STUDY ON RELATIONSHIP BETWEEN MICRO VICKERS HARDNESS AND INDENTATION HARDNESS

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Abstract: The relationship between micro Vickers hardness and indentation hardness of GCr15 and 9CrSi materials under different test forces is studied, and the corresponding formulas are given. This not only makes it easy to get the unknown information of the two materials under any limited test conditions, but also provides a direction for exploring the property change of other materials in the whole test process and related researches. The experimental results are compared with the equations given by the finite element method, which provides a powerful reference for the further improvement of the theoretical analysis.

Keywords: Micro Vickers hardness, Indentation hardness, 9CrSi, GCr15, Relationship.

1. INTRODUCTION

Micro Vickers hardness and indentation hardness tests are important means of material science and engineering research [1, 2]. Micro Vickers hardness is a main parameter to evaluate the plastic deformation of material. The micro Vickers hardness test focus on learning the material ability to restore the deformation, and its test force is generally in the range of (10 gf ~ 200 gf). Indentation hardness is to evaluate the material ability to resist deformation and damage. Its test force is generally in the range of (0.05 gf ~ 200 gf). Because of their differences in the time points of interest in the test procedure, micro Vickers hardness and indentation hardness test methods have different principles and the material properties they exhibit are also different. Micro Vickers hardness is usually measured and evaluated using a micro Vickers hardness tester, while indentation hardness is measured and reported by a nanoindenter. Because the force ranges of the two hardness test methods have an overlap and the indenters they use have a certain correlation, establishing a link between micro Vickers hardness and indentation hardness is an effective way for analyzing the whole process of elastic and plastic deformation of materials. It has very obvious practical application value for obtaining an unknown information through another known information under limited test conditions. In ISO 14577 [3], the indentation hardness H_{IT} is related to the Vickers hardness HV by a scaling factor, but it

is pointed out that the simple correlation may break down for small indentation depths since the indenter geometry is generally not perfect. In order for a better understanding of the relationship between the micro Vickers hardness and indentation hardness, the correlation between the two hardness evaluation methods are studied experimentally in this paper.

2. THEORETICAL CONNECTION OF MICRO VICKERS HARDNESS AND INDENTATION HARDNESS

In the micro Vickers hardness test and the indentation hardness test, the indentation depth and the contact area between the indenter and the material are important parameters for understanding the elastic-plastic indentation. Figure 1 shows the relevant parameters of the elastic-plastic indentation process. The hardness calculation equation is shown in equation (1).
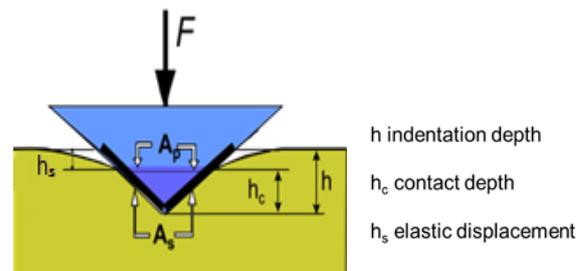

Figure 1 Parameters of elastic-plastic indentation process

$$hardness = \frac{forceF}{surface[A_s(h)\,or\,A_p(h_c)]} \tag{1}$$

Micro Vickers hardness HV is calculated using the surface area A_s, and indentation hardness H_{IT} is calculated using the projected area A_p. When both the micro Vickers hardness and indentation hardness are measured using a pyramid indenter, the indentation parameter diagram is shown in figure 2. The surface area and projected area can be calculated according to equation (2) and equation (3), respectively. For a perfect Vickers indenter, the angle between the two opposite faces is 136 °.
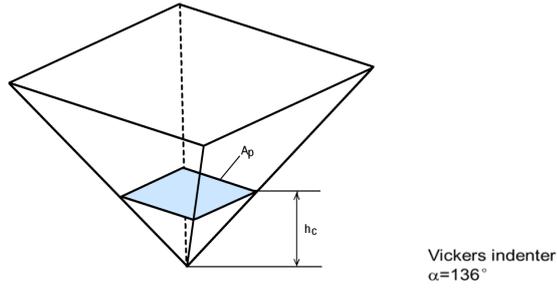
Figure 2 Schematic diagram of pyramid indenter

$$A_s = \frac{4(h\tan 68°)^2}{\sin 68°} = 26.429h^2 \tag{2}$$

$$A_p = 4(h\tan 68°)^2 = 24.504h^2 \tag{3}$$

It is shown from above equations that the ratio of projected area to surface area at any particular distance from the tip of a perfect Vickers indenter is a constant. According to ISO 14577 [3], indentation hardness H_{IT} may be correlated to Vickers hardness HV by using a suitable scaling function. For a Vickers indenter, H_{IT} are related to the Vickers Hardness HV by the following equation.

$$HV = \frac{A_p}{g_n \times A_s} H_{IT} = 0.0945 H_{IT} \tag{4}$$

where g_n is acceleration due to gravity.

