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APPLICATION OF SMALL PUNCH TEST TO ESTIMATE MECHANICAL BEHAVIOUR OF SUS304 AUSTENITIC STAINLESS STEEL

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Abstract. The small punch test with an application of a relatively small specimen has recently become a reliable material mechanics testing method. In this study, the small punch test is set up based on the conventional mechanical testing machine for SUS304 stainless steel to evaluate the mechanical properties of SUS304 steel at different displacement rates of the punch in quasi-static loading condition in the case of with and without heat treatment. Although heat treatment has an insignificant effect on the microstructure and hardness of the material, the mechanical properties of the material in the small punch test are greatly reduced after heat treatment. Both cases with and without heat treatment have a similar tendency for the rate - sensitivity of the applied force - displacement curve. A higher value of force is applied to obtain the same value of displacement at a low displacement rate in the stable plastic deformation zone. Meanwhile, the maximum value of applied force is higher at a higher displacement rate in the stage that initiation of crack might appear In the examined range of displacement rate, a positive rate - sensitivity of displacement at the maximum force. Therefore, a correlation between equivalent fracture strain and fracture toughness of the material can be achieved.

Keywords: small punch test, SUS304 steel, strength of material, fracture toughness.

1. INTRODUCTION

The mechanical properties of materials such as strength and ductility are usually evaluated by traditional testing techniques, for example, tension, compression or three-point bending test performed on a conventional mechanical testing machine. In 1982, a new experimental methodology called the small punch test has been designed by Manahan et al. [1] for assessing the mechanical properties of irradiated materials by using very small specimen. Then, this technique has been developed to investigate the mechanical properties and fracture toughness of both ductile and brittle materials [2,3] during last decades. This testing method has many advantages through the application of a relatively small specimen with a disc shape having a diameter of 3–10 mm and a thickness of 0.1–07 mm [4,5]. Moreover, the small punch test in quasi-static condition can be performed on a conventional tensile testing machine with the design of a new fixture [6,7]. Therefore, this experimental method is cost-effective and has become a reliable material mechanics testing method that has attracted the attention of the scientific community.

On the other hand, SUS304 austenitic stainless steel is widely used not only in the chemical and food industries but also for mechanical structures due to its good corrosion resistance and high mechanical properties [8]. This steel is considered as a representative of the steels with phase transformation by plastic deformation [9,10]. The unstable austenite phase of SUS304 steel can transform into martensitic phase during plastic deformation of the steel. Due to the formation of martensitic phase, the mechanical properties of the steel are considerably improved. Although some past studies examined the influence of strain-induced martensitic transformation in SUS304 steel in various deformation modes, the influence of phase transformation of this steel due to plastic deformation during the small punch test is still unclear. Furthermore, according to previous study [11], the stability of austenitic phase of this steel is strongly affected by heat treatment process. Therefore, an investigation on the effect of heat treatment on the mechanical properties of SUS304 stainless steel in the small punch test is indispensable.

Recently, several studies have been carried out on the mechanical properties of austenitic stainless steel in the small punch test. Sunjaya et al. [12] performed finite element simulation for material behaviors of 304H stainless steel after different heat treatment conditions during the small punch test It is reported that the ductility of the investigated material is strongly affected by heat treatment. Mahmudi et al. [13] established the correlation between results from the small punch test and tensile yield as well as ultimate stress for type-304 austenitic stainless steel. Yang et al. [14] investigated the effect of the geometrical factors and some process parameters on plastic damage of SUS304 steel in the small punch test. Then, ductile fracture of 306L stainless steel in the small punch test was examined by Kubík et al. [15]. Rate - sensitivity of fracture characteristics of SUS304 was investigated by Pham et al. [9] during the small punch test in quasi-static and impact loading condition. More recently, the small punch test was applied for an investigation of the influence of the inhomogeneous microstructure of 316L stainless steel multi-pass weld joint of a nuclear power plant done by Fan et al. [16]. In the previous study [6], the authors established the small punch test for an investigation of rate - sensitivity of mechanical properties for aluminum alloy A1050-H14. According to this study, the value of maximum force and the punch displacement at the maximum force obtained from the small punch test can be used for an evaluation of strength and fracture toughness of material, respectively. On the other hand, the investigation of Pham et al. [11] presented that the α'-martensitic phase can be observed in the microstructure of type-304 austenitic stainless steel after an appropriate heat treatment during grinding and polishing because of strain-induced martensitic transformation mechanism.

In this study, the small punch test using relatively small specimen is set up based on the conventional mechanical testing machine for SUS304 stainless steel. The experimental works are performed at different displacement rate of the punch in quasi-static condition. The results on the curve of applied force and punch displacement are used to discuss the mechanical behavior of the material. The influence of heat treatment process on the results of force - displacement curve is examined. Then, the rate - sensitivity in the range of low displacement rate of mechanical properties of the steel obtained from the small punch test is discussed in the case of with and without heat treatment.

