Remanent Magnetization for Non-Destructive Testing of Spot Welds

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Abstract. Resistance spot welding is one of the most frequently used joining methods in automotive and rail vehicle engineering due to its high process reliability and economic efficiency. In consequence of the process characteristics, the spot weld is localized within the overlapping area of the welded plates. For the non-destructive quality assurance, the concealed position of the joint is problematic. Recent research at Dresden University of Technology focuses on a non-destructive testing (NDT) method for resistance spot welding of ferromagnetic steel plates. The joint is magnetized by coils and the remanent magnetization is analyzed afterwards.

The talk introduces this new NDT method, compares it to established testing systems for NDT in resistance spot welding and presents the results of its application on two and three sheet metal combinations.

1 Introduction

Conventional resistance spot welding (RSW) is a welding process where usually two overlapping sheet metals with single thicknesses up to 3 mm are joined together. The process is completely automatable, e.g. in mass production of automotive body parts. The process is characterized by high efficiency and productivity. Theoretically, all electrically conductive materials can be welded by RSW, but most commonly steel or aluminum alloys are used. The sheets are pressed together by two copper electrodes. Copper is used as material for the electrodes due to its high specific electrical and thermal conductivity. A welding current $I$ is passed through the sheets via the electrodes for a certain period of time $t$. As a result of the contact and material resistance $R$, heat $Q$ is generated in-between the sheet metals according to Joule's first law (Equation 1). The electrical resistances of the sheet metals are higher compared to the copper electrodes. This causes a higher heat generation within the sheets and in their contact area until the metals melt. After solidification, the molten volume is called nugget. The size of the nugget depends among others on:

- process parameters (e.g. electrode force, welding current, weld time)
- material combination
- thicknesses of the sheet metals
- coatings of the sheet metals.
For quality assurance, the extension of the nugget is of central interest. In particular, an indication about the quality of the weld is given by the nugget diameter $d_n$ and the nugget penetration $p_u,l$ into the sheet metals. The nugget is usually not visible from outside and thus not measurable or readily evaluable (Fig. 1). The concealed position of the joint or nugget is a major challenge for non-destructive testing (NDT).

$$Q = \int t^2 R \, dt$$ (1)

![Fig. 1. Schematic cross-sectional view of a resistance spot weld in accordance with DIN EN ISO 17677-1 [1]](image)

According to the current state of the art, random collected samples are tested by laboratory-based destructive methods such as the chisel test. This statistical information regarding the quality of the joint are possible, but only after destructing components and thus not on the component itself. Therefore, methods that allow non-destructive evaluation of the joint are increasingly examined.

According to DVS 2916-5 [2], which reflects the current state of technology of NDT of resistance welding, three methods are available for quality assurance:

- NDT after the process
- process parameter monitoring
- process control.

The last two methods record and analyze process parameters. This provides indications of process fluctuations and intervene directly in the process. Both methods are not regarded as testing methods because they do not permit direct assessment of the joint. Different NDT methods for an assessment after the process are described in detail in [2]. The only method industrially used in large scale is the ultrasonic pulse echo technique. However, this method also has its technical restrictions, regarding high demands on the test personnel and the material thickness combinations [2]. Therefore, existing systems are enhanced and other possibilities for NDT of spot welds are investigated. Recent research at Technische Universität Dresden focuses on a NDT method for RSW of ferromagnetic steel [3]. During the research project IGF 17.539 BR [3] a new method was developed and investigated, where coils magnetize the joint and the remanent magnetization of the joint is analyzed afterwards. This paper introduces this method for NDT of spot welds. It presents results of experiments on two and three sheet metal combinations and shows the high potential by comparing it to established testing systems for NDT in RSW.
2 Theoretical Background

2.1 Fundamentals

Among others, materials can be divided into diamagnetic, paramagnetic and ferromagnetic materials. In contrast to the diamagnetic ($\mu_r < 1$) and paramagnetic ($\mu_r > 1$) materials, ferromagnetic ($\mu_r \gg 1$) materials enhance the magnetic flux density $B$ in their interior when an external electromagnetic field $H$ occurs significantly. The relationship between the electromagnetic field and the magnetic flux density can be described by Equation 2 ($\mu_0$: vacuum permeability, $\mu_r$: relative permeability) and Fig. 2. Applying an external magnetic field $H$, the magnetization of a previously non-magnetic material follows curve a (Fig. 2). The materials magnetic moments align themselves parallel to the exterior magnetic field. $B$ increases very sharp, depending on the materials $\mu_r$. On a certain amount of $H$ the magnetization of the material reaches the point of saturation, $B$ no longer rises. After removing the external magnetic field, the magnetization of the material follows curve $b$. If $H = 0$, a residual magnetization (remanence) $B_r$ remains in ferromagnetic materials. This means that the magnetic moments remain aligned. Applying a negative magnetic field, the magnetization decreases. $B = 0$ at the materials coercivity $H_c$.

