Material , Structure and Hardness testing of Cast-iron safety parts by using NDT methods

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1-Abstract.

In the past , the producers of safety cast-iron parts were executing only random check to control their production line as relatively high rate of defective parts were acceptable .

Nowadays due to the market demand because of producing high speed vehicles , continuos decreasing the weight of parts and consequently using lower safety design factor and finally due to the high competition in the world market , very high quality parts are only demanded and very low rate of defective parts even lower than the range of PPM is acceptable .

Therefore , random check is no more sufficient at all , and 100% of products should be tested . In testing safety parts , 2 categories of test must be executed :

1-Flaw detection to find defects like : porosity , shrinkage , cracks and inclusions .

2-Checking material mix , structure , heat treating process , Microscopic texture , graphite type and properties like tensile strength , hardness and case depth .

In this study we concentrate on the second category of tests .

All of these tests can be done only by fast ,reliable and re-producable NDT methods . Different NDT methods like Eddy Current testing (ET) , Ultrasonic Testing (UT) , Resonance Testing , Vibration analysis (VA) or Thermography are used for 100% testing of such parts .

In this paper more common methods i.e ET and UT and their capabilities as well as applications are described . The practical test on production line of Pride passenger cars to check the nodularity and hardness of 3 types of cast-iron safety parts by both methods have been reported . By comparison of the results of both methods on the same parts , the conclusion and comments to select the proper test method has been presented .

2-Introduction

To achieve on the production of cast iron safety parts without any defect and with desired properties in different industries particularly in car industries , 100% non-destructive testing is an exclusive solution . By implementing NDT methods , besides of testing all products and sorting the defective parts , the process is also acting as the simultaneous condition monitoring of production line as all test results are used as a feedback to production process and improving it .

The major properties of cast-iron is defined by its graphite structure and its metal matrix . Some properties of cast iron are formed directly during the solidification process and cannot be changed by further heat treatment . For example the graphite structure of cast-iron is not changed after solidification . Therefore , if the graphite structure of a cast iron part is out of acceptable range , it would be desirable if it can be sorted out immediately after casting . This will lead to prevent any further costs on such part . But some other major properties of the cast iron like matrix structure can be changed in some extent by heat treatment process . So , by considering the demand of standards or technical specification , the suitable point to execute tests in production line should be selected .

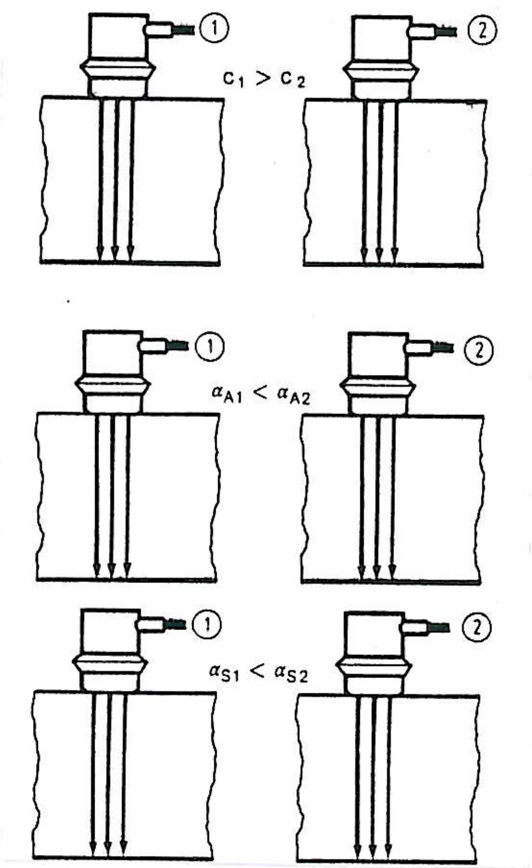
3-Ultrasonic Testing (UT)

In this method the Ultrasonic waves either Longitudinal or Transverse Waves with the frequency of 0.5 to 5 MHz is transferred inside the material . By analyzing the sound velocity or the reaction of the material to propagation of Ultrasonic waves useful information about the material can be obtained . One application of this method is detecting the defects like cracks , porosity or inclusion in material . Besides of that UT can be used to check some properties of the material . Any changes on material properties may cause alteration of sound propagation inside the material like sound velocity (C) , Sound Absorption Coefficient αA or scattering coefficient αs . Thus , by evaluation and measuring these parameters , any alteration of the material properties can be evaluated accordingly . For example in metals , any changes of mechanical features like tensile strength , impact strength , elongation , hardness , ... , may cause alteration of sound velocity . In Fig. 1 the application method of using Ultrasonic waves by considering three parameters (C , αA , αs) for testing similar parts have been shown . In Fig. 1-a , the sound velocity (C) is measured . The difference of sound velocity in two similar parts with the same thickness will indicate the alteration of material properties .

In Fig.1-b , the evaluation is based on the difference of absorption of sound energy inside the material . In this case , in both materials 1 and 2 the first back wall echo is appeared on the same point on the time base line , so the sound velocities are the same on both parts but the absorption of the second part is higher than the first part . Therefore the successive back wall echoes can not be obtained .

In Fig.1-C , the evaluation is based on the rate of scattering of the sound inside the material . The scattering inside the second material is higher than the first part that is due to the larger size of crystal grains . In such cases, usually the signal to noise ratio (S/N) is used to evaluate the scattering rate .

In this Fig. S/N ratio is 20db for the first part and 6 db for the second part .



a-Sound velocity (C) is the evaluation base to comparing 2 materials (Similar to thickness measuring)

b-Sound attenuation due to absorption (αA) is the evaluation base .The height and number of back-wall echoes are compared.

c-Sound attenuation due to scattering (αS) is the evaluation base . The signal to noise ratio is evaluated .

