DETERMINATION OF RESISTANCE SPOT WELD QUALITY IN REAL TIME USING REFLECTED ACOUSTIC WAVES. COMPARISON WITH THROUGH-TRANSMISSION MODE

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Abstract: The determination of quality parameters of resistance spot weld in real time is of great importance in today's industry. Acoustic waves can solve this problem in the sense of measuring certain features directly related to the weld quality – degree of heating of the weld zone, moment of beginning of melting and some others. The ultrasonic transducer incorporated into an electrode sends short acoustic pulses into the weld area and receives the signals reflected from different interfaces in heat affected zone during welding process. The specific image and signal processing algorithms applied to the received signals enable us to localize weak reflections from internal interfaces, recognize their nature and use this information to characterize the weld quality.

Introduction: The inspection of resistance spot weld quality in real time is quite a challenging and at the same time promising field of NDT. It enables one to monitor the dynamics of the spot weld properties right at the moment of the weld manufacturing. It is extremely important on the industrial floor as it gives the operator information about the quality of the product and thus enables him to correct the mistake before it is too late. Quality inspection of "hot" welds is relatively new field of NDT studies which is potentially capable of providing 100% quality output of the production line. It becomes especially important as long as implementation of the in-line quality inspection techniques will help save a lot of time by elimination or, at least, reduction of costs of after-production inspection and fixing bad parts.

Our approach to the above mentioned problem is using the acoustic waves which pass through the spot weld structure during welding. On their way through the setup the waves are modified by the media and thus carry some information about the processes taking place inside the system. The setup consists of a set of one or two ultrasonic transducers incorporated into the electrodes of the spot welder. The ultrasonic transducers are driven by pulser-receiver; the last is controlled by the computer. The schematic view of the setup is presented in Figure 1.

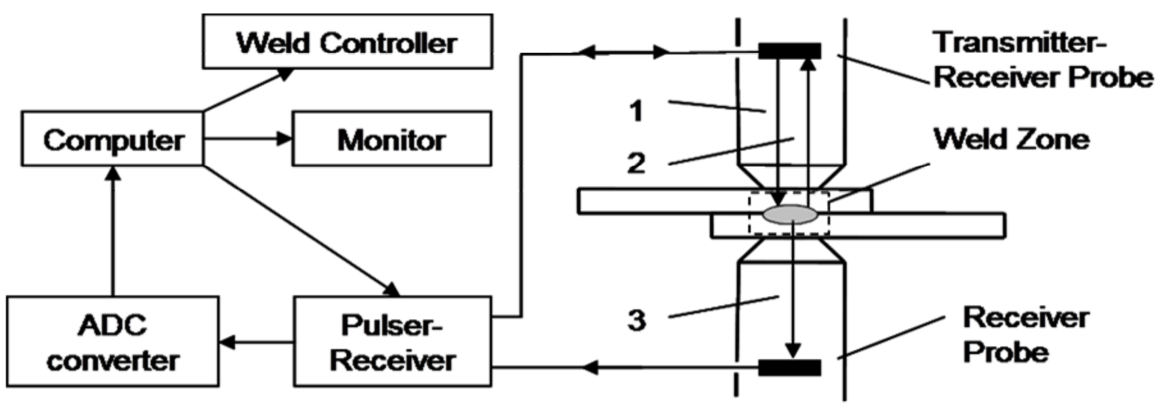

Figure 1. Schematic view of the experimental setup. 1 – incident wave, 2 – reflected wave, 3 – transmitted wave.

The detailed description of the operational process of the setup can be found in [1, 2]. In this article we will present the most important results obtained previously in the transmission mode and compare them with the reflection mode. The comparison of the two methods and advantages of application of either method will be discussed in this paper.