The NDT method shown in this paper uses the characteristic behaviour of ferromagnetic materials for quality assurances of spot welds joined by RSW as described above.

$$B = \mu_0 \mu_r H$$

(2)

2.2 Application on Spot Welds for Quality Assurances

The size of the nugget in the cross-sectional area of joined sheet metals influences the magnetic field applied from outside. Fig. 3 shows the result of a FEM simulation of the magnetization process. The magnetization of a small nugget is significantly different from a large nugget. The authors assume that the reason for this can be described by the always-existing gap (e.g. air, zinc coating, adhesives) between the sheet metals. While the gap is non-magnetic, the nugget or cross-sectional area is ferromagnetic. This results in a concentration of the magnetic field lines across the ferromagnetic cross-sectional area. This context has an effect on the direction of the magnetic moments in the joint and consequently on the shape of the remanence.
2.3 Experimental Setup

For the investigations, typical material combinations (MC) used in automotive industry were examined (Table 1). Within each MC, the samples were welded with constant weld time and electrode force using medium-frequency inverter technique. Different sizes of the nuggets were realized by varying the welding current.

Table 1. Investigated material combinations (MC) with their thicknesses

<table>
<thead>
<tr>
<th>MC</th>
<th>Upper sheet</th>
<th>middle sheet</th>
<th>Lower sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1</td>
<td>DC04+ZE75/75 (0.65 mm)</td>
<td>-</td>
<td>HX220YD+Z110MB (0.65 mm)</td>
</tr>
<tr>
<td>MC2</td>
<td>DC04+ZE75/75 (0.65 mm)</td>
<td>-</td>
<td>HDT780C+Z150MB (2.0 mm)</td>
</tr>
<tr>
<td>MC3</td>
<td>22MnB5+AS150 (2.0 mm)</td>
<td>-</td>
<td>22MnB5+AS150 (2.0 mm)</td>
</tr>
<tr>
<td>MC4</td>
<td>HX340LAD+Z110 (1.0 mm)</td>
<td>-</td>
<td>HX340LAD+Z110 (1.0 mm)</td>
</tr>
<tr>
<td>MC5</td>
<td>HX340LAD+Z100 (2.0 mm)</td>
<td>-</td>
<td>HX340LAD+Z100 (2.0 mm)</td>
</tr>
<tr>
<td>MC6</td>
<td>HX340LAD+Z100 (1.5 mm)</td>
<td>HX340LAD+Z100 (1.5 mm)</td>
<td>HX340LAD+Z100 (1.5 mm)</td>
</tr>
<tr>
<td>MC7</td>
<td>DC04+ZE75/75 (0.65 mm)</td>
<td>22MnB5+AS150 (2.0 mm)</td>
<td>22MnB5+AS150 (1.5 mm)</td>
</tr>
</tbody>
</table>

The testing procedure can be carried out any time after welding and consists of two steps (Fig. 4). In the first step, the joint is magnetized by a magnetic field perpendicular to the sheet surface. After magnetization, the coils are removed and the remanence is measured on the surface across the area of the joint and processed in the second step. In the following section will describe each step in detail.

Fig. 4. Testing procedure
2.3.1 Step One: Magnetizing the Joint

For the experimental setup, two co-directional coils carrying the same amount of current were used, one on each side of the sample (Fig. 5). The sample with the joint is positioned between the coils and the magnetic field is applied by turning on the electrical current. The magnetization time is less than 0.1 s. The coil cores are of plastic or iron.

![Fig. 5. Experimental setup to magnetize the samples](image)

2.3.2 Step Two: Measuring the Remanence and Processing the Measured Data

The remanence was measured by scanning the region of interest on the surface of each sample with a Hall Effect sensor (Fig. 6a). To reduce the influence of interfering environmental magnetic fields as much as possible, the Hall Effect sensor was balanced against these environmental magnetic fields. The measured data is processed in a specially developed program and depicted in an intensity chart by false colors (Fig. 6b). During processing the measured data, a characteristic contour (Fig. 6b, green line) is captured and the inner area $A_{mag}$ of the contour is determined.

![Fig. 6. Experimental setup to measure the remanence and an example of a measurement](image)

2.4 Validating the Test Results of the NDT Method

To validate the test results, the joints are destroyed by torsion test and the area of the joint $A_{sp}$ is estimated of an elliptic area (Equation 2, $a$: major radius, $b$: minor radius). Therefore, the diameters of the joint are measured according to DIN EN ISO 14329 [5]. Each sample result of both NDT and torsion test are compared with each other. Fig. 7b shows an example of an overlay of the sample of Fig. 6b and Fig. 7a. The relationship shown in the overlay of Fig. 7b leads to the hypothesis that the inner area of the contour equals the area of the joint (Equation 3).
3 Results and Discussion

3.1 Two Sheet Metal Combinations with Same Thicknesses

The relation between $A_{sp}$ and $A_{mag}$ of MC1 and MC4 shows Fig. 8. While MC4 is of the same alloy of steel, MC1 consists of different steel materials. The samples of MC1 were magnetized using plastic cores for the coils. Most of the results are within the confidence interval. The influence of the materials for the coil cores were compared using MC4 (Fig. 8b). This MC was the reference combination during the investigations because it is simple to weld. The comparison of the two core materials shows less scatter of results in the use of the iron core. A large part of these samples is in the range of the confidence interval. When comparing the results of the measurements of upper and lower side of the samples the respective measurement results with steel cores differ less from each other than with plastic cores. The differences between the upper and lower side arise on the varying distances between the sheet surface and Hall Effect sensor. The distances have to be adjusted for each measurement, depending on the topography of the sheet surfaces.