It is made clear in ISO14577 that although H_{IT} may be correlated to HV in this way, any equivalent HV value so calculated should not be used as a substitute for HV. The relationship shown in equation (4) is only a theoretical reference, but can not be used as a basis for judgments and guidance. So it is more valuable to look for the actual correspondence.

3. TEST

3.1 Material preparation

Considering the universality and testability of the materials, the standard micro Vickers hardness blocks of 9CrSi and GCr15, which are the most commonly used materials in micro Vickers hardness metrology, were chosen for the micro Vickers hardness HV test and the H_{IT} hardness test. The micro Vickers hardness of the samples are in the range of (210 ~ 850) HV with an interval of about 40 HV. The compositions of materials are shown in table 1.

Table 1. Compositions of 9CrSi and GCr15

Material	C	Si	Mn	P	S
9CrSi	0.89	1.42	0.46	0.016	0.0023
	Cr	Ni	Cu	Mo	/
	1.12	0.17	0.051	/	/
GCr15	C	Si	Mn	P	S
	1.00	0.27	0.37	0.0077	0.0018
	Cr	Ni	Cu	Mo	/
	1.44	0.082	0.098	0.020	/

3.2 Test process

The samples of the two types of materials were measured using micro Vickers hardness tester and nanoindentation tester, respectively. Both tests were carried out with Vickers indenter. The micro Vickers hardness (HV) was obtained by measuring the sample with a micro Vickers hardness tester according to ISO 6507 [4]. The indentation hardness H_{IT} was measured using a nanoindenter according to ISO 14577. Both test instruments have been calibrated and are traceable to the basic quantity to ensure the accuracy of test data. Considering the compatibility and operability of the two instruments, the test forces applied in the tests are in the range of (50 gf ~ 200 gf).

3.3 Test results

In the micro Vickers hardness and indentation hardness tests described above, the samples of 9CrSi and GCr15 that have different hardness are measured under different test forces. A total of 10 sets of HV, H_{IT} and HM data were obtained by the 9CrSi material, and 15 sets of corresponding data were obtained by the GCr15 material. The measurement data of 9CrSi are listed in table 2, and the data of GCr15 are listed in table 3. Each value is an average of five measurement values. The measurement results are also shown in figure 3 and figure 4, respectively. Figure 5 shows an example of nanoindentation test curve.

Table 2. Measurement results of HV, H_{IT} and HM for 9CrSi

Scale Number	HV0.2			HV0.1			HV0.05		
	HV	H_{IT}	HM	HV	H_{IT}	HM	HV	H_{IT}	HM
1	840.3	10078.42	6603.71	842.0	10118.83	6619.72	833.6	9995.20	6530.58
2	752.0	9062.35	6170.69	746.1	8976.44	6072.73	755.0	9055.24	6126.84
3	746.0	9013.83	6121.23	741.0	8972.15	6079.33	743.0	9000.07	6100.06
4	648.0	7887.48	5565.49	642.0	7820.77	5503.26	647.2	7875.42	5534.44
5	628.0	7722.21	5504.59	628.5	7734.29	5490.23	626.5	7721.52	5473.34
6	587.0	7255.79	5194.46	583.8	7188.37	5136.26	582.8	7214.99	5161.06
7	525.0	6513.76	4766.06	518.6	6404.94	4700.63	516.8	6433.22	4708.08
8	484.1	6145.14	4593.26	482.7	6088.25	4534.73	481.5	6036.21	4508.22
9	334.2	4258.18	3348.31	329.0	4171.42	3263.72	332.4	4218.47	3316.3
10	286.8	3663.76	2929.91	283.0	3597.31	2875.84	286.6	3662.14	2926.59

