand paper.

All measurements were done on the device VEB Werkstoffprüfmaschine "Fritz Hecker" (Figure 1). The following loads were used: 196,1; 294,1; 392,2; 490,2 and 980,4 N.

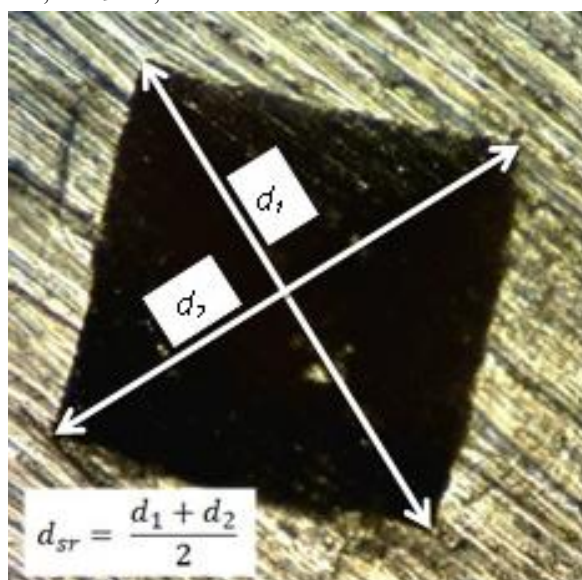


Figure 1. Vickers imprint of diamond pyramid

The microstructure of 42CrMo4 steel is homogeneous and has a very low share of non-metallic inclusions. Table 1 shows the chemical composition of 42CrMo4 steel which was measured by spectroscopy Arun PolySpek model M.

Table 1. Steel chemistry 42CrMo4 [4]

C, %	Si, %	Mn, %	Cr, %	Mo, %
0,41	0,20	0,75	1,05	0,23

2.1. Regression analysis

When the mathematical model of behavior is not known, there are several methods to obtain it from

experimental results. One such method is regression analysis. Results are experimentally obtained for various levels of factors. From each level and appropriate results, couples of numerical values are formed [5]:

$$(x_i, y_i) = x_1 y_1, x_2 y_2, x_3 y_3, \dots, x_n y_n \quad (1)$$

which in the case of the tests can be shown by table 2.

2.2. Regression analysis in Matlab

The regression of analysis was used to determine impact of the load on the hardness. There are several mathematical models that are used for the quantitative determination of dependence of the applied load and the size of the print like Meyer's law and model of resistance proportional to the properties of the sample [6,7].

Numerical processing of the experimental data was performed using the software package MATLAB (v.R2012.a, The MathWorks, Inc., Natick, MA, USA). As an input data for the calculations measured data was used (Table 2).

Table 2. Summary results

Load, N	d_{sr} , mm	Hardness, HV
196,1	$0,3643 \pm 0,0063$	285,1
294,1	$0,4480 \pm 0,0046$	278,3
392,2	$0,5170 \pm 0,0065$	273,8
490,2	$0,5808 \pm 0,0118$	204,4
980,4	$0,8259 \pm 0,0056$	269,9

2.3. Polynomial regression - Meyer law

Meyer's law is mathematical model that describes connection between the applied force F and measured diagonal base print d of Vickers pyramid in the material. According to the literature value of Meyer index n is in the range from 1.5 to 2.0. If Meyer's index is $n < 2$ then the hardness depends on the applied load, and if $n = 2$ then the applied load has no effect on the measured hardness (Figure 2). The mathematical form of Meyer's law states [3]:

$$F = k \cdot d^n \quad (2)$$

where:

F [N] - applied force,

k - material constant,

n - Meyer's index

d [mm] - diagonal imprint.

The most commonly used regression models are those which meet the description of the regression line using a polynomial. In this case, polynomial regression was performed using Meyers law.

To be able to make a polynomial regression, function describing Meyer's law must first be linearized.

$$F = k \cdot d^n \quad (3)$$

$$\log F = \log(k \cdot d^n) \quad (4)$$

$$\log F = \log k + \log d^n \quad (5)$$

$$\log F = \log k + n \cdot \log d$$

(6)

$$y = \log F$$

(7)

$$b = \log k$$

(8)

$$n \cdot \log d = n \cdot x$$

(9)

$$y = nx + b \quad (10)$$

Once the function is linearized it is necessary to adapt the measured data, to the new linearized model. Adjusted data for Meyer's law are shown in table 3.

Table 3. Example of coding data for Meyer's law

Log(F)	Log(d)
5.2786	-1.0099
5.6839	-0.8029
5.9718	-0.6598
6.1948	-0.5434
6.8880	-0.1913

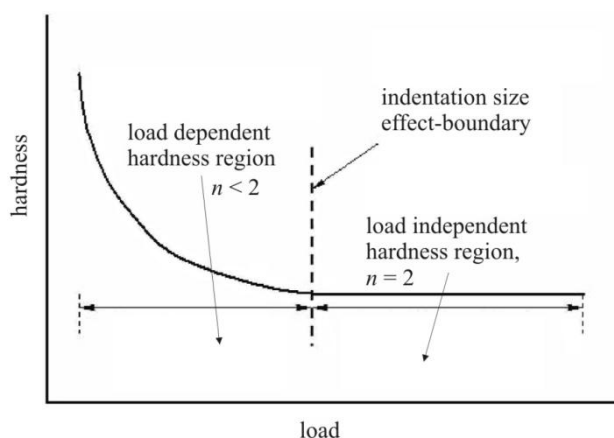


Figure 2. Meyer index [3]

2.4. Results - Meyer law

The most common interpretation of the load on the hardness, according to the professional literature, is directly connected with the structural factor of the material. Meyer proposed an empirical relationship between the applied load F and the size of the print d . This relationship is commonly called Meyer's law. Measure of the impact of load on the hardness is the coefficient n . The parameters were obtained from the logarithmic dependency of hardness on the display diagonal (Figure 3). Figure 3 represents the slope of Meyer index n , and the ordinates axis intercept represents the $\log(k)$.