Results: In transmission mode a series of pulses **1** is sent through the weld zone (see Figure 1) and is picked up by the receiving transducer as waves **3**. As the welding current heats and melts the media, the material properties at different moments of welding change much. For this reason the waves passing through the weld at different moments of welding differ much from each other. The comparison of the wave characteristics provides useful information about the processes inside the stack-up. The finite-difference model of spot weld formation described in [2] shows the dynamics of the temperature and some material properties inside the weld zone during the spot weld formation. Figure 2 shows the temperature distributions in the spot weld at different phases of welding procedure. The calculations have shown very high inhomogeneity of the temperature distributions along the vertical direction in the weld setup. The temperature gradients in the middle of the structure reach 700-800 K/mm. The longitudinal velocity gradients at the same region are in the order of 1000 m/s per mm. It means that in the center of the liquid (white) area the velocity of sound propagation is around 3800 m/s while at the steel-copper interface the velocity is close to 5000 m/s. The same high gradients are for the other material properties such as stiffness, thermal expansion coefficient, density, etc. The acoustic impedance mismatch at all interfaces is also dependent on the temperature distribution at the given moment. Acoustic reflectivity and acoustic transparency of the structure also fluctuate during welding, thus affecting the amplitude and the magnitude spectrum of the signal. All these factors give rise to the modifications the wave experiences on its way through the weld zone.

Previous analysis [1] has shown that among half a dozen of different parameters of the signal the time of flight is the most reliable one. There was found high correlation of through-transmitted signal delay with the nugget size of the spot weld. Figure 3 shows the signature of the weld obtained in transmission mode. Such an image is sometimes called M-scan; here each vertical line represents one A-scan obtained consequently during 500 ms. In the given picture there are 200 waveforms put together to form an image.

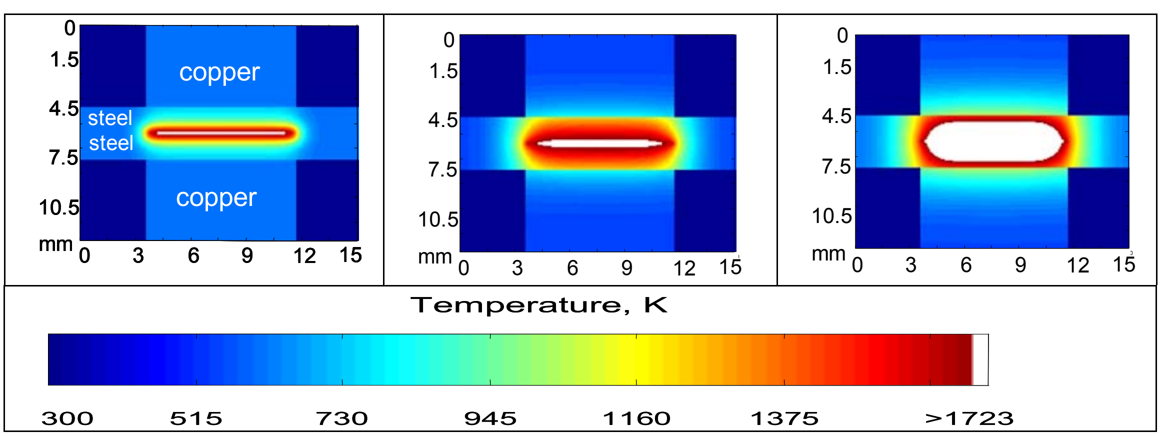

Figure 2. Three samples of temperature distribution in the spot weld during 12 cycles 60 Hz welding procedure. Left picture – second cycle of welding, middle – sixth, right – eleventh cycle.

The maximum delay of the signal marked as TOF in the figure has 90-95% correlation with the nugget size. Such correlation was verified in numerous experiments with different metal thicknesses, coatings and welding times. For every trial there was made a series of welds with different nugget sizes and their correlation with TOF was studied.

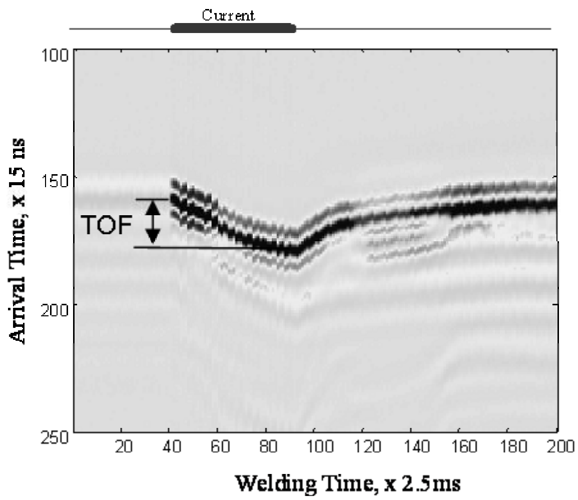

Figure 3. Signature of the spot weld. Through-transmission mode.