Table 3. Measurement results of HV, H_{IT} and HM for GCr15

| Scale Number	HV0.2			HV0.1			HV0.05		
	HV	H_{IT}	HM	HV	H_{IT}	HM	HV	H_{IT}	HM
1	809.8	9553.23	6501.75	798.0	9393.67	6362.12	810.0	9590.28	6475.02
2	740.9	8741.4	6070.03	749.2	8876.17	6116.86	741.2	8779.70	6044.32
3	721.0	8544.41	5995.44	713.8	8455.92	5927.58	709.1	8419.50	5896.31
4	657.0	7806.09	5475.11	657.4	7790.41	5519.60	655.7	7792.13	5521.45
5	598.2	7110.28	5136.77	599.9	7111.42	5153.83	616.0	7444.83	5361.52
6	564.9	6811.10	5031.11	561.3	6735.92	4970.21	566.0	6857.97	5038.80
7	552.0	6659.35	4962.13	554.0	6732.37	4936.28	543.8	6596.62	4875.65
8	531.0	6441.60	4805.11	531.4	6490.42	4795.39	529.4	6476.30	4812.72
9	470.1	5726.50	4337.60	466.3	5719.75	4304.65	464.0	5698.45	4291.82
10	421.0	5160.79	3983.96	411.3	5050.98	3902.95	409.1	5050.81	3881.17
11	377.9	4712.18	3705.18	374.1	4626.12	3643.87	374.0	4625.86	3636.67
12	350.9	4412.46	3503.32	345.6	4354.51	3453.18	339.9	4248.17	3369.02
13	289.2	3658.38	2960.29	287.4	3652.60	2951.22	288.5	3661.03	2963.20
14	275.2	3501.35	2848.40	270.1	3442.32	2804.80	272.1	3468.74	2818.80
15	210.5	2663.78	2208.24	214.0	2668.27	2213.31	211.4	2675.43	2219.44
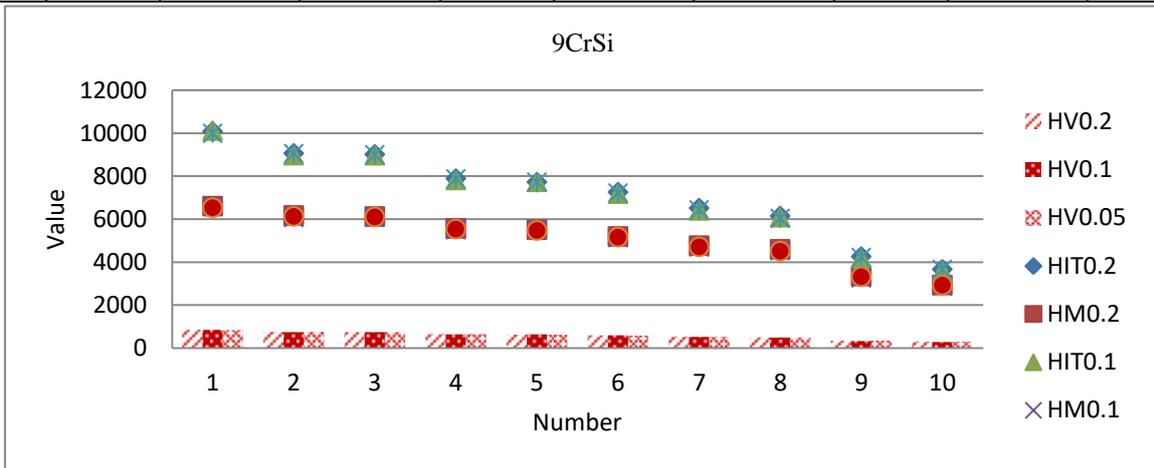
Figure 3. The correlation of HV, H_{IT} and HM for 9CrSi
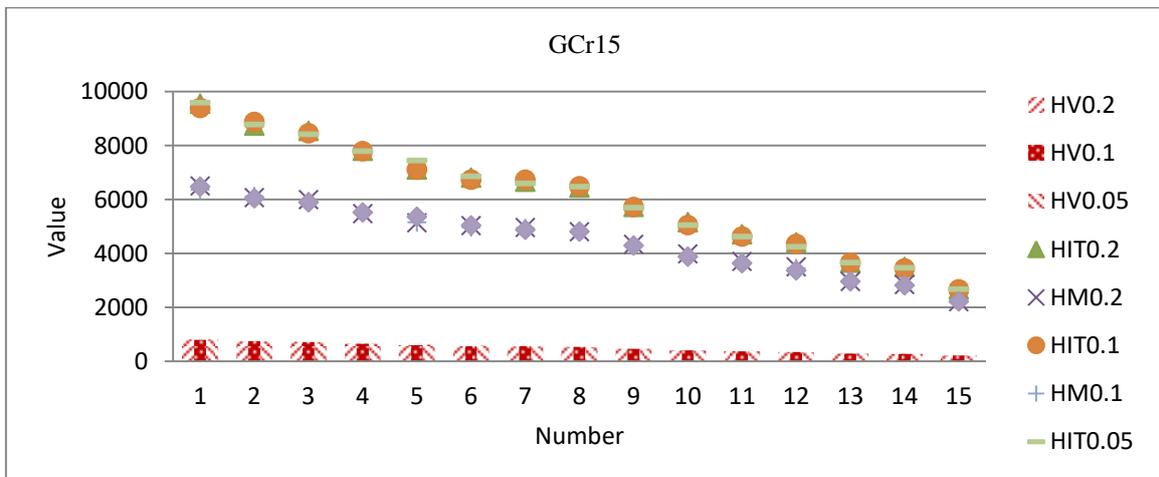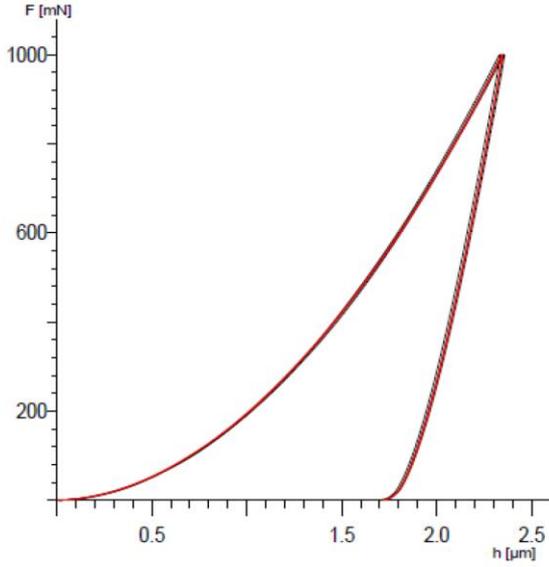