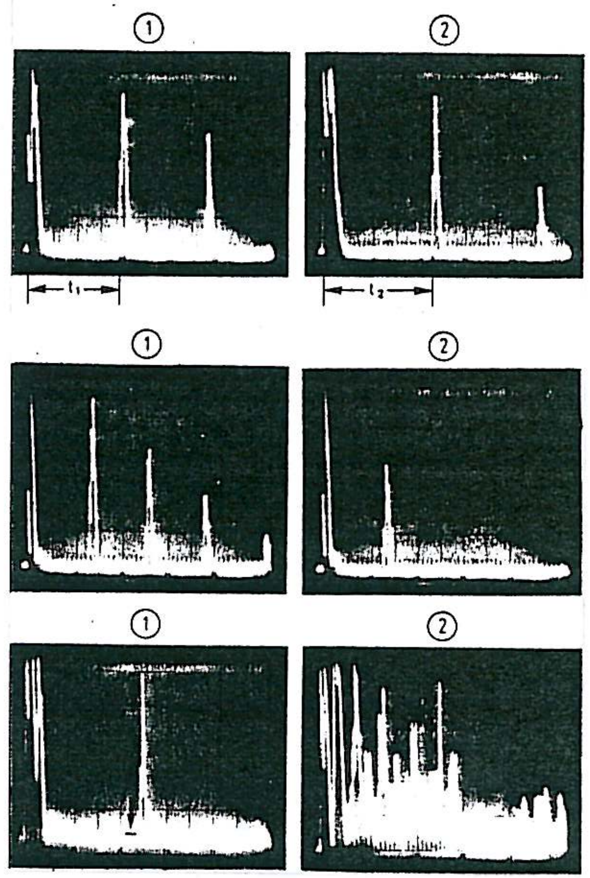


Fig. 1–Material Test by Ultrasonic Waves

An interesting application of UT for testing cast-iron parts is the evaluation of the content of nodular graphits (nodularity) in nodular cast iron material (Fig. 2) .

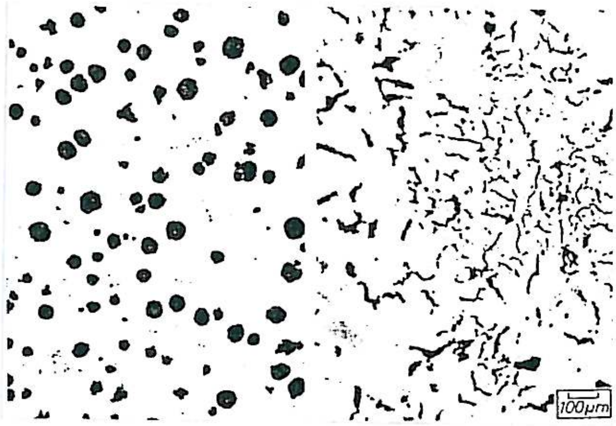
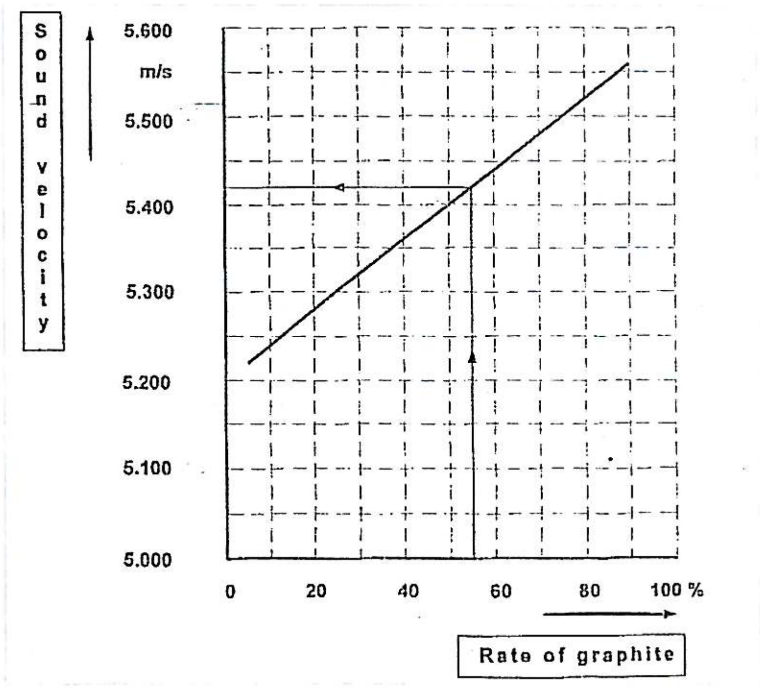


Fig.2-Nodular (desirable –left) and non-nodular (undesirable-right) graphite in cast iron

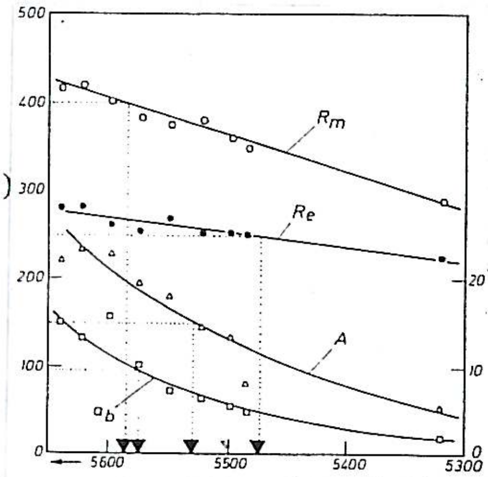
Any changes in nodularity causes change in the elasticity of the material that lead to alteration of sound velocity. Hence , the sound velocity will indicate the nodularity indirectly .Of course , there is no direct relationship between the nodularity and sound velocity as many other physical parameters affect on sound velocity . Therefore , the practical method in this evaluation would be preparing some similar sample parts by measuring sound velocity by sound velocity meter and determining the nodularity by metalographyic method in laboratory . Then by correlating 2 parameters the respective graph can be drawn . For all sample parts this graph is used to evaluate the nodularity of all production parts . There is no general graph available for this purpose and for each production part a new graph should be constructed particularly . Obviously the measurement of sound velocity must be done just after casting of the ductile cast iron so that without any relation to the metalic matrix of the material the requirements of standard DIN 1963 for mechanical properties is fulfilled . (Fig. 3)

Fig.3-The correlation between Sound velocity and nodularity in cast iron .



The results of tests on a part made by Ferritic nodular cast iron GGG-40 is shown in Fig. 4 .The sound velocity has been measured just after casting but the mechanical properties : Tensile strength (Rm) , Yield strength (Re) , Impact strength (ab) and elongation (A) have been determined after annealing . It can be seen from the graphs that by reduction on the sound velocity , the rate of spherodical graphite and all other four properties are also reduced .Therefore , it would be possible to select a base and substitute sound velocity measurement instead of measuring the four other properties.
In this figure , the critical sound velocity on the base of the minimum required tensile strength (400 N/mm²) is about 5590 m/Sec . The critical sound velocity for the minimum impact strength is about 5570 m/Sec , for elongation is 5530 m/Sec and for yield strength is 5485 m/Sec .
Therefore it would be possible to select the sound velocity of 5590 m/Sec as a minimum acceptable base for this parts and reject any part that shows sound velocity less than this base .