As the next step in our research we tried to use reflection mode to obtain analogous results. This mode is more advantageous as long as in this case only one transducer is required which is much more appropriate in industrial environment. Figure 4 shows schematic of the welding assembly and waves received in reflection mode. The incident wave **1** enters the weld zone (as in Figure 1) and experiences multiple reflections from several interfaces. Wave **2** is the reflection from the top side of the upper steel plate; wave **3** is the wave coming from the interface between the plates; and wave **4** comes from the bottom side of the lower plate.

Figure **5** shows the typical signature obtained in the reflection mode. Before the current is on, one can see three sets of straight lines going parallel to the horizontal axis. As the current begins to heat the stack-up the waves require longer time to reach the receiver due to several reasons. The main one is the acoustic velocity decrease in the metal at elevated temperatures. The difference between longitudinal velocity at melting point and that at the room temperature is 1800 m/s. This is more than 30% velocity drop. Another reason is thermal expansion of heated material. However, calculations have shown that its contribution to the total delay of the signal does not exceed 5-10 %. This is one of the evidences of the higher sensitivity of acoustic methods compared to the thermal expansion measuring methods. Thus, heating leads to the delay of signals **2**, **3**, and **4**. The delay of the reflected signal **4** is due to the heating of the welded plates and the upper electrode. The delay of the reflected signal **2** is due to the heating of the copper electrode. It is mush smaller than that of the signal **4** as long as copper has higher conductivity than steel welded plates and thus develops less heat. Subtraction of the delay of signal **2** from that of signal **4** provides pure delay inside the weld zone. As long as in the reflection mode the wave passes through the weld zone twice the accuracy of measuring the total delay is higher than that of the transmission mode. This can be a big advantage while measuring delays through the stack-ups of the thin plates (0.8 mm and less). In this case the reflection method is capable to provide more accurate results in measuring the degree of heating of the system and thus the better prediction of the weld nugget size.

At some certain moment the intermediate interface **3** disappears, and one can see only waves **2** and **4**. The disappearance of the signal can be explained by the disappearance of the interface between the two welded plates. This fact can be used as a reliable evidence of the fact that the melting in the system takes place, and it happens from some certain moment which can be easily determined. Thus, the time between the moment of disappearance of interface **3** and the moment of turning off the current is the time of nugget growth. This is extremely important fact in the process of prediction of the future nugget size: the time of melting can be correlated with the nugget sizes obtained during destructive tests of corresponding welds.

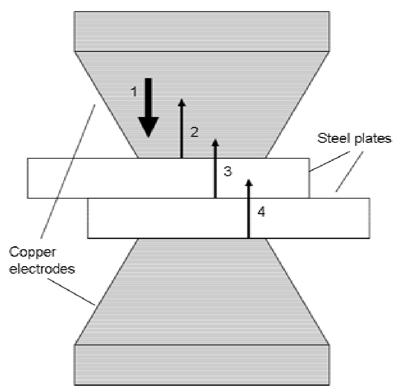

Figure 4. Reflection mode.

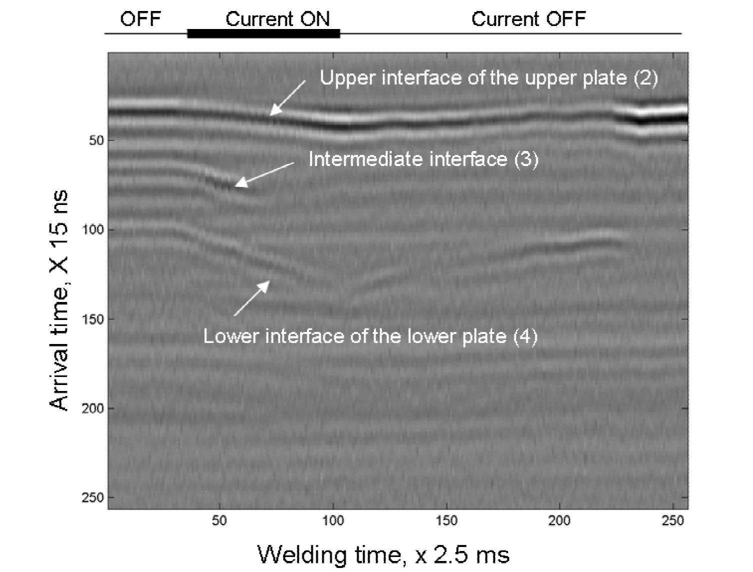

Figure 5. Reflection mode acoustic signature.