Figure 4. The correlation of HV, H_{IT} and HM for GCr15

Figure 5. Example of nanoindentation test curve

4. RESULTS ANALYSIS

4.1 Analysis of actual correspondence of HV to H_{IT}

According to the measurement results of micro Vickers hardness HV and indentation hardness H_{IT}, the valid test data were first determined by the elimination of coarse error. Then the data obtained by the two test methods were compared, and the best fitting equation was determined by fitting calculation of the data. Finally, the actual correspondences between the micro Vickers hardness HV and the indentation hardness H_{IT} for both 9CrSi and GCr15 materials were given. The relevant coefficients were determined. The correlation of HV to H_{IT} for the 9CrSi is shown in table 4 and that for GCr15 is shown in table 5.

It can be concluded from table 4, table 5, figure 3 and figure 4 that:

1) For a same sample, the measurement results of HV0.2, HV0.1 and HV0.05 conform to each other. Their ratio to the respective H_{IT} also has a consistent coefficient.
2) In the hardness range of (285~850) HV, the ratios of HV to H_{IT} are in the range of (0.07827 ~ 0.08340) for 9CrSi.

4.2 Comparison with the results of finite element analysis

At present, some researchers use the finite element method to study the relationship between micro Vickers hardness and indentation hardness [5-8]. Wang and Ma et al. [9] gives the relationship between Vickers hardness HV and Martens hardness HM as shown in equation 6.

$$HV = HM[0.8558 + 2.0986(W_e/W_t) - 6.4328(W_e/W_t)^2$$
$$+19.3017)(W_e/W_t)^3 - 34.1189(W_e/W_t)^4$$
$$+32.7043(W_e/W_t)^5 - 12.923(W_e/W_t)^6] \tag{6}$$

where W_e and W_t are the instrumented indentation unloading work and loading work, respectively, as shown in figure 6.

