Archives of Materials Science and Engineering

Volume 28
Issue 2
February 2007
Pages 113-118

International Scientific Journal
published monthly as the organ of
the Committee of Materials Science
of the Polish Academy of Sciences

Examination of conditions in contact interface using ultrasonic measurement

H. Saiki [a], Y. Marumo [a,*], L. Ruan [a], T. Matsukawa [b],
Z.H. Zhan [c], Y. Sakata [d]
[a] Graduate School of Science and Technology, Kumamoto University,
2-39-1 Kurokami, Kuammoto 860-8555, Japan
[b] ISEKI & CO., LTD., 5-3-14, Nishi-Nippori, Arakawa-ku, Tokyo, 116-8541, Japan
[c] Fujitsu Kyushu System Engineering Ltd., 2-2-1 Momochihama Sawara-ku,
Fukuoka 814-8589, Japan
[d] Department of Mechanical Engineering, Nishinippon Institute of Technology,
1-11 Aratsu Kanda-machi, Miyako-gun, Fukuoka 800-0394, Japan
* Corresponding author: E-mail address: marumo@gpo.kumamoto-u.ac.jp

Received 15.11.2006; accepted in revised form 25.01.2007

ABSTRACT

Purpose: In metal forming, the conditions of contact interface have a great effect on the characteristics of interface friction and heat transfer between tool and workpiece. Estimation of contact conditions in the tool-workpiece interface is required in order to optimize process conditions. Ultrasonic examination is an effective method to estimate the contact conditions. In this study, we investigated the effects of ultrasonic frequencies and intermediate air/lubricant films in the contact interface on the properties of penetration and reflection of incident ultrasonic waves.

Design/methodology/approach: We have presented a method by which the contact conditions are evaluated from the relative intensity of reflected ultrasonic waves at the interface. Using this evaluation method, the relative intensity was measured continuously during processes.

Findings: The effects of ultrasonic frequencies and intermediate films on the properties of penetration and reflection of incident ultrasonic waves were revealed. The presented method was effective for evaluating the variation of contact interface conditions.

Research limitations/implications: Thickness of intermediate films can be measured using this ultrasonic examination. The performance of lubricants can be estimated.

Practical implications: The optimization of forming processes will be achieved based on the evaluation results of contact conditions.

Originality/value: Tribological conditions including intermediate air/lubricants were evaluated by ultrasonic examination. This shows the possibility that the lubricant behaviour in the contact interface is examined during processes.

Keywords: Plastic forming; Tribology; Contact conditions; Ultrasonic examination

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

In metal forming, contact conditions in a tool-workpiece interface have great effects on the material flow of workpiece and the heat transfer between tool and workpiece. The evaluation of the contact conditions is required for optimizing the process conditions in order to manufacture high-quality products. However, it is very difficult to examine the contact conditions during forming processes. In a metal forming process, the forming load is supported by the asperities and the lubricants trapped in valleys on the surface roughness in the contact interface. The ratio of the real contact area of asperities to the apparent contact area, i.e., contact ratio, is a main factor to evaluate the contact conditions. Intermediate air/lubricant films in the tool-workpiece interface is also a main evaluation factor. During a forming process, contact ratio, contact positions and intermediate films will change with the surface expansion of the workpiece and the flow of lubricants due to the deformation of the workpiece. Such behaviors should be revealed in order to evaluate contact conditions including frictional shear stress, wear, adhesion and heat transfer at the interface. Many studies for evaluating and testing contact conditions concerning elastic contact problem, friction, wear, adhesion, welding and metal forming processes have been done[1-17]. Several methods for testing contact conditions have been reported, for examples, (a) method by the measurement of surface roughness or topography after deformation, (b) method by the measurement of electrical resistance between tool and workpiece during forming process, (c) method by the direct observation of contact area using transparent glass tools, (d) theoretical method. However, more effective methods are required to attain satisfactory evaluation.

Ultrasonic examination is an effective method to examine various inner states and properties non-destructively and continuously [4-7, 13-27]. In our previous study [16], we evaluated contact conditions measuring the intensity of reflected ultrasonic waves at the tool-workpiece contact interface during upsetting process. The method has the advantage of evaluating the varying contact conditions continuously during forming process.
Incident ultrasonic waves penetrate not only real metal contact areas but also intermediate air films and lubricant films at an interface. The frequencies of ultrasonic waves influence the properties of reflection and penetration at the contact interface between tool and workpiece. This effect varies from frequency to frequency. In order to evaluate contact conditions at an interface accurately, the effects of ultrasonic frequencies and intermediate films on the properties of penetration and reflection of incident ultrasonic waves should be revealed. In this study, the effect of the ultrasonic frequencies and the thickness of intermediate air/lubricant films on the intensity of reflected ultrasonic waves was investigated.