One of the problems which arise during the signal analysis is determination of the dynamically changing position of the reflected signal. Peak tracing techniques were successfully applied to the transmission mode as long as the amplitude of the transmitted signal is high (signal-to-noise ratio ~ 10). However in reflection mode determination of the peak position becomes quite a challenging problem. The main reason is very low SNR which is in some cases less than 1. Peak tracing, filtering, convolution with original signal do not always help in this case. One of the possible solutions to the given problem comes from the observation of the fact that many interfaces of interest can be subdivided into a set of straight line segments. For example, the interfaces in Figure 5 can be represented by straight lines as shown in Figure 6. Two moments which are responsible for the change of the slopes are explicitly defined externally – the moment of start **10** and moment of end **20** of the weld current. The accuracy of approximation of interfaces on M-scan with straight lines is high enough for the given measurements: the least squares approximation gives R^2 value in the range of 0.97-0.99.

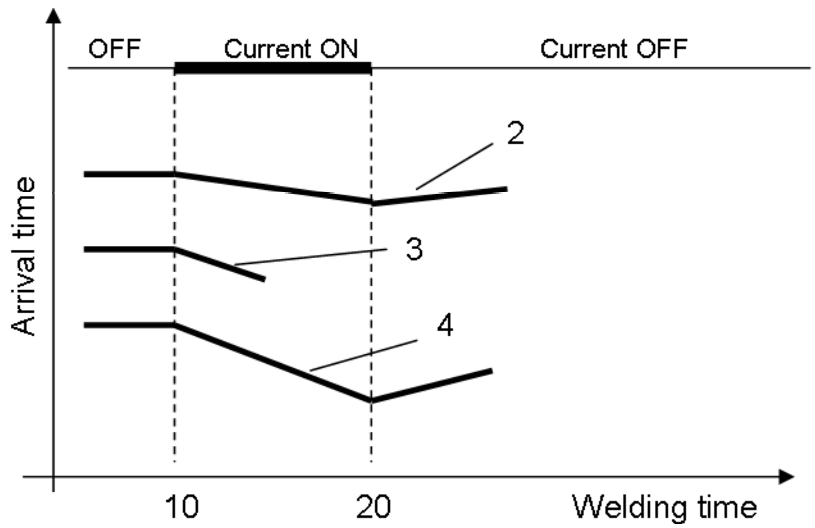

Figure 6. Interfaces as in Figure 5, – 2, 3 and 4, represented by straight line segments.

The idea of location of these interfaces in the 2D image comes from the computer tomography image creation, when projections of the object at different angles are combined together to form the object's internal structure. In our case the problem even easier – we know the "internal structure" of the 2D object – this is our image. And we need to find its projections at different angles and locate maximums and their orientations. The Radon transform can do this job easily. The Radon transform is defined as

$$R(p,\tau)[f(x,y)] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta[y-(\tau+px)]dydx\,, \tag{1}$$

where *f(x, y)* is the image to process, *p* is the slope of a line and τ is its intercept. Another way to get the same result is to apply the following equations:

$$R(\theta,x') = \int_{-\infty}^{\infty} f(x'\cos\theta - y'\sin\theta, x'\sin\theta + y'\cos\theta)dy'\,, \tag{2}$$

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}. \tag{3}$$

These formulas can be understood as performing the line integration along vertical directions (along every column) of the gradually rotated image. The computer algorithm consists of two steps: rotation of image and finding "projection" of the rotated image on horizontal axis. Image should always be rotated around its center. If image contains the straight line, the projection of the image when line is perpendicular to horizontal axis will have a strong maximum. Angle of rotation and position of maximum with respect to the image center are the two variables which are required to locate the line position in the image. These two variables are used to find *a* and *b* coefficients in the linear approximation equation

$$y = ax + b. \tag{4}$$

Figure 7 shows the gradually rotated image segment and its normalized projections on the horizontal axis at different angles of rotation. Projection of the straight line in the image has maximum when this line is perpendicular to the horizontal axis. When the absolute maximum is found the rotation angle is recorded. This angle will be used in calculations of the slope of the approximation line, *a*. The position of the peak with respect to the center of rotation of the image provides information needed to calculate the intercept *b*. These two coefficients provide enough information to locate the straight line (4) in the image segment and then map it to the original image from which the image segment was taken.