3) In the hardness range of (210 ~ 810) HV, the ratios of HV to H_{IT} are in the range of (0.07844 ~ 0.08495) for GCr15.
4) For the test under each scale, HV and H_{IT} has a good linear relationship.
5) With the decrease of HV and H_{IT}, the coefficient decreases and converges or picks up at the lowest hardness value.

Table 4. The correlation of HV to H_{IT} for the 9CrSi

Measurement number	HV0.2/ H_{IT}	HV0.1/ H_{IT}	HV0.05/ H_{IT}
1	0.08338	0.08321	0.08340
2	0.08298	0.08312	0.08338
3	0.08276	0.08259	0.08255
4	0.08216	0.08209	0.08218
5	0.08132	0.08126	0.08114
6	0.08090	0.08121	0.08078
7	0.08060	0.08097	0.08033
8	0.07878	0.07928	0.07977
9	0.07848	0.07887	0.07880
10	0.07828	0.07867	0.07827

Table 5. The correlation of HV to H_{IT} for the GCr15

| Measurement number	HV0.2/ H_{IT}	HV0.1/ H_{IT}	HV0.05/ H_{IT}
1	0.08477	0.08495	0.08446
2	0.08476	0.08441	0.08442
3	0.08438	0.08441	0.08422
4	0.08417	0.08439	0.08415
5	0.08413	0.08436	0.08274
6	0.08294	0.08332	0.08253
7	0.08289	0.08229	0.08244
8	0.08243	0.08187	0.08174
9	0.08209	0.08152	0.08143
10	0.08158	0.08143	0.08100
11	0.08020	0.08087	0.08085
12	0.07952	0.07937	0.08002
13	0.07905	0.07868	0.07880
14	0.07860	0.07846	0.07844
15	0.07902	0.08020	0.07903
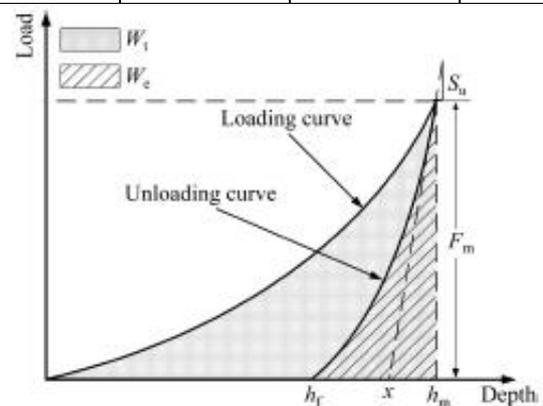
Figure 6 Schematic diagram of instrumented indentation load-displacement curve [9]

Many instrument manufacturers also provide the relevant conversion function. However, the large differences between these results often make the users confused. After obtaining the actual correspondence between the micro Vickers hardness HV and the indentation hardness H_{IT}, the results are compared with the corresponding formulas given by the finite element analysis method.

The equation 6 is validated according to the HV and H_{IT} obtained by the experiments. First, the model function curve is plotted according to the equation, and the relationship coefficient f between HV and H_{IT} is determined. Then the experiment data are compared to the model function curve. The result for 9CrSi is shown in figure 7 and table 7, and the result for GCr15 is shown in figure 8 and table 8.
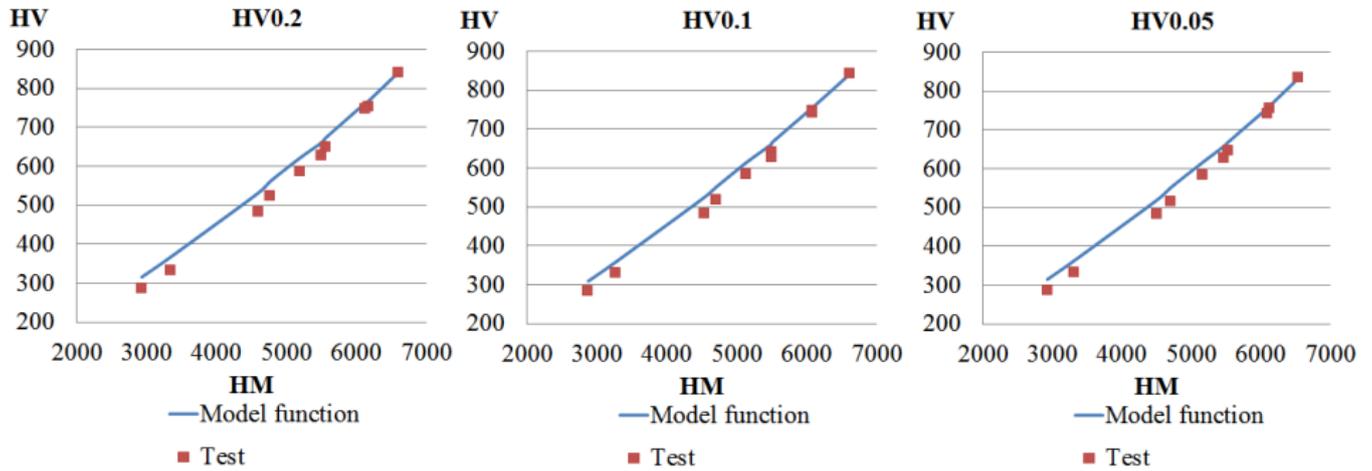