Rm Tensile strength (N/mm²)
Re Yield strength (N/mm²)
A Elongation (%)
ab Impact strength J/10

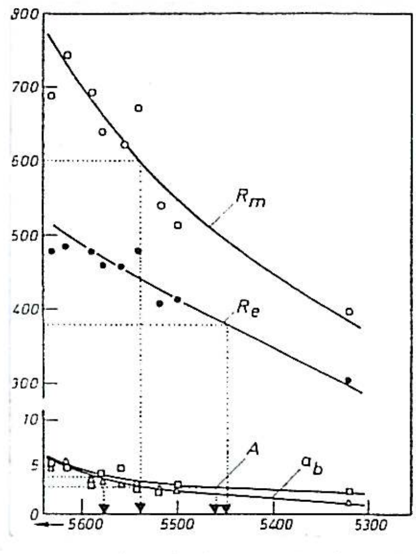


Sound velocity VL (m/Sec.)

Fig.4-
The correlation between mechanical properties of ferritic nodular cast iron with sound velocity.

In Fig. 5 , the minimum base for sound velocity in a part made by pearlitic nodular graphite cast iron GGG-60 is 5580 m/Sec . In this case the respective property that governs to select the critical sound velocity is impact strength , but since GGG-60 is a brittle material , we can neglect this property and evaluate the parts by critical sound velocity on the base of tensile strength as well (5540 m/Sec).

Fig. 5
The correlation between mechanical properties of pearlitic nodular cast iron with sound velocity.



Sound Velocity VL(m/Sec.)

4-Eddy Current Testing (or Magneto-Inductive method)

In this method , an alternating current generator feeds a transmitter coil with an alternating current . This current creates an alternating magnetic field , which in turn induces a certain voltage in the upper and lower receiver coils . (U1 and U2) . Both voltages are equal in value , but opposite in direction at any time . The total voltage is therefore 0 (Fig. 6) .

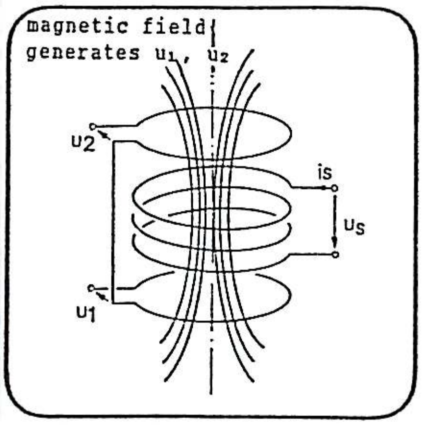


Fig. 6

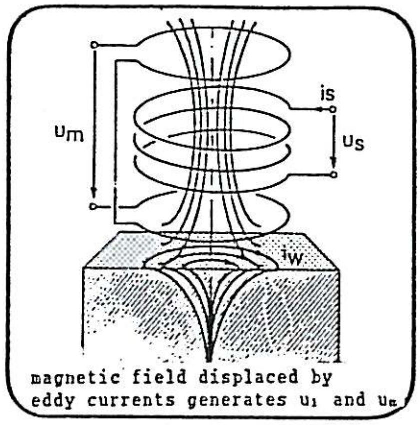


Fig. 7

When an electrically conductive material is placed closed to this coil system , the magnetic field also induces a voltage in the material , which causes eddy currents to flow in the material (short-circuit winding of the material Fig. 7) The eddy current and also the transmitter coil create a magnetic field reacting to the generating magnetic field . The latter will be distorted , so that less flux lines traverse the lower receiver coil than the upper coil , the result being a different voltage , called U'1 . Now, the result of the vector addition will not be 0 , but a typical " material voltage " (Um) which its value depends on the response of the eddy currents to the coil system (Fig. 8) .

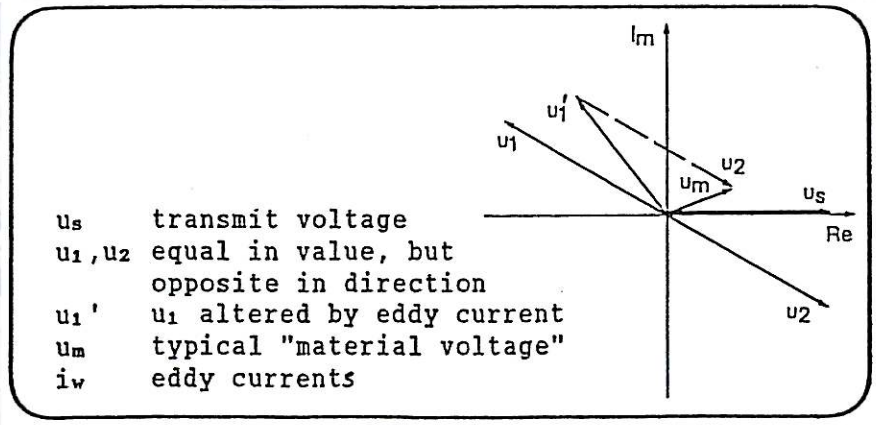


Fig. 8

Only two physical properties of the material i.e : Electrical Conductivity (σ) and Magnetic Conductivity (Permeability μ) influence on eddy current . Therefore , any mechanical or metallurgical properties of the material that can alter one or both of these properties can be distinguished by evaluating the induced eddy currents . The following table shows the correlation of the material characteristics with σ and μ .

Material Characteristic	σ	μ
Chemical Composition	++	+
Mixed crystal composition	+	+
Structure , size of grains	-	++
Mixed structure composition	+	+
Precipitations	-	++
Occlusions , Pores	-	+
Inner stress	+	++
Lamellar Tearing , anisotropy	-	+
Microcracking zones , stress corrosion cracking	+	+
Deformation	-	+
δ-ferrite in austenite	+	++
Dendrites in steel	-	-

(-) without influence   (+) influence   (++) strong influence

Table 1-Correlation of material characteristics with σ and μ

All metals either Ferrous or non-ferrous are electrical conductive and their electrical conductivity (σ) is between 1 to 60 m/Ωmm² . But only ferrous metals are considered magnetic conductive . The magnetic conductivity (permeability μ) of air and non-ferrous metals is about 1 (Relative permeability μr and dimensionless) .
The relative permeability (μr) for ferrous metals that shows ferromagnetic properties can be between 10 to million .
As shown in the diagram Fig. 9 , permeability mainly depends on the strength of the magnetic field that is generated in the test specimen . Initial permeability implies only very small field strength . Increasing field strength increases permeability up to a maximum value but by further increasing the field strength the permeability subsequently decreases .