The resulting linear relationship indicates that Meyer's model is suitable to describe the impact of load on the hardness of 42CrMo4 steel ($R^2 = 1.00$).

Parameter values k are determined by linear regression analysis and amount (Figure 3):

$$b = \log(k) = 7.1647 \quad (11)$$

$$n = 1.9662$$

(12)

$$R^2 = 1.00$$

(13)

The resulting function is:

$$y = 1.9662 \cdot x + 7.1647 \quad (14)$$

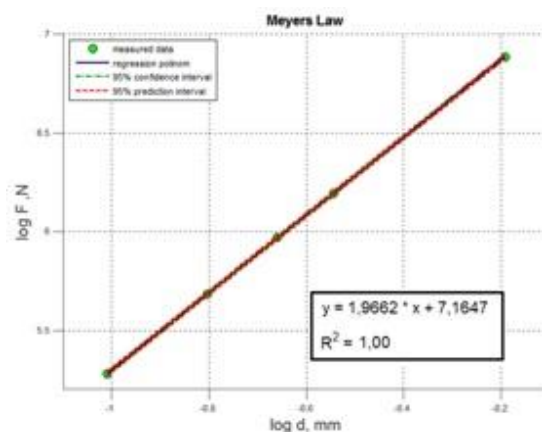


Figure 3. F-d correlation according to Meyer's law

The resulting value of Meyer's index n is less than 2 ($n=1.9662$) and therefore indicates that the applied load affects the hardness of the tested material (Figure 2).

2.5. Polynomial regression - PSR model

As an alternative to Meyer's law we also used model of resistance proportional to the properties of the sample (PSR) model.

PSR model was developed by the researchers Li and Bradt [3]. In this model, applied load F and print size d are connected in mathematical expression of the form:

$$F = a_1 d + a_2 d^2 \quad (15)$$

In the above equation a_1 and a_2 are coefficients that are related to the apparent hardness of the sample hardness (plasticity). a_1 is in the unit of N/mm, and a_2 in N/mm². The parameters a_1 and a_2 can be assessed from the linear - regression analysis of the relationship $F - d$, but it is necessary to linearize the mathematical function:

$$F = a_1 d + a_2 d^2 \quad (16)$$

$$F/d = a_1 + a_2 d \quad (17)$$

$$y = \frac{F}{d} \quad (18)$$

$$b = a_1 \quad (19)$$

$$a \cdot x = a_2 \cdot d \quad (20)$$

$$y = ax + b \quad (21)$$

Once the function is linearized it is necessary to code the measured data, or adjust them to the new linearized model as well as in the application of Meyer's law.

Table 4. Example of coding data for PSR model

$F/d, \text{N/mm}$	d_{sr}, mm
1.5656	$0,3643 \pm 0,0063$
0.8499	$0,4480 \pm 0,0046$
0.9566	$0,5170 \pm 0,0065$
1.0569	$0,5808 \pm 0,0118$
1.5563	$0,8259 \pm 0,0056$

2.6. Results - PSR model

The parameters a_1 and a_2 are obtained from the display depending on the size of the Vickers pyramid diagonal (Figure 4). The slope represents the parameter a_2 and section on the vertical axis is represented by the parameter a_1 .

The resulting linear relation indicates that the PSR model is suitable for describing the impact of load on the hardness of 42CrMo4 steel ($R^2 = 0.99$).

The values of the parameters a_1 and a_2 are determined by linear regression analysis (Figure 4):

$$a_1 = 28.7069 \quad (22)$$

$$a_2 = 1403.9693 \quad (23)$$

$$R^2 = 0.99 \quad (24)$$

The resulting function is:

$$y = 1403.9693 \cdot x + 28.7069 \quad (25)$$

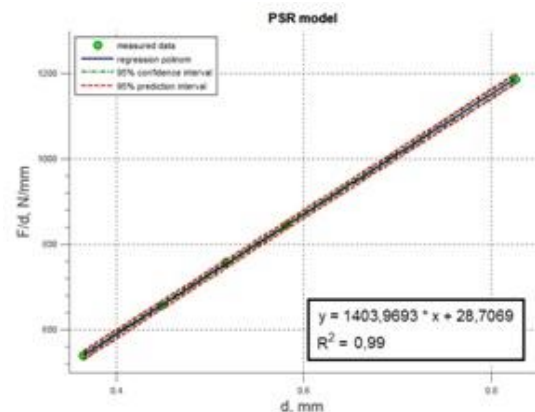


Figure 4. $F-d$ correlation according to PSR model

Conclusion

For the quantitative determination of the load impact on the hardness, two suitable mathematical models were used - Meyer's law and a model of resistance proportional to the properties of the sample. The calculated value of correlation coefficient $R^2 = 1.00$ clearly indicates that Meyer's law can be applied for the purpose of quantitative determination of the impact load on the hardness of 42CrMo4 steel manufactured by metal injection molding process. The resulting value of Meyer's index is $n = 1.9662$, and is less than 2, which indicates that the applied load affects the measured hardness of the material.

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