Figure 7. Comparison of experiment data and model function curve for 9CrSi

Table 7. Comparison of HV test results and values given by model function for 9CrSi

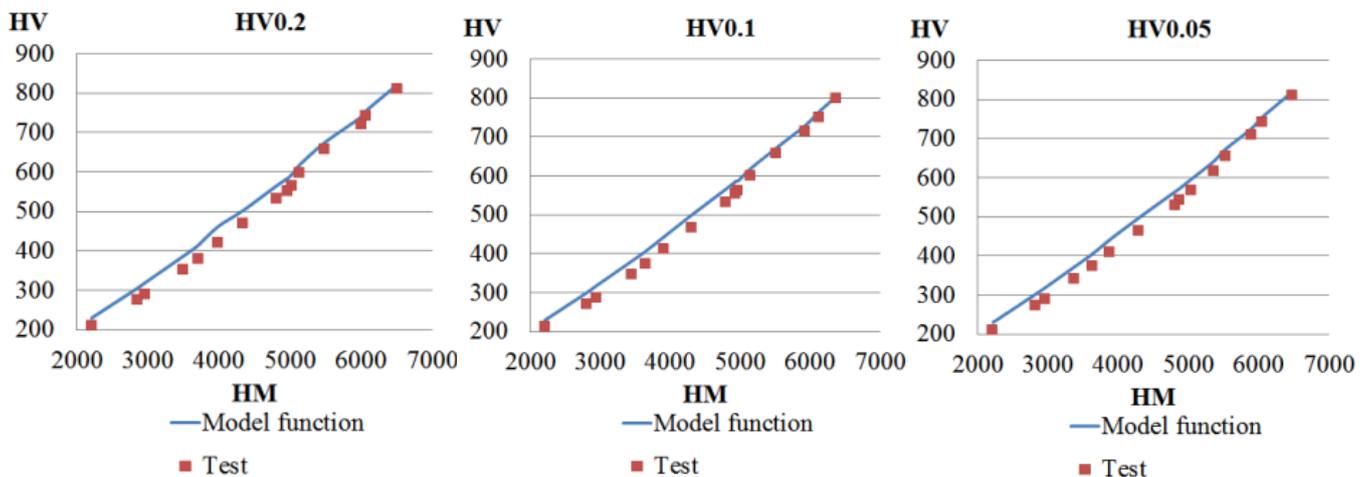| Scale Number	HV0.2				HV0.1				HV0.05			
	f	HV model	HV test	Relative deviation	f	HV model	HV test	Relative deviation	f	HV model	HV test	Relative deviation
1	1.25	841.8	840.3	-0.2%	1.25	842.6	842.0	-0.1%	1.25	831.4	833.6	0.3%
2	1.22	767.5	752.0	-2.0%	1.22	754.2	746.1	-1.1%	1.22	762.0	755.0	-0.9%
3	1.22	761.7	746.0	-2.1%	1.22	755.6	741.0	-1.9%	1.22	757.2	743.0	-1.9%
4	1.19	674.0	648.0	-3.9%	1.19	666.0	642.0	-3.6%	1.19	669.6	647.2	-3.3%
5	1.18	661.4	628.0	-5.0%	1.18	660.8	628.5	-4.9%	1.18	658.7	626.5	-4.9%
6	1.17	621.9	587.0	-5.6%	1.17	614.5	583.8	-5.0%	1.17	616.3	582.8	-5.4%
7	1.15	561.3	525.0	-6.5%	1.15	550.9	518.6	-5.9%	1.15	552.3	516.8	-6.4%
8	1.13	531.4	484.1	-8.9%	1.14	524.9	482.7	-8.0%	1.13	520.0	481.5	-7.4%
9	1.08	368.0	334.2	-9.2%	1.08	358.0	329.0	-8.1%	1.08	363.8	332.4	-8.6%
10	1.06	315.9	286.8	-9.2%	1.06	309.6	283.0	-8.6%	1.06	314.9	286.6	-9.0%