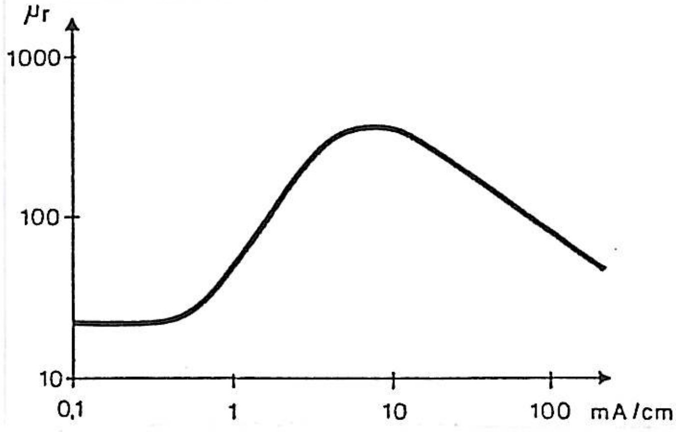
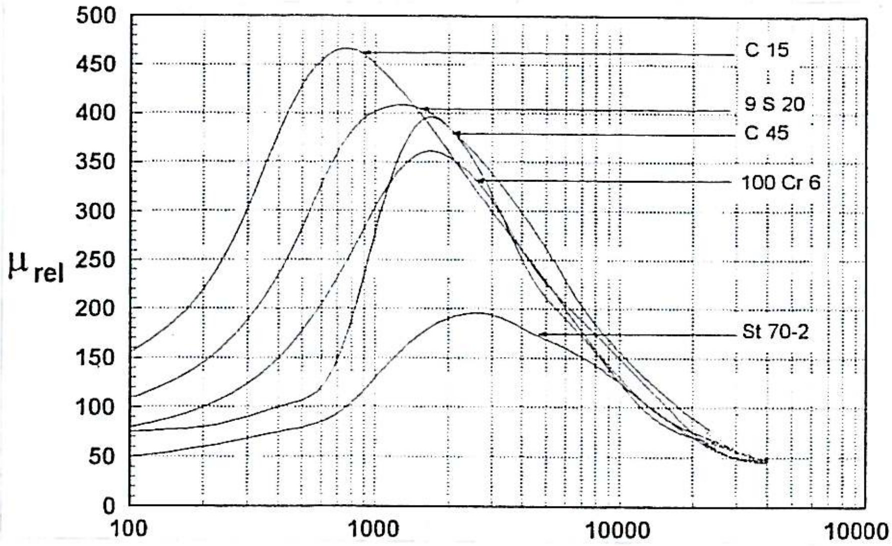


Fig. 9-Dependence of permeability to the magnetic field strength .

Fig. 10 shows the diagram of alteration of relative permeability with respect to the changes of magnetic field strength for different ferromagnetic steels .

Fig.10- Different Permeability curves of several materials in dependence on its field strength .



In Fig. 11 the similar diagram is shown for different full annealing conditions of one material 100 Cr6 . One can clearly see that different material and different structures show different permeability curves . The major point that can be distinguished on these graphs is that despite of good separation between different graphs , there is still some overlapping at some areas where separation by applying this method would be impossible .

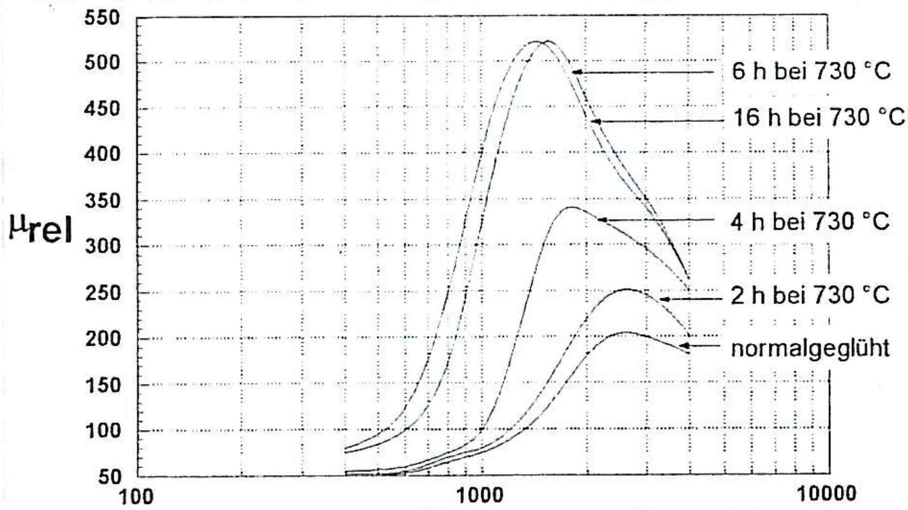
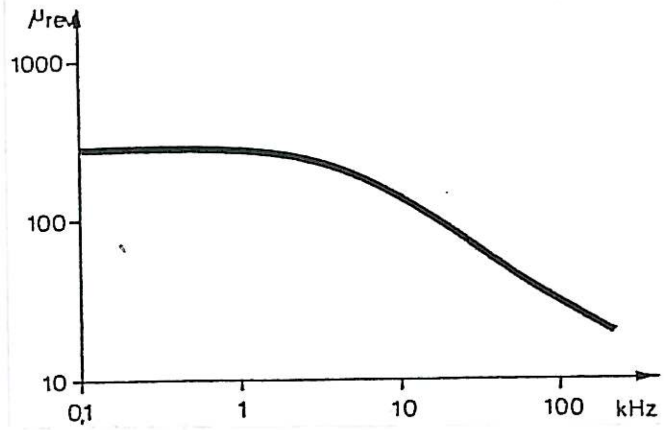


Fig. 11-Different full annealing conditions of 100Cr 6 and their permeability behavior in dependence on its field strength .

