[Article ID] 1003 - 6326(2002)06 - 1058 - 05

Development and application of WGQ type micro-computer-based electromagnetic nondestructive testing instrument for quality of metal material①

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[Abstract] The WGQ type micro-computer-based electromagnetic nondestructive testing instrument for quality of metal material was developed on the principle of electromagnetic induction. The invention and marketing of the WGQ instrument has solved the world-wide tough problem of the "N" shape relation between the indicated values of testing instruments and the hardness of most metal parts, particularly steel and iron parts. It has also greatly improved the hardness testing precision of aluminium alloy. Consequently the instrument can accurately perform either the quantitative testing of aluminium alloy, steel and iron parts' hardness or the qualitative testing of their internal and external defects such as cracks, over-burnt and so on. Its hardness testing precision is HRB ±0.7, HRC ±1 and HB ±10. The testing speed can reach 1 500 parts per hour. The instrument has already been successfully applied to the spot of lots of factories.

[Key words] hardness; electromagnetic nondestructive testing; magnetic conductivity; electrical conductivity

[CLC number] TH 878 **[Document code]** A

1 INTRODUCTION

Since 1979, our electromagnetic nondestructive testing research group has developed a series of automatic separator for metal material quality in our country's electromagnetic nondestructive testing application field. Among them the WGF-I type micro-computer-based automatic separator for quality of steel and iron material has passed the authentication of the Department of Engineering Industry(DEI) and gained the third-class reward of the DEI in 1995. Various types of instruments of the series have been widely applied to thousands of domestic factories and mines. Employing these instruments, we have realized the rapid electromagnetic nondestructive testing of mixed materials' separation, structural steels' carbon content, hardness, tensile strength, internal and external defects such as cracks, porosity, over-burnt, etc for metal materials and parts on the production spot[1~6].

However, the "N" shape relation between the displayed values of the electromagnetic nondestructive testing instruments (including eddy current testing instrument) and hardness of metal parts, particularly steel and iron parts which have been massively used has hindered further popularization and application of various domestic and foreign electromagnetic nondestructive testing instruments[3]. According to the Electromagnetic Testing Volume of American Nondestructive Testing Handbook[7], since allowing variation of parts' components can affect their magnetic property, the hardness tested by way of eddy-current can't be always much accurate, especially for cast parts. Almost none of the eddy-current hardness testing instances referred mentioned the hardness testing precision. Researchers of the Forster Academe in West Germany considered that, in virtue of computer, one can probably compute the regression function of reference parts in the near future, so one can obtain a direct reading on the instrument such as surface layer depth or hardness[3]. A factory in Shanghai once imported an eddy-current testing auto-mechanism which cost millions of dollars, but it couldn't be used at all because of the considerable testing error. However, since there was no hardness testing precision indexes in the specification, the factory couldn't sue the foreign side for compensation. This is due to the fact that not enough recognition has been taken for the investigation of nondestructive testing of property indexes such as hardness in our country[8,9]. Russia has also strived to resolve the problem of "N" shape relation[3], but the application report hasn't come out yet.

We have been continuously investigating for many years to radically resolve the difficult problem of the "N" shape relation between hardness and displayed values of electromagnetic nondestructive testing instruments and to improve the hardness testing precision of aluminium al-

① **[Received date]** 2002 - 07 - 17; **[Accepted date]** 2002 - 09 - 27

loy. A few years ago, we successfully developed the WGQ type micro-computer-based electromagnetic nondestructive testing instrument for metal material quality by means of synthetically utilizing the output amplitude and phase under the condition of special magnetization. We've got the single-valued or linear relationship between WGQ instrument's digital displayed values and hardness of aluminium alloy LD10 and steel parts, typically 40Cr and 65 Mn, etc. We've radically solved the tough problem of the double-value or even three-value relationship between displayed values of electromagnetic testing instrument and hardness of steel and iron parts. The hardness testing precision of aluminium alloy has also been greatly improved. The instrument can accomplish the performance test and quality control either for aluminium alloy parts or for steel and iron parts. And the instrument has already been successfully applied to factories' production spot.

2 TESTING PRINCIPLE

Many capabilities and states of metals, such as component, hardness, tensile strength, heat-treatment state, under-aging, over-aging, overheat, over-burnt and defects such as internal and external cracks caused by various factors will directly affect metals' electrical conductivity or magnetic conductivity. So we can separate, differentiate or quantitatively test metal's components, hardness and defects like cracks by directly or indirectly testing parameters such as electrical conductivity or magnetic conductivity[1, 3].