2. Reflection of ultrasonic waves

In this study, we examined how the reflection and penetration of ultrasonic waves changes due to the presence of air/lubricants between tool and workpiece. Figure 1 shows the three-layered contact model, i.e., the tool-intermediate film-workpiece model. Assuming this model, the reflection intensity of sound pressure is evaluated by Eq. (1) [17].

$$T_1 = (4Z_1/Z_3)/\{(Z_1/Z_3+1)^2\cos^2\theta + (Z_1/Z_2+Z_2/Z_3)^2\sin^2\theta\} \qquad (1)$$

Here, $\theta = 2\pi L/\lambda_2$

Z_1, Z_2 and Z_3 are acoustic impedances, L is the thickness of the intermediate film, and λ_2 is the wavelength of ultrasonic waves in the intermediate film.

The reflection ratio of sound pressure r_1 is shown by Eq. (2).

$$r_1 = P_r/P_0 = (1-T_1)^{1/2} \qquad (2)$$

Thus, relative intensity of a reflected ultrasonic wave, I/I_0, is represented as

$$I/I_0 = P_r/P_0 = r_1 = (1-T_1)^{1/2} \qquad (3)$$

where I is the maximum intensity of an ultrasonic wave reflected at the interface (Fig. 2), and I_0 is the maximum reflection intensity when an ultrasonic wave is reflected totally at the interface. The relative intensity I/I_0 can be used as a measure of the conditions of ultrasonic reflection at the interface.

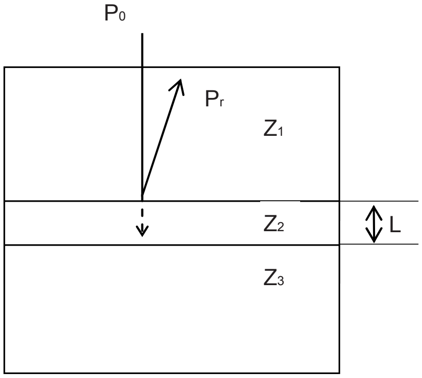

Fig. 1. Schematic illustration of a tool - intermediate film - workpiece model for the reflection and penetration of an ultrosonic wave at the contact interface

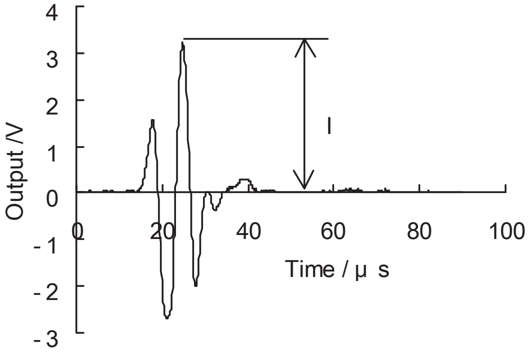

Fig. 2. An example of the measured ultrasonic wave that was reflected at the contact interface

3. Experimental conditions and procedures

The experimental setup developed by us for ultrasonic examination is shown in Fig. 3. It consists of the compression die set and the measurement equipments. Cylindrical specimens with 8mm in height and 24mm in diameter were used in the experiments. We used the ultrasonic transducers with frequencies of 2.25MHz, 5MHz, 10MHz, 20MHz, 50MHz and 100MHz. The reflected waves from the contact interface between the tool and the specimen were measured at a high velocity of sampling and continuously by using the GP-IB interface system and the digital storage oscilloscope with 8 bits 32 level/division and 200MHz sampling. It took approximately 0.2 seconds to obtain a reflected wave (2048 bites). In the experimental setup shown in Fig. 3, the ultrasonic transducer was placed on the top surface of the upper tool. The part of the incident waves is reflected at the contact interface *U* between the upper tool and the specimen. The rest part penetrates the interface *U*. Figure 2 shows a sample of a measured wave that is reflected at the interface *U*. In this study, relative intensity I/I_0 was used for a measure of reflection intensity.