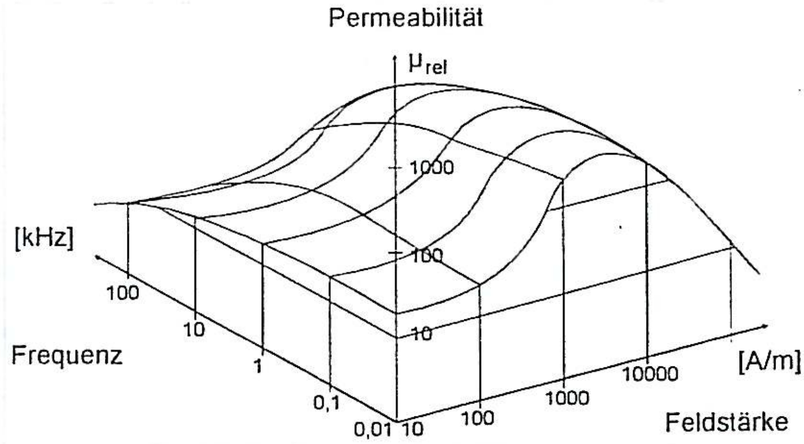
To overcome on this problem , besides of dependence of permeability on field strength , one should consider its dependence on the frequency at which the field strength is generated around the test specimen (Fig. 12) . At lower frequencies the elementary magnet of the material have sufficient time to change direction , i.e the permeability value is only slightly changed . At higher frequencies these elementary magnets have not sufficient time to change direction that leads to high reduction of the permeability .

Fig.12- Dependence of Permeability on frequency



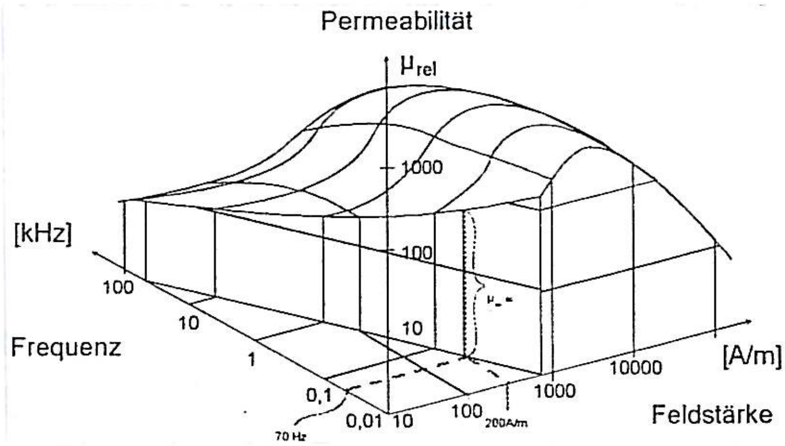
Arranging the permeability , field strength and frequency parameters in a tridimensional diagram a "Permeability Hill " results (Fig. 13) . The surface of this " Permeability Hill " indicates the corresponding permeability value for each field strength and frequency value . The permeability hill is strongly dependent on the crystalline structure and material . Different structures or different alloys form totally different permeability hills , which , in simple cases , are only different in height .

Fig.13-Permeability Hill



In more complicated cases , those cases which often cause problems to eddy current testing , permeability hills overlap in certain area .If by chance a setting of frequency and field strength is chosen which gives permeability values along the overlapping line , the 2 materials concerned cannot be separated . To overcome on this problem another setting of frequency and field strength would be needed that requires multi-frequency testing that applies different frequencies on the material simultaneously .
By multi-frequency method a cutting plane is formed diagonally through the permeability hill . Low frequencies imply high field strength , which decreases with increasing frequency . For this reason , the cutting plane is located inclined to the axis (Fig. 14) .

Fig.14-Interface through the Permeability Hill



As already known , different material structures form a different permeability hills . The tridimensional diagram shows that difference in permeability is significant at certain operational points of the cutting plane whereas it is only a minor at other points . By eddy current testing no separation is possible at overlapping points of permeability hills . (Fig. 15) or at transition areas where permeability hills are crossing each other .(Fig. 16)

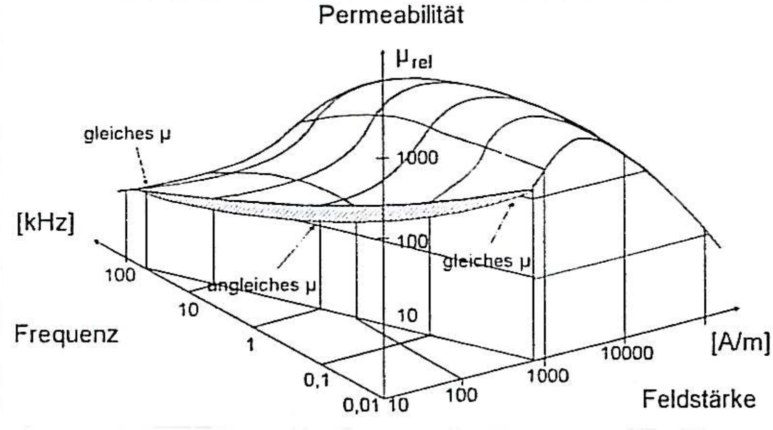


Fig.15-Overlapping permeability Hills

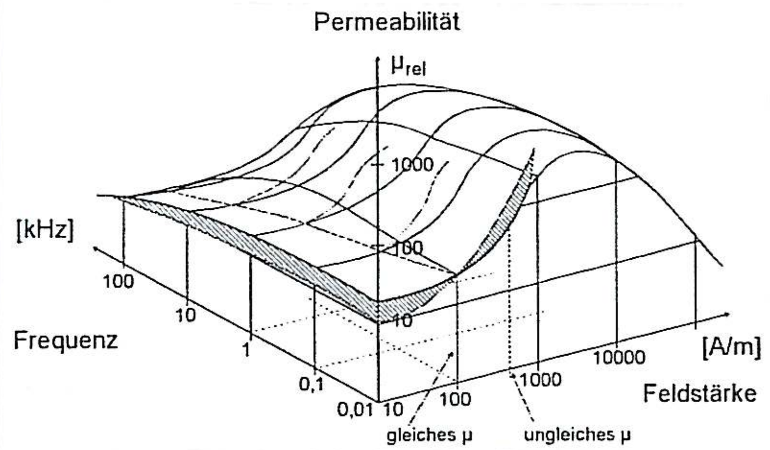


Fig.16-Crossing Permeability Hills

5- Experimental Tests

Extensive tests have been executed on different safety parts of passenger cars . All these parts are ductile cast iron made by casting . In some cases experiments have carried out before and after heat treatment to evaluate the influence of heat treatment on eddy current testing . The test instrument was the state of the art microprocessed control multi-frequency eddy current system Eddyliner P from IBG/Germany that is specially designed for sorting . This system works with 2 similar test coil where one coil is used to put a reference part that is a good and acceptable part and the second coil is used as test coil where the parts are located either manually or through a conveyor on automatic on-line testing . The test system applies 8 different frequencies in successive process but in very short intervals only a milisecond so that all frequencies can be considered are applied simultaneously .