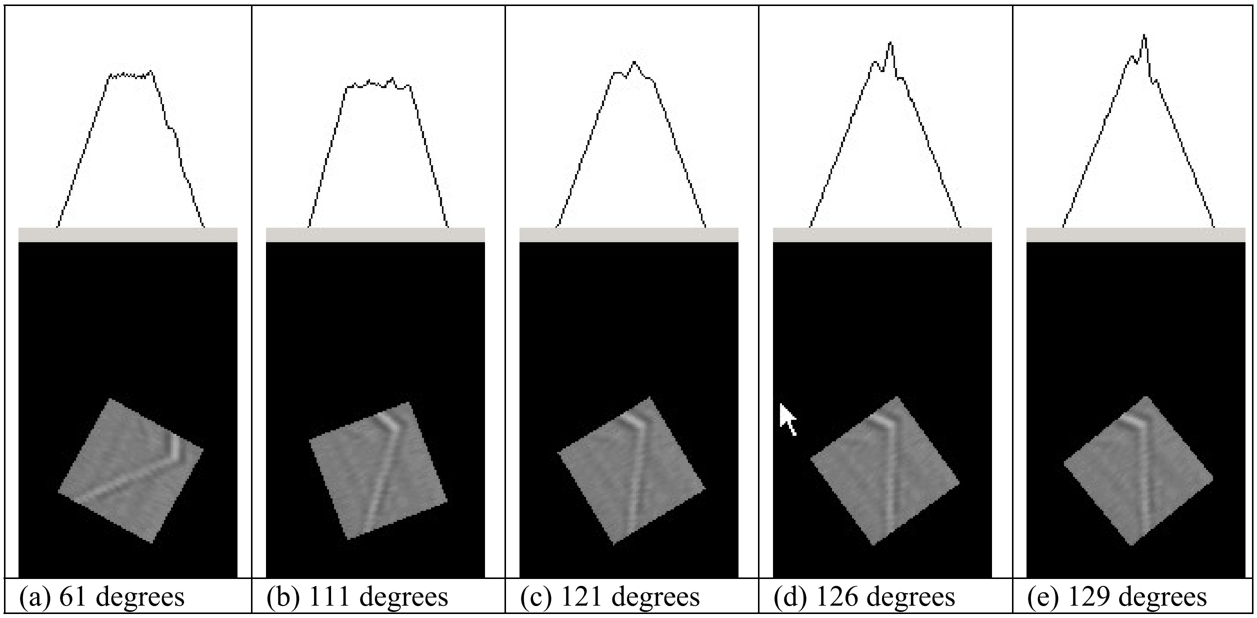

Figure 7. Rotated image segment (bottom) and corresponding normalized projections of the image on the horizontal axis (top).

Figure 8 represents the image segment and its Radon transform image in the range of 0-180 degrees. The point shown with the arrow is the location of the strongest projection (maximum) found in the given angle range. From this image the straight line slope and intercept can be obtained