The WGQ instrument was invented on the principle of electromagnetic induction. Under certain condition, it can test metal's components, hardness and crack defects by way of comparatively testing metal's electrical conductivity or magnetic conductivity.

3 WGQ INSTRUMENT'S SYSTEM DESIGN

3.1 WGQ instrument's hardware system design

The circuit principle of WGQ instrument is illustrated in Fig. 1. The instrument was successfully developed by differential method based on the fact that under certain condition, the voltage output caused by tested metal parts is in proportion with the parts' electrical conductivity (non-ferrous metal such as aluminium alloy) or magnetic conductivity (ferrous metal), namely the parts' capability indexes such as component, hardness and stress.

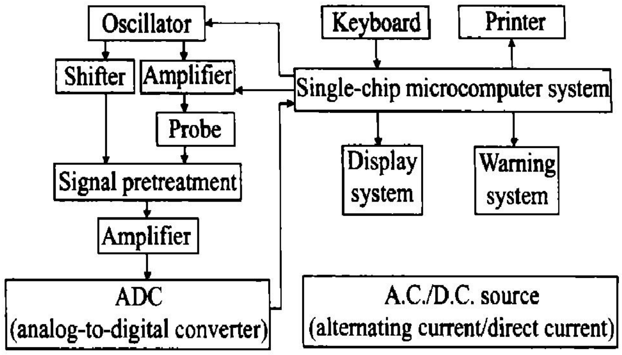

Fig. 1 Circuit principle of WGQ instrument

The WGQ instrument is equipped with two coils or a single pen-shape probe. After the signal pretreatment system and the single-chip micro-computer system have processed the induction signal obtained by magnetizing the tested metal parts, the tested metal parts' components, hardness and defects like cracks can be directly displayed on a 6-digit digital meter. With light and sound alarm, the instrument can separate the parts into three classes: exceed-upper-limit parts (or material 1), qualified parts (or material 2) and exceed-lower-limit parts (or material 3). The operation is very convenient.

Since WGQ instrument's basic hardware system is developed by improving the WGF-I instrument, we'll leave out the illustration of the single-chip microcomputer system, the keyboard, display and print system[3].

Among the induction output signals caused by putting metal parts into the electromagnetic testing probes, there are three independent parameters that can be exploited, namely the output signal's amplitude, phase shift and modulation frequency[10, 11]. Since various variants of metal parts such as electrical conductivity or magnetic conductivity can perform different modulations of the induction output signal, we can synthetically utilize the three independent parameters mentioned above to design corresponding signal oscillating and processing circuit. Eventually we obtained the single-valued or even linear relationship between metals' hardness and WGQ instrument's displayed values.

3.1.1 Oscillator design

Properly selected magnetization frequency is critical to electromagnetic nondestructive testing. It's an important task to design an oscillator with perfect performance. The WGQ instrument employs square wave and frequency from 1 Hz to 9 999 Hz which can be continuously selected. Years of practice shows that square wave can provide the driving source and reference source for the electromagnetic testing probes and the signal pretreatment system respectively with extremely stable frequency and amplitude[7]. The frequency is confined to below 10 kHz, since within this frequency range, the complex permeability of tested metal parts can be hardly affected by the alteration of frequency[12].

3.1.2 System design of induction signal pretreatment

To synthetically exploit the amplitude and phase shift, two independent information of the induction voltage output signal, we designed a unique shifter. The phase shift can be arbitrarily and continuously selected from 0° to 360°. The selection can be performed manually or automatically by single-chip microcomputer system.

Practice shows that, the WGQ instrument's hardness system design sets a reliable foundation for quantitative testing of hardness, etc.

3.2 WGQ instrument's software system design

WGQ instrument's software system design employs modularity. The whole system consists of three modules: monitoring main program, data collecting and processing program and subroutine library.

After the operator has chosen the function module via keyboard, the system transfers control to automatic data collecting and processing program. It includes four function modules: mixed-material separating module, hardness testing module, carbon-content testing module and crack separating module. Each function module can implement the automatic data collecting for tested parts according to different functional requirements and the automatic data processing according to different mathematic models.

The mixed-material separating, hardness testing and crack separating are provided with four testing methods respectively for users to choose.

The feature of WGQ instrument's software is that it takes at most 10 tested metal parts to adjust the instrument and then can qualitatively or quantitatively separate and test thousands of parts. It greatly facilitates the operation.

4 TESTING RESULTS AND DISCUSSION

Hardness testing results of LD10 wrought aluminium alloy, 40Cr and 65 Mn parts by WGQ instruments is as follows.