The results of tests on 3 different parts are reported in the following :

5-1-Steering Knuckle

13 pieces of good parts of steering knuckles (Fig. 17) are selected from the production line . First all parts were tested by ultrasonic flaw detector to sort out any defective part due to any internal pore . Then the hardness of all parts we checked that were all in acceptable range 174-191 HB . Also, the sound velocity were measured by a digital ultrasonic sound velocity gauge that was all in acceptable range of 5500-5600 m/Sec. Four parts nos. 1 , 2 , 3 and 4 were tested by metalographic method .Also all parts were checked by universal tensile test machine . Part no 4 was selected as a reference part to put in the Reference test coil . Then the instrument was calibrated by 13 OK parts . To check the correct calibration the part no.14 was made by a different material (Gray Cast iron) and after checking hardness and sound velocity it was tested by eddy current unit and the results are shown in Table 2 .

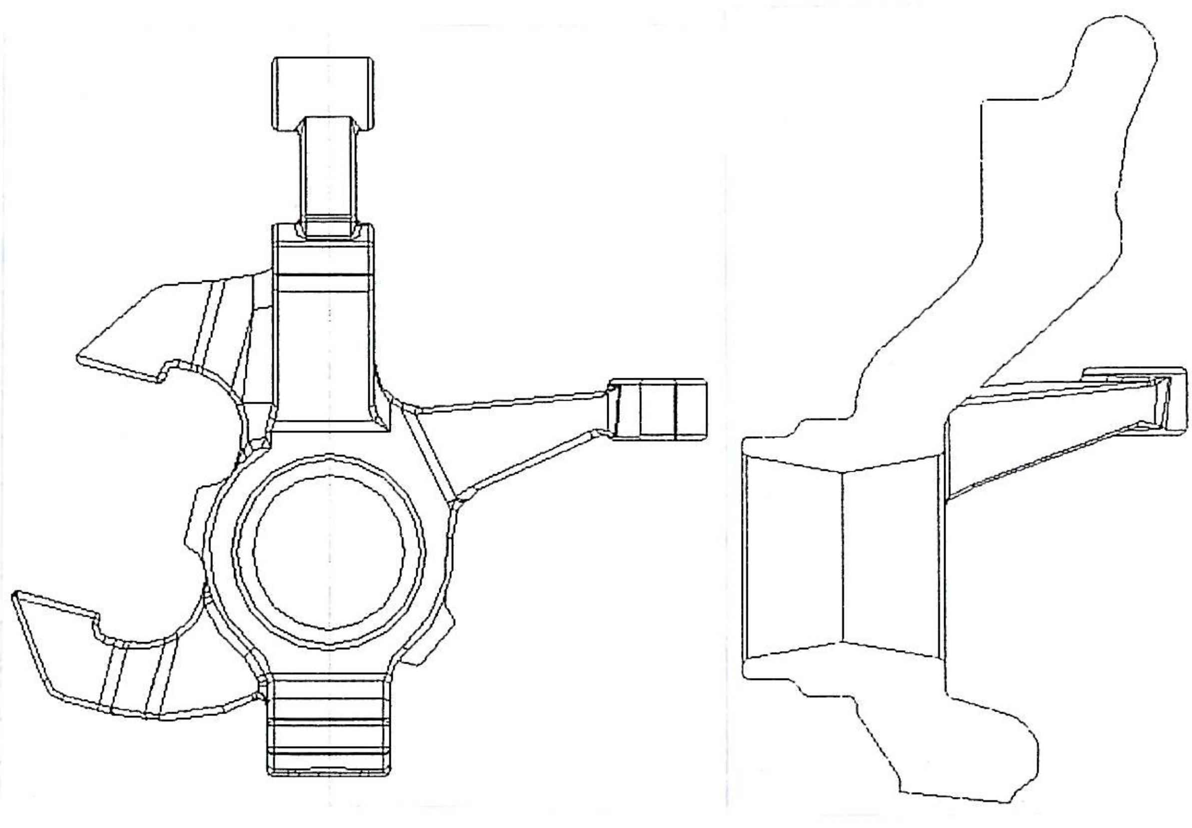


Fig.17-Steering knuckle of passenger car

As a sample the test results of 2 rejected parts nos. 15 and 16 from the production line have been shown in table 2 . The part no. 15 is rejected only because of wrong matrix and there is a possibility to improve it by heat treatment . But part no. 16 was rejected due to the less rate of nodular graphite besides of wrong matrix and its quality cannot be improved by heat treatment .

Also 4 parts nos. 17 , 18 , 19 and 20 were tested after heat treatment . Three of them were accepted but the last part (no. 20) despite of acceptable nodularity still had a wrong matrix where there is a chance to improve the quality by re-heat treatment .

Part No.	Hardness H.B	Sound Velocity m/Sec	Tensile Strength N/mm²	Type of Graphite	Microscopic Matrix	Result and reason
1	177	5590	225	>90%nodular <10%Semi-nodular	95%Ferrite 5%Pearlite	OK
2	179	5580	200	90%nodular 10% Semi-nodular	>95%Ferrite <5%Pearlite	OK
3	174	5600	225	>90% nodular <10% Semi-nodular	>100 Ferrite	OK
4 Reference Part	179	5560	255	90% nodular 10% Semi-nodular	>95% Ferrite <5% Pearlite	OK
5	177	5580	220			OK
6	180	5550	225			OK
7	174	5600	210			OK
8	179	5560	225			OK
9	178	5570	255			OK
10	191	5500	255			OK
11	184	5530	250			OK
12	180	5550	230			OK
13	180	5550	225			OK
14 Gray Cast iron	240	3500	180			NOK Totally Different material
15	234	5530	225	90% nodular 10% Semi-nodular	55% Ferrite 35% Pearlite 10%Carbide	NOK wrong matrix high hardness
16	340	4500	150	70% nodular 30% Semi-nodular	60% Carbide 40% Ferrite +Pearlite	NOK wrong nodular wrong matrix high hardness
17	184	5550	200	85% nodular 10% Semi-nodular 5% Compressed	>90% Ferrite <5% Carbide 5% Pearlite	OK
18	190	5570	220	90% nodular 10% Semi-nodular	95% Ferrite 5% Pearlite	OK
19	186	5560	200	>85% nodular <15% Semi-nodular	80% Ferrite 10% Pearlite 10% Carbide	OK
20	234	5560	220	90% nodular 10% Semi-nodular	55% Ferrite 40% Pearlite 5% Carbide	NOK wrong matrix

Table 2 – Test results of steering knuckle

5-2-Caliper for Brake system

Same as the steering knuckle, 15 good pieces of caliper for brake system of the passenger cars (Fig 18) are selected from the production line . All similar tests were executed on all parts . The sound velocity is 5500-5600 m/Sec and the hardness is in the acceptable range of 179-193 HB . Also tensile strength of all parts are in the desired range . Three parts nos. 1 , 2 & 3 were tested by metalography . The part no. 16 was made by a different material (Gray cast iron) to check the calibration .The part no. 3 was selected as the reference part to put in reference coil . The test results are shown in table 3 .