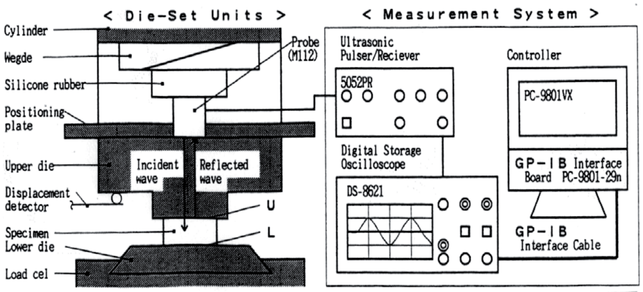

Fig. 3. Schematic illustration of the experimental setup for measuring a reflected ultrasonic wave [16]

4. Results and discussion

In this section, the effect of ultrasonic frequencies and intermediate films on the reflection and penetration of ultrasonic waves are described. Figure 4 shows influence of the intermediate air film thickness on the relative intensity of reflected waves for ultrasonic frequencies of 2.25MHz, 5MHz, 10MHz, 20MHz, 50MHz and 100MHz. Here, it is assumed that an intermediate air film exists between two steel layers. This relationship was obtained from Eq. (3). With lower frequency, the thickness of an intermediate air film that the ultrasonic wave can penetrate increases. When the air film thickness is 1 nm or greater, the ultrasonic wave reflects totally for these frequencies. Similarly, when an intermediate lubricant film exists between two steel layers, the result shown in Fig. 5 is obtained from Eq. (3). When the ultrasonic frequency is as low as 2.25 MHz, approximately 80% of the incident ultrasonic wave penetrates the lubricant film of approximately 1μm thickness. In contrast, when ultrasonic frequency is 100 MHz, the ultrasonic wave reflects totally with the lubricant film of approximately 1μm thickness. Figures 6 and 7 show influence of ultrasonic frequencies on the relative intensity of reflected waves for intermediate air and lubricant films, respectively.

In addition to the theoretical results described above, the properties of reflection and penetration of incident ultrasonic waves were also investigated experimentally. Reflected waves were measured during compressing a steel cylindrical specimen as shown in Fig. 3. The relative intensity of the ultrasonic wave reflected at the contact interface between the specimen and the upper tool were evaluated for various frequencies. The ten-point mean roughness, RZ, of the surfaces of the tool and specimen was approximately 0.4μm and 0.5μm, respectively.

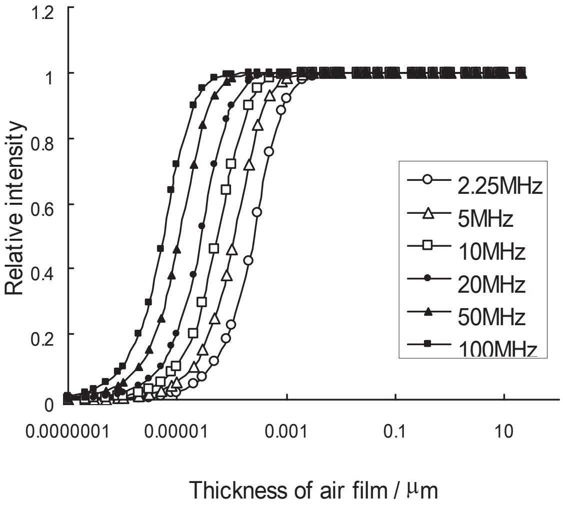

Fig. 4. Influence of the intermediate air film thickness on the relative intensity of reflected waves

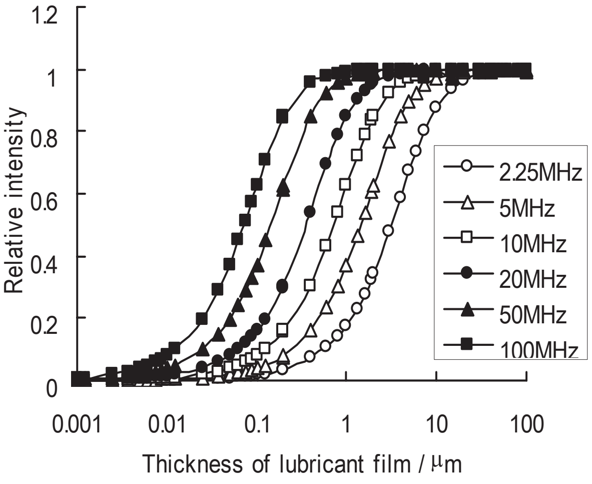

Fig. 5. Influence of the intermediate lubricant film thickness on the relative intensity of reflected waves