Poorly welded samples or stick welds, so called “zinc-adhesives”, can be clearly assessed (Fig. 9a). The measured remanence of these samples have no clear contour. As shown in
Fig. 9b and Fig. 9c, the shape of the nugget in the cross sectional plane can be examined by measuring and analyzing the remanence. Looking at the amount of the measured flux density, differences between poorly welded samples and good welds become obvious. Stick welds have no or a very small volume of a nugget, at which the sheet metals are welded together with a steel-to-steel connection. Thus, the magnetic field lines cannot concentrate as much as in a well-defined nugget. Therefore, the measured flux density is almost entirely in positive range.

3.2 Two Sheet Metal Combinations with Different Thicknesses

In the previously examined MC, both sheet metals had the same thicknesses. MC2 is characterized by a large difference of the welded sheet metal thicknesses. The ratio of the sheet thickness is about 1:3, which provides great challenges to the welding task. For the investigations, the metal sheets are magnetized with plastic cores and the upper and lower side was measured. The results show that even with big differences of the sheet metal thicknesses $A_{sp}$ and $A_{mag}$ correlate to each other (Fig. 10).
3.3 Three Sheet Metal Combinations

MC7 is a combination of two high-strength martensitic and a dual-phase steel, which differ in their material-technical properties significantly. This can be seen also in the images of the measured remanence. Using the black and white colour scale, a good evaluation of the nugget diameter between the upper and middle sheet (Fig. 11a) is possible. The nugget diameter of the middle and lower sheet can be assessed by partial derivation of the remanence in x- and y-directions (Fig. 11b). The results in Fig. 12 show that a separate evaluation of the corresponding sectional plane is possible.

Fig. 11. Example of the measured remanence to evaluate the nugget diameters of each sectional plane of MC7

Fig. 12. Relations between $A_{sp}$ and $A_{mag}$ at three-sheet metal combination MC7 with different thicknesses

3.4 Results of all Investigated MC

Fig. 13 shows the results of all investigated MC. The evaluations of all MC show good correlations between $A_{sp}$ and $A_{mag}$. This applies to two- as well as to three-sheet metal combinations. It is evident that with the developed algorithms to analyze the measured remanence a nondestructive assessment of the nugget is possible. Not only can the diameter of the nugget but also the area of the nugget in the cross-sectional plane be assessed.
nondestructively. The results confirm the theoretical assumptions and the numerical previews of section 2.

![Diagram](image1)

Fig. 13. Results of all investigated MC

3.5 Comparison with Test Systems for NDT in RSW

As part of the research project, evaluation measurements were carried out with established ultrasonic test systems for NDT in RSW. There are single transducer (US-ST) and multi transducer systems (US-ST) available. Another test system using ultrasonic for evaluating measurements is the USM 4.0 developed at Technische Universität Dresden. This system sends transverse ultrasonic waves through the joint during welding, which are evaluated afterwards [6, 7]. The test system is based on the Bosch Rexroth ultrasonic system PSQ 6000 and uses its ultrasonic transmitter and receiver. The measurements are compared with the developed NDT test system of this article (RMZ). First, the welded samples were tested nondestructively with all systems. Afterwards, the samples were destroyed by torsion and measured as described in section 2.4. The results of the evaluation measurements are shown in Fig. 14. The comparison of the different systems was performed by the statistical test by McNemar [8]. The decisive criteria for the test are based on the minimum nugget diameter $d_{n,\text{min}} = 3.5\sqrt{t}$, where $t$ represents the thickness of the thinner sheet metal (Fig. 14). The results show that the test system developed in this paper provides a high potential for NDT in RSW. A reason for this could be that the test results of analyzing the remanence are less subjective compared to the reliable ultrasonic test systems.

![Diagram](image2)

Fig. 14. Comparison with Test Systems for NDT in RSW ($d_n$: nugget diameter, $t$: thickness of the thinner sheet metal)
4 Conclusion and Outlook

In conclusion, the results show great potential of the introduced NDT method for quality assurance of spot welds by measuring and analyzing the remanence. The assessment can be carried out automatically and both the nugget diameter and the cross-sectional area of the nugget can be evaluated. The area might be the better choice for the quality assurance since loads are transferred from one sheet to another through this area. In addition, stick welds and too small nuggets can be detected reliably. A great advantage is that no couplants are necessary for this method as it is for NDT by ultrasonic with hard delay lines.

Future research should analyse the influence of the electrode indentation and the material characteristics on the test result to get a better understanding of this method. Along with this, the functionality for extreme material combinations with large differences in thicknesses needs to be examined because of the great potential the method shows especially for these combinations.

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References