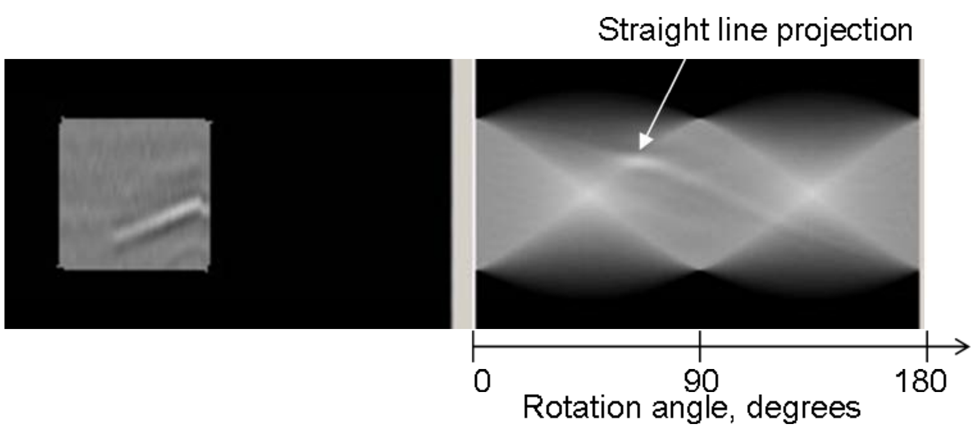

Figure 8. Image with line segment (left) and Radon transform image (right).

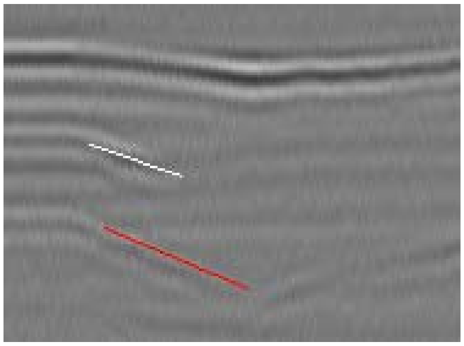

Figure 9. Signature of the weld with the segments of lines located using Radon transform technique.

One of the main elements in obtaining quality Radon transform is smooth rotation of the image. In our program the bilinear transformation was used to rotate the image. In this case the four neighbouring points are used to find the intensity of the rotated image in the inter-grid space. When the grid is rotated the grid nodes fall into the spaces between the location of the original nodes. Thus, the approximation is required to better represent the rotated image. Intensities in four points around the point of interest help find the coefficients for bilinear approximation:

$$H = a_0 + a_1 x + a_2 y + a_3 xy\,. \tag{5}$$

Here H is the intensity of 8-bit image in the node of the rotated image x, y.

Discussion: The determination of the spot weld quality using through transmission and reflection modes is quite reliable method. Still both of these methods have some drawbacks.

The through transmission mode is pretty straightforward from the signal processing point of view. The transmitted signal received by the second probe has high SNR, and position of the signal can be easily defined by zero-crossing or peak tracing techniques at every moment of welding. But the thinner the welded plates are the smaller the delay of the signal is and the bigger the error introduced by the electrodes. In the reflection mode this problem can be easily solved by subtraction of the electrode delay from the total delay. Also, higher sensitivity to the degree of heating in terms of TOF delay is achieved by the fact that the reflected signal passes twice through the area of interest. But at the same time, due to low SNR in reflection mode, some pre-processing should be done before the pattern can be extracted. This could include filtering the separate waveforms or filtering the whole image formed by the waveforms. If the whole image is filtered, the removal of the 2D low-frequency noise helps reveal the parts of the waveforms representing reflections from interfaces. In the very noisy or weak signals the Radon transform helps establish the dynamics of the signal reflecting from the given interface.

Also, reflection mode provides information about the moment of the beginning of melting of the welded plates. This is what can not be explicitly seen in the transmission mode signatures. The time of melting can be calculated for each weld and later correlated with the corresponding nugget size. It can be used as additional parameter for quality characterization.

The total melting time, the delay of the reflected signal and some other parameters such as signal amplitude dynamics can be used as the inputs for the neural network algorithms. Development of the reliable prediction algorithms based on neural network analysis could provide a reliable tool which can be used in in-line spot weld quality monitoring.

Conclusions: The described method of obtaining spot weld characteristics using reflection mode seems to be much more effective compared to the transmission mode. It provides the same information as the transmission mode does plus some other important properties. The development of better signal processing algorithms could provide even more information about the internal structure of the weld.

Also, the reflection mode is more desirable one as long as it uses just one probe instead of two. Such problems as misalignment of the tips, angle problem and electrode mushrooming are expected to less affect the process of testing of the weld quality in real time.

Still, some problems exist in the field of better noise removal. Also, extraction of the signal not as a set of straight lines but as a complex of connected line segments representing a pattern could be much more advantageous approach. Design of pattern recognition algorithms capable to extract the picture of all interfaces as a whole is considered as one of the main future steps in the given research.

References:

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