2. METHODOLOGY

2.1. Materials

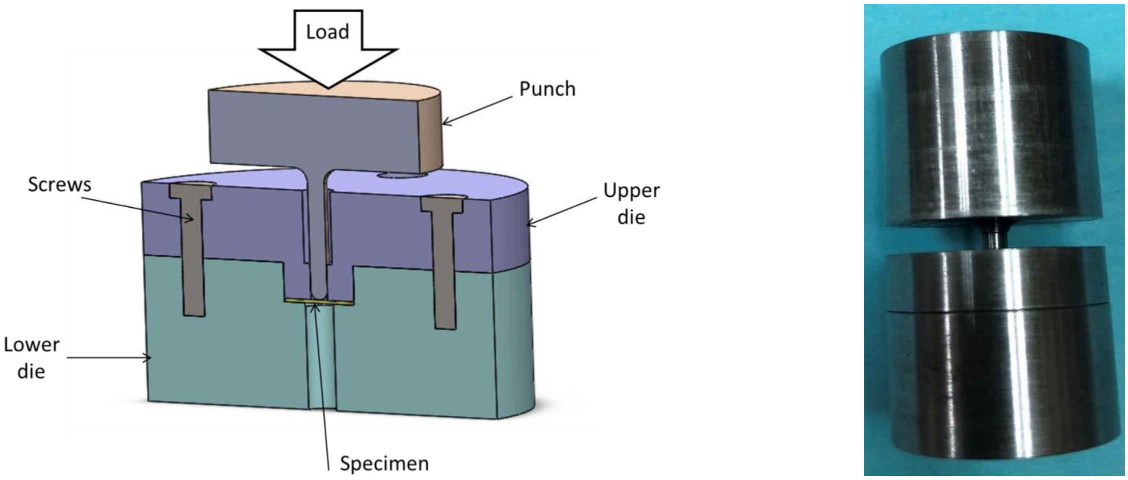
The material used in present study is SUS304 austenitic stainless steel. The investigated material was analyzed for chemical composition with the results shown in Table 1. Compared to Japanese Industrial Standards (JIS), the chemical composition of the main elements such as carbon, chromium, nickel, ... is all within the standard range for SUS304 stainless steel. The specimen is heated by the electrical resistance furnace device LHT08/16. According to previous investigation [11], the heating temperature of heat treatment process should be over than 1000 °C to increase the probability for martensitic transformation by plastic deformation. Therefore, in present study, the heating temperature is set up at 1050 °C and the holding time is 20 minutes. After that, the specimen is quenched in water. The hardness of material is measured by a Rockwell hardness tester AR-20. The microstructure observation is performed on a metallurgical microscope Olympus GX41.

Table 1. Chemical compositions of SUS304 steel

Chemical element	C	Si	Mn	Cr	Ni	Co	N	V
Wt. (%)	0.053	0.31	1.17	18.8	8.03	0.22	0.113	0.103
Chemical element	P	S	Mo	Al	Cu	Ti	W	Fe
Wt. (%)	0.023	0.004	0.007	0.001	0.02	0.001	0.007	Blan.

2.2. Small punch test

Fig. 1 shows the schematic view and a photograph of the jig for the small punch test. The experimental model basically consists of an upper die, a lower die and a punch. A steel rod punch with a hemispherical head of 1.2 mm radius is used. A small disc-shaped specimen is placed in the center of the lower die. Then, the lower die and upper die are clamped by the screws. The specimens with dimensions of 0.5 mm thickness and 10 mm in diameter are applied in this study. The load is applied via vertical direction to the center of the specimen through the punch, leading the plastic deformation of material.



(a) (b)

Fig. 1. (a) Schematic presentation and (b) A photograph of the jig for the small punch test

Fig. 2 shows a photograph of the experimental arrangement for the small punch based on a conventional testing machine VEB Thuringer Industriewerk Rauenstein 5 KN, Typ Z0M5/91. A new fixture as above described for the small punch test is placed on a rigid plate. A force sensor is placed between the load block and the testing jig to obtain the applied force value during the experiment. At the same time, the displacement sensor is used to record the displacement of the supporting plate. It is necessary to ensure that the movement of the supporting plate and the punch head via vertical direction are equivalent. The results of applied force and movement of the punch are processes through a data processor Multi Recorder TMR-2111. The experimental results obtained from the sensors will be plotted for applied force - time curve and punch displacement - time curve, respectively. Then, the curve of the relationship between applied force and displacement of the punch for the small punch test can be achieved. The experiments are conducted at different displacement rate of the punch in quasi-static condition as 0.82, 1.09, 1.63, and 2.17 mm/s.

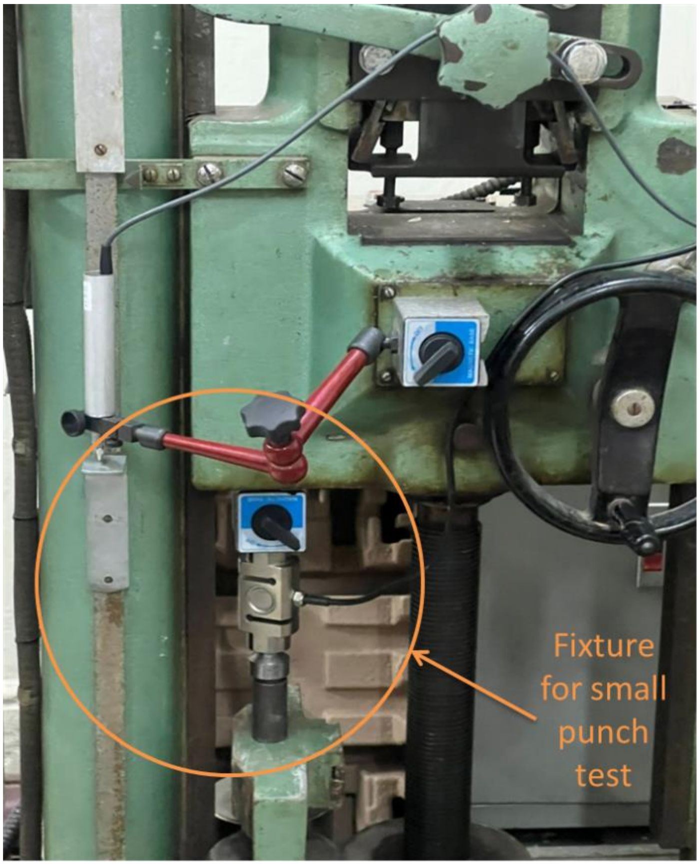


Fig. 2. Experimental arrangement of the small punch