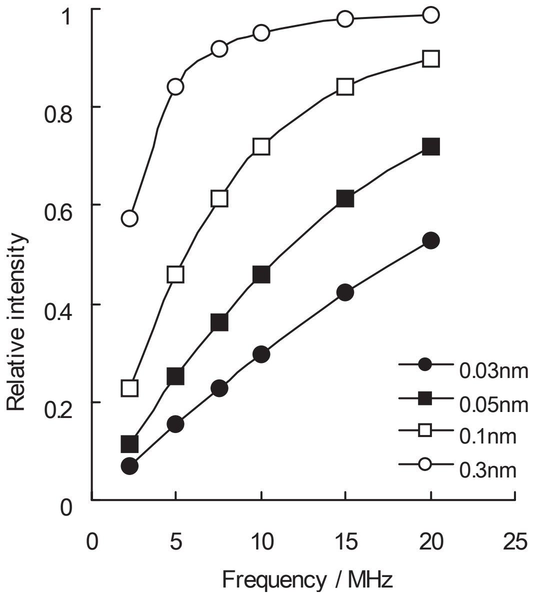

Fig. 6. Influence of ultrasonic frequencies on the relative intensity of reflected waves in the case of the intermediate air film

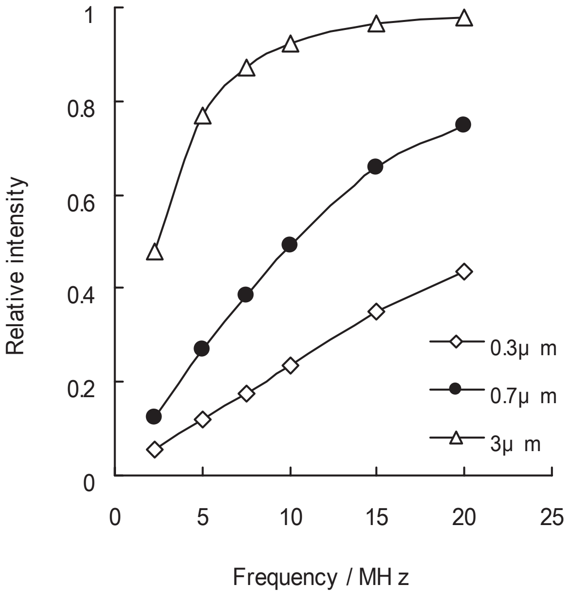

Fig. 7. Influence of ultrasonic frequencies on the relative intensity of reflected waves in the case of the intermediate lubricant film

Figure 8 shows influence of ultrasonic frequencies and applied loads on the relative intensity of reflected waves under nonlubricated condition. On increasing the load, the relative intensity decreases for all frequencies. The causes for this variation can be the increase in the real contact area and the decrease in the intermediate film thickness at the contact interface along with the increase in compression load. Under the same loads, except for the case of 7.5 MHz, the relative intensity decreases with decreasing frequency. Considering that the contact conditions are identical under the same loads, the lower the ultrasonic frequency, the more the ultrasonic wave penetrates through the intermediate air film. Figure 9 shows influence of ultrasonic frequencies and applied loads on the relative intensity of reflected waves when an intermediate lubricant film exists at the contact interface. Oil lubricant VG2 was used for an intermediate film. Similar to the case under nonlubricated conditions, except for 7.5 MHz, the lower the ultrasonic frequency, the more the ultrasonic wave penetrates through the intermediate lubricant film at the same loads.

From these results, the effect of ultrasonic frequency and intermediate film thickness on the reflection and penetration of ultrasonic waves can be understood. By clarifying the effect of ultrasonic frequency and presence of intermediate film on relative intensity in greater detail, it will be possible to evaluate the average thickness of the intermediate lubricant film.