4.1 Making of tested parts

4.1.1 Making of LD10 aluminium alloy tested parts

We processed several tested parts to be d 10 mm × 80 mm in dimensions.

Their solid solution temperatures were respectively 460, 480, 490, 500, 505, 510, 515, 520 and 530 ℃. Their heat preservation time was all 45 min. Then they were water hardened at room temperature and underwent natural aging.

We tested the hardness of the above-mentioned heat-treatment tested parts by HR150 type hardometer.

4.1.2 Making of 40Cr and 65 Mn tested parts

We processed several 40Cr tested parts to be d 11 mm × 80 mm in dimensions. Having oil hardened them at 850 ℃, we tempered them at 200, 250, 280, 300, 320, 350, 400, 450, 500, 550, 580, 600, 640 and 700 ℃ respectively to get the tested parts with different hardness values.

Similarly, we made several 65Mn tested parts of d 8 mm × 80 mm with different hardness values. We also tested the Rockwell hardness of the above-mentioned tested parts by R. B187-5 type mechanical hardometer.

4.2 Results of testing LD10 aluminium alloy, 40Cr and 65 Mn tested parts' hardness by WGQ instrument

4.2.1 Results of testing LD10 aluminium alloy parts' hardness using WGQ instrument

We tested the hardness of LD10 aluminium alloy tested parts by the WGQ instrument after we had properly selected the grades of magnetizing frequency, phase and sensitivity for it. The testing results of LD10 aluminium alloy tested parts' hardness are listed in Table 1.

Table 1 Hardness testing results of LD10 aluminium alloy tested parts using WGQ instrument

Part number	HRB	WGQ instrument's displayed value	Difference
1	67.0	66.3	+0.7
2	69.0	69.3	−0.3
3	69.5	69.6	−0.1
4	71.5	71.5	0
5	72.0	71.6	+0.4
6	75.0	75.5	−0.5
7	75.5	76.2	−0.7
8	76.0	75.7	+0.3
9	76.5	75.9	+0.6
10	77.0	77.7	−0.7
11	77.0	76.9	+0.1
12	71.0	80.8	−9.8
13	71.0	81.2	−10.2
14	70.5	81.5	−11.0
15	66.5	82.0	−15.5

Seen from Table 1, there is a single-valued relationship between LD10 aluminium alloy's hardness and the WGQ instrument's displayed value. While the relationship between the WGQ instrument's displayed value and the hardness of parts (part 1 to part 11), which were processed at the solid solution temperatures from 460 ℃ to 515 ℃ and then underwent natural aging is linear. The WGQ instrument's displayed value is actually the LD10 aluminium alloy tested parts' real hardness value. Its hardness testing precision has been greatly improved. The testing precision can be HRB ±0.7.

It should be noticed that in Table 1, the displayed values of the tested part 12, 13, 14 and 15 are 80.8, 81.2, 81.5 and 82.0 respectively. They have already exceeded the maximum limit of HRB77.0 in this experiment. The four tested parts had been processed at the solid solution temperatures of 520 ℃ and 530 ℃. We examined them and found that they were over-burnt. And tested part 15 was found to bear crack with it. The WGQ instrument can accurately distinguish over-burnt parts and crack parts. Their displayed values are abnormally increment.

4.2.2 Results of testing 40Cr and 65 Mn parts' hardness using WGQ instrument

We tested the hardness of 40Cr and 65 Mn tested parts by the WGQ instrument after we had properly selected the grades of magnetizing frequency, phase and sensitivity for it. The testing result is seen in Fig. 2 and Fig. 3.

Seen from Fig. 2, there is a linear relationship between WGQ instrument's displayed values and hardness of 40Cr tested parts tempered at different temperatures. The testing precision can be HRC ±1.

Seen from Fig. 3, the relationship between 65Mn tested parts' hardness and WGQ instrument's displayed values is linear and the testing precision is also HRC ± 1. The WGQ instrument's displayed value is actually the tested part's real hardness value. So WGQ instrument can be used to quantitatively test metal parts' hardness.