Figure 8. Comparison of experiment data and model function curve for GCr15

Table 8. Comparison of HV test results and values given by model function for GCr15

Scale Number	HV0.2				HV0.1				HV0.05			
	f	HV model	HV test	Relative deviation	f	HV model	HV test	Relative deviation	f	HV model	HV test	Relative deviation
1	1.24	820.6	809.8	-1.3%	1.24	802.8	798.0	-0.6%	1.24	819.5	810.0	-1.2%
2	1.22	755.7	740.9	-2.0%	1.22	763.3	749.2	-1.8%	1.22	754.2	741.2	-1.7%
3	1.21	739.2	721.0	-2.5%	1.21	729.6	713.8	-2.2%	1.21	725.9	709.1	-2.3%
4	1.21	673.3	657.0	-2.4%	1.19	672.3	657.4	-2.2%	1.19	672.3	655.7	-2.5%
5	1.18	618.8	598.2	-3.3%	1.18	619.7	599.9	-3.2%	1.18	642.5	616.0	-4.1%
6	1.16	595.7	564.9	-5.2%	1.16	587.6	561.3	-4.5%	1.16	596.3	566.0	-5.1%
7	1.15	583.8	552.0	-5.4%	1.16	586.0	554.0	-5.5%	1.15	572.8	543.8	-5.1%
8	1.15	564.6	531.0	-6.0%	1.16	566.1	531.4	-6.1%	1.15	564.8	529.4	-6.3%
9	1.14	502.3	470.1	-6.4%	1.14	499.4	466.3	-6.6%	1.14	497.2	464.0	-6.7%
10	1.14	461.4	421.0	-8.8%	1.11	442.5	411.3	-7.1%	1.12	441.7	409.1	-7.4%
11	1.10	4140	377.9	-8.7%	1.09	406.1	374.1	-7.9%	1.09	405.6	374.0	-7.8%
12	1.08	387.4	350.9	-9.4%	1.08	381.7	345.6	-9.4%	1.08	371.3	339.9	-8.4%
13	1.06	319.4	289.2	-9.5%	1.06	318.9	287.4	-9.9%	1.06	319.4	288.5	-9.7%
14	1.05	305.0	275.2	-9.8%	1.05	299.9	270.1	-9.9%	1.05	301.7	272.1	-9.8%
15	1.02	230.0	210.5	-8.5%	1.02	230.1	214.0	-7.0%	1.02	230.4	211.4	-8.2%

It can be seen from figure 7, figure 8, table 7 and table 8 that:

1) On the same sample, HV0.2, HV0.1 and HV0.05 have a consistent hardness relationship.
2) With the decrease of hardness, that is the increase of indentation depth, the difference between the experiment data and model function increases for both materials.
3) The differences between experiment data and model function are in the range of (0.3%~-9.2%) for 9CrSi and in the range of (-0.6%~-9.9%) for GCr15.
4) With the decrease of hardness, the coefficient f of the model function of HV and HM decreases.
5) The test results and model functions will have a better fit if f decreases slower.

5. CONCLUSION

In this paper, the correlation of micro Vickers hardness HV to indentation hardness H_{IT} and HM for two types of materials, 9CrSi and GCr15, are studied experimentally. On the one hand, the actual correlation coefficients of HV to H_{IT} are given. On the other hand, the model functions of HV and HM given in [9] are verified and deviations are given. This work can not only facilitate the acquisition of any unknown information of the two materials under limited experimental conditions in the future, but also provides a direction for related researches of other materials. It will provide a strong reference for further improvement of the theoretical analysis and also contribute to the unity of various model functions.

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