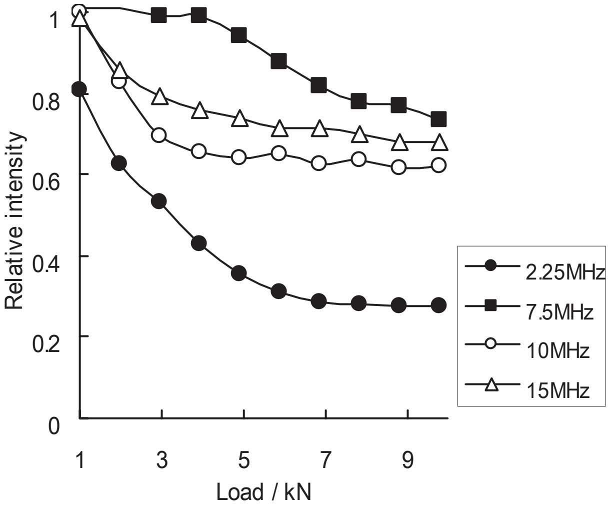

Fig. 8. Influence of ultrasonic frequencies and applied loads on the relative intensity of reflected waves in the case of no lubricants

5. Conclusions

The effects of ultrasonic frequencies and intermediate films on the properties of reflection and penetration of incident ultrasonic waves were investigated.

(1) With lower frequency, the thickness of intermediate film that an ultrasonic wave penetrates increased for the cases of air film and lubricant film.
(2) For intermediate air film, when the thickness is 1 nm or greater, the ultrasonic wave reflects completely. For intermediate lubricant film, when the thickness is approximately 1μm and the ultrasonic frequency is as low as 2.25 MHz, approximately 80% of the incident ultrasonic wave penetrates the lubricant film. In contrast, when ultrasonic

frequency is 100 MHz, the ultrasonic wave is totally reflected with the lubricant film of approximately 1μm thickness.

(3) When increasing compression load, the relative intensity of reflected wave decreases for all frequencies. The lower the ultrasonic frequency, the more the ultrasonic wave penetrates through the intermediate film.

(4) The ultrasonic examination was an effective method for evaluating the variation of contact conditions. By clarifying the effect of ultrasonic frequency and presence of intermediate film on relative intensity in greater detail, it will be possible to evaluate the average thickness of the intermediate lubricant film. Moreover, the performance and behaviour of lubricants can be examined.

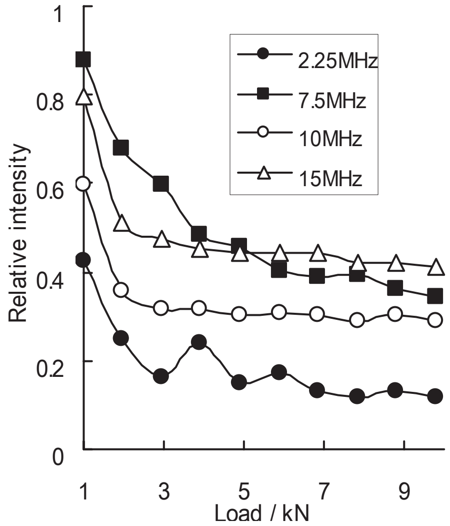

Fig. 9. Influence of ultrasonic frequencies and applied loads on the relative intensity of reflected waves in the case of the lubricant VG2

Acknowledgements

This research was partially supported by the Amada Foundation for Metal Work Technology in Japan.

Additional information

The presentation connected with the subject matter of the paper was presented by the authors during the 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2005 in Gliwice-Zakopane, Poland on 6th-9th December 2005.

References

[1] W.R.D, Wilson, Mixed Lubrication in Metal forming processes, Advanced Technology of Plasticity 4 (1990) 1667-1676.

[2] N. Bay, T. Wanheim, Contact phenomena under bulk plastic deformation conditions, Advanced Technology of Plasticity 4 (1990) 1677-1691.

[3] F.P. Bowden, D. Tabor, The Friction and Lubrication of Solods, Oxford University Press, 1964.

[4] M. Geiger, U. Engel, F. Vollersten, In situ ultrasonic measurement of the real contact area in bulk metal forming, Annals of the CIRP 41 (1992) 255-258.

[5] S. Stancu-Niederkom, U. Engel, M. Geiger, Ultrasonic investigation of friction mechanism in metal forming, Journal of Materials Processing Technology 45 (1994) 613-618.

[6] P.B. Nagy, L. Adler, Surface roughness induced attenuation of reflected and transmitted ultrasonic waves, Journal of Acoustical Society of America 82 (1987) 193-197.