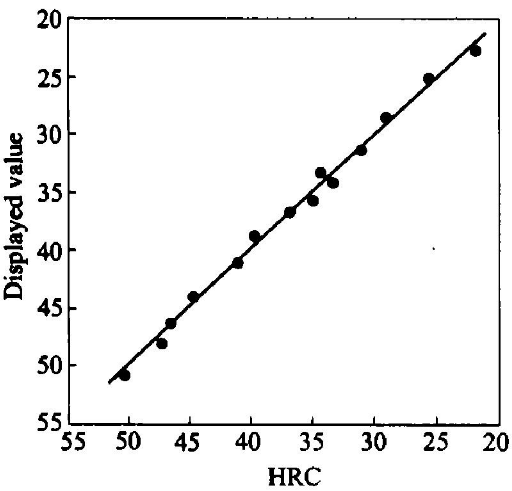

Fig. 2 Relationship between 40Cr tested parts' hardness and WGQ instrument's displayed values under condition of properly selected frequency and phase

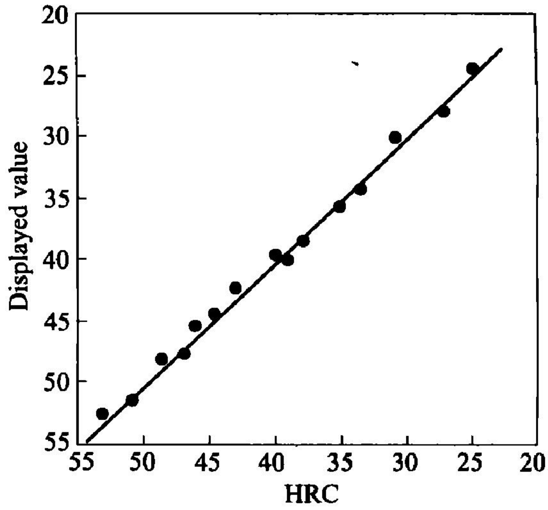

Fig. 3 Corresponding relation between 65 Mn tested parts' hardness and WGQ instrument's displayed values under conditions of properly selected frequency and phase

4.3 Results of on-the-spot application to factories

The WGQ instrument has already been successfully applied to many factories in our country. The result of the on-the-spot hardness testing by WGQ instrument for 42CrMo binder bolts of *d* 12 mm × 90 mm is shown in Table 2.

Table 2 Hardness testing result of 42CrMo binder bolts using WGQ instrument

Part Number	Rockwell Hardness, HRC	WGQ instrument's displayed value	Difference HRC
1	38.0	38.1	−0.1
2	37.4	37.2	0.2
3	42.5	42.5	0
4	36.8	36.8	0
5	43.8	43.8	0
6	44.1	44.2	−0.1
7	40.5	40.9	−0.4
8	39.7	39.7	0
9	42.7	42.3	0.4
10	44.0	44.0	0

Seen from Table 2, the testing precision is within HRC ±1.

We also successfully tested the hardness of *d* 30 mm × 220 mm net-frame high-strength bolts which can hardly be tested in the past, resolved the tough problem of low hardness parts' mixing into qualified parts.

WGQ instrument can be used to test not only metal parts' hardness, but also metal parts' mixed material, carbon content, carburized layer depth, defects such as over-burnt, internal and external cracks. It has already been practically applied to the factory spot. Those applications will be discussed in another paper.

4.4 Discussion

As early as 1996, we have observed that, there was a "N" shape relation between electromagnetic testing instrument's displayed values and hardness of steels like 40Cr and 65 Mn under the condition of low frequency. While within the high frequency range, the relation came to be a reverse "N" shape. Based on this phenomenon, we adopted the unbalanced bridge to attain the single-valued or even linear relationship between hardness of above mentioned steels and displayed values of the electromagnetic testing instrument[3]. However, since its signal was too weak and its adjustment was too complicated, the instrument could hardly be applied. Nevertheless, we can conclude that frequency is an important factor that affects quantitative hardness testing. Thus, to researchers of electromagnetic hardness testing, the accurate selection of testing frequency is a premise for successful testing. Normally, higher frequency is selected for small parts and lower frequency is selected for large parts of the same component.

The selection of magnetizing frequency should co-operate closely with the selection of phase. We should select different phases for metal parts with different components. For example, we usually select phase of about 60° for aluminium alloy like LD10, etc. However, for ferrite forge pig iron we should select phase of about 0° to get the linear relation between its hardness and WGQ instrument's displayed values.

We should further investigate and get the regularity of how to correctly select frequency, amplitude and phase in order to further popularize and facilitate the instrument's application.

5 CONCLUSIONS

1) It is proved that under special testing condition, the relationship between displayed values of the WGQ type micro-computer-based electromagnetic nondestructive testing instrument for metal material quality and the real hardness of structural steels such as 40Cr and 65Mn that have been hardened and tempered can be single-valued or even linear.

2) The WGQ instrument can be absolutely used to qualitatively or quantitatively test metal parts' components, hardness and defects such as crack. By the on-the-spot testing, the instrument shows its features of high precision (HRC ±1 or HB ±10), high speed (1500 parts per hour) and high economic benefit, etc.

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(Edited by PENG Chao-qun)