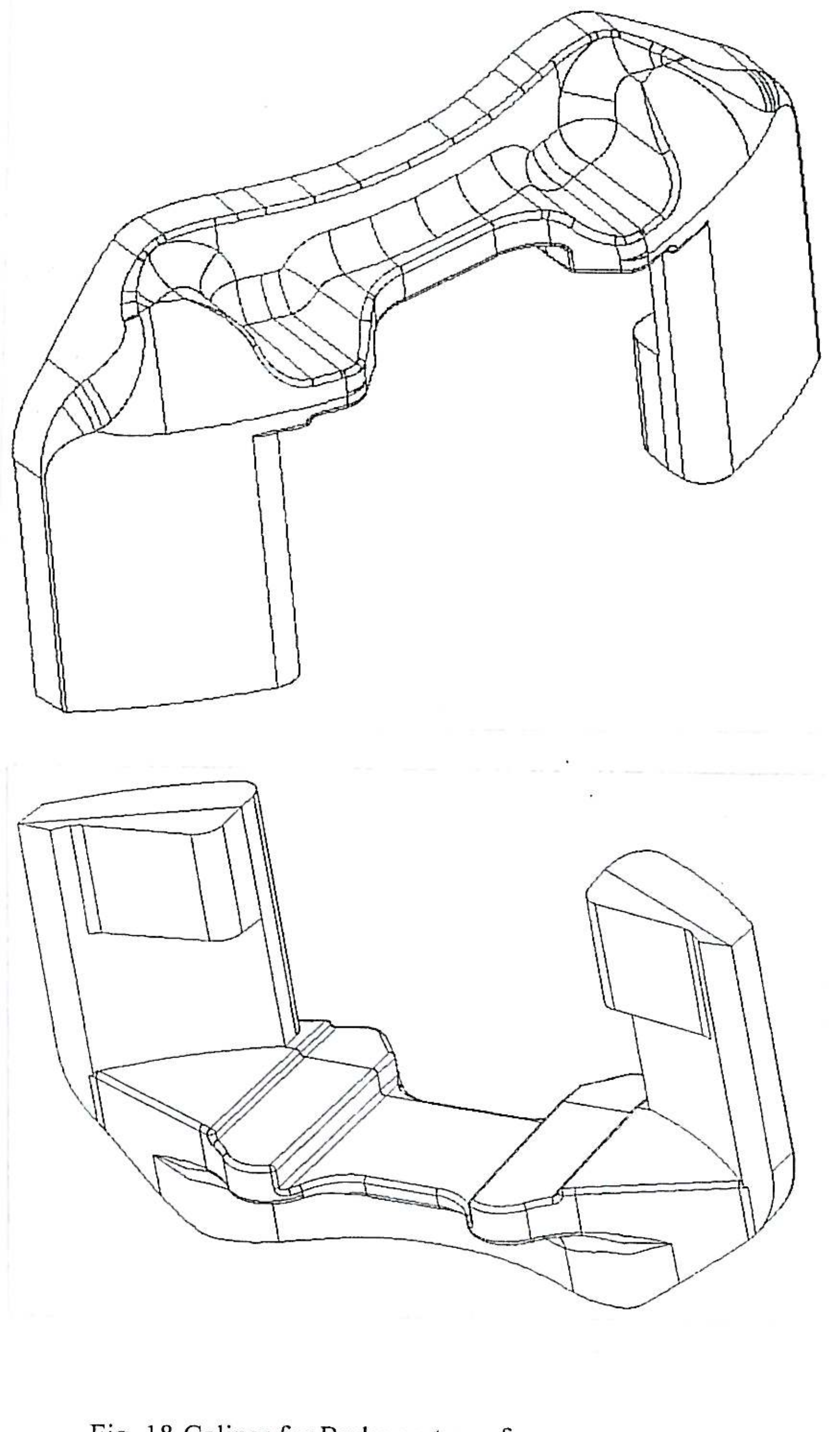


Fig. 18-Caliper for Brake system of passenger cars

Part No.	Hardness H.B	Sound Velocity m/Sec	Tensile Strength N/mm²	Type of Graphite	Microscopic Matrix	Result and reason
1	187	5590	250	95% nodular 5 %Semi-nodular	90%Ferrite 10%Pearlite	OK
2	191	5580	225	90%nodular 10% Semi-nodular	>85%Ferrite <15% Pearlite	OK
3 Reference Part	194	5560	225	85% nodular 5% Semi-nodular 10% compressed	85% Ferrite 15% Pearlite	OK
4	191	5560	225			OK
5	193	5520	220			OK
6	187	5590	230			OK
7	180	5580	250			OK
8	182	5580	240			OK
9	180	5590	245			OK
10	179	5600	250			OK
11	184	5560	230			OK
12	191	5570	225			OK
13	193	5510	230			OK
14	187	5580	250			OK
15	192	5520	225			OK
16 Gray Cast Iron	250	3500	190			NOK
17	375	4600	120	75% nodular 25% Semi-nodular + Compressed	60% Carbide 30% Ferrite + Pearlite	NOK less nodularity high carbide high hardness
18	234	5500	220	90% nodular 10% Semi-nodular	55% Ferrite 40% Pearlite 5% Carbide	NOK wrong matrix
19	329	4200	150	All compressed Graphite	60% Carbide 25% Pearlite 15% Ferrite	NOK less nodularity wrong matrix
20	229	5500	210	90% nodular 10% Semi-nodular	70% Ferrite 30% Pearlite	NOK wrong matrix high hardness
21	230	5550	220	>90% nodular <10% Semi-nodular	70% Ferrite 30% Pearlite	NOK wrong matrix high hardness

Table 3-Test Results of caliper

5-3-Cylinder of caliper for Brake system (Fig. 19)

Similar to the other parts , 13 good parts were selected for calibration . Parts 1 and 2 were checked by metalography and part no. 2 was selected as the reference part . The sound velocity is 5500-5600 m/Sec and the acceptable hardness is 170-187 HB . Part no. 14 is gray cast iron . The part no. 15 is a wrong part from the production line .

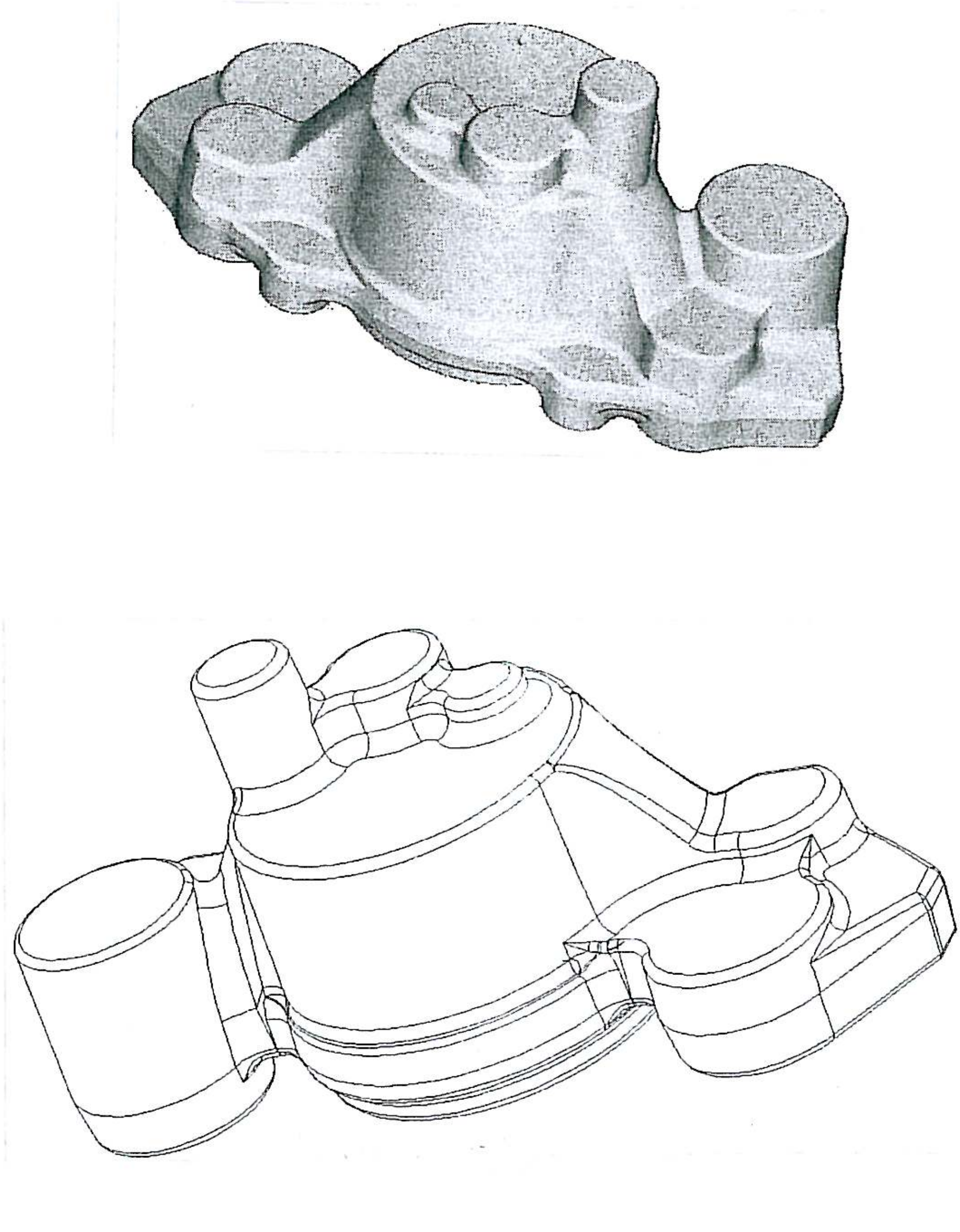


Fig.19-Caliper Cylinder for Brake system of passenger cars

Part No.	Hardness H.B	Sound Velocity m/Sec	Tensile Strength N/mm²	Type of Graphite	Microscopic Matrix	Result and reason
1	184	5580	250	> 90% nodular <10%Semi-nodular	>90%Ferrite <10%Pearlite	OK
2	180	5600	250	> 95%nodular <5% Semi-nodular	>90%Ferrite <10% Pearlite	OK
3	179	5570	240			OK
4	182	5600	250			OK
6	184	5550	230			OK
6	187	5540	235			OK
7	170	5600	250			OK
8	174	5590	250			OK
9	177	5580	245			OK
10	170	5600	250			OK
11	177	5580	225			OK
12	184	5550	230			OK
13	180	5550	235			OK
14 Gray cast iron	245	3400	190			NOK
15	229	5570	250	>90% nodular <10% Semi-nodular	>70% Ferrite <30% Pearlite	NOK Wrong Matrix

Table 4-Test Results of caliper cylinder

6-Conclusion

Experimental results shows that just by a simple test of sound velocity measuring it is possible to evaluate the nodularity rate in ductile cast-iron even before heat treatment . By this simple and fast test , one can decide to sort the part as a defective part that cannot be improved by heat treatment. But hardness testing and matrix check is not possible by sound velocity measuring and it would be possible only using Ultrasonic Flaw Detectors and analyzing the rate of absorption and scattering of ultrasonic waves inside the material that obviously will not provide quantitative and reliable results . But by using multi-frequency eddy current technique test before or after heat treatment will provide reliable and reproducible test results .

By eddy current testing it would be distinguishable that whether the rejection of a part is due to the less nodular graphite or because of the wrong matrix as the rejection due to the different effects occurs in different frequencies . Therefore , after eddy current testing , one may find out that whether heat treatment will improve the quality of the rejected part or not ?

By considering the production process , quality level and required technical specification or applicable standard , eddy current testing can be carried out for controlling casting or heat treatment process or both . By implementing this test also heat treatment can be limited only for some parts that cannot pass the eddy current test.

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