[7] H. Saiki, Y. Marumo, Influence of the roughness geometry of tool surface and the flow stress of coated solid lubricants on tribo-conditions in cold forging, Journal of Materials Processing Technology 140 (2003) 25-29.

[8] L. Ruan, H. Saiki, Y. Marumo, Y. Imamura, Evaluation of coating-based lubricants for cold forging using the localized rod-drawing test, Wear 259 (2005) 1117-1122.

[9] H. Saiki, Y. Marumo, A. Minami, T. Sonoi, Effect of the surface structure on the resistance to plastic deformation of a hot forging tool, Journal of Materials Processing Technology 113 (2001) 22-27.

[10] H. Saiki, Z. Zhan, Y. Marumo, H. Ando, Evaluation of thermal contact resistance in hot and warm forging, Advanced Technology of Plasticity 1(1996) 457-460.

[11] D. Siminiati, FEM numerical algorithm on contact problem for non-conform elastic bodies, Proceedings of the 11th International Scientific Conference on Achievements in Mechanical and Materials Engineering AMME'2002, Gliwice-Zakopane, Poland, 2002, 495-498.

[12] A.M. Camacho, M. Marin, L. Sevilla, R. Domingo, Influence of strain hardening on forces and contact pressure distributions in forging processes, Journal of Achievements in Materials and Manufacturing Engineering 15 (2006) 166-173.

[13] L. Pazdera, M. Korenska, J. Smutny, Study of metal timber join by Acoustic Emission method, International Journal of Microstructure and Materials Properties 1-3/4 (2006) 353-363.

[14] Y. Mizuguchi, T. Koizumi, K. Yoshimine, Contact pressure measurement by means of ultrasonic waves, Journal of the Japanese Society for Non-Destructive Inspection 32-12 (1983) 956-963.

[15] M. Tsutsumi, A. Miyakawa, Y. Ito, Topographical representation of interface pressure distribution in a multiple bolt-flange assembly-measurement by means of ultrasonic waves, ASME paper No.81-DE-7 (1981) 1-8.

[16] H. Saiki, Y. Sakata, S. Satonaka, Z. Zhan, Y. Marumo, Estimation of contact conditions in lubricated frictional interface of forging processes by ultrasonic examination, Advanced Technology of Plasticity 2 (1993) 1126-1131.

[17] The Japan Promotion of Science and Technology, Methods of Ultrasonic Detection, Syouken-do, 1974 (in Japanese).

[18] J.B. Hull, A. Lofti, Identification of different polymer types by broadband ultrasound attenuation analysis, Proceedings of the 8th International Scientific Conference on Achievements in Mechanical and Materials Engineering AMME'1999, Gliwice-Rydzyna-Pawłowice-Rokosowo, 1999, 253-256.

[19] M. Rojek, J. Stabik, S. Sokol, Fatigue and ultrasonic testing of epoxy-glass composites, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 183-186.

[20] G. Wrobel, L. Wierzbicki, Ultrasonic methods in diagnostics of glass-polyester composites, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 203-206.

[21] G. Wrobel, S. Pawlak, The effect of fiber content on the ultrasonic wave velocity in glass/polyester composites, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 295-298.

[22] H. Saiki, Y, Marumo, L. Ruan, T. Matsukawa, Z.H. Zhan, Y. Sakata, Estimation of contact interface using ultrasonic measurement, Proceedings of the 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science, Gliwice-Zakopane, Poland, 2005 (CD ROM).

[23] G. Wrobel, S. Pawlak, Ultrasonic evaluation of the fibre content in glass/epoxy composites, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 187-190.

[24] M. Vural, A. Akkus, The ultrasonic testing of the spot welded different steel sheets, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 247-250.

[25] J. Koutský, J. Veselá, Evaluation of white metal adhesion (conventional casting and thermal wire arc spraying) by ultrasonic non-destructive method, Proceedings of the 11th International Scientific Conference on Achievements in Mechanical and Materials Engineering AMME'2002, Gliwice-Zakopane, 2002, 303-306.

[26] I.N. Prassianakis, The non-destructive testing method of ultrasounds, an excellent tool for solving fracture mechanics problems, International Journal of Materials and Product Technology 26 (2006) 71-88.

[27] K. Edalati, A. Kermani, M. Seiedi, A. Movafeghi, Defect detection in thin plates by ultrasonic lamb wave techniques, International Journal of Materials and Product Technology 27 (2006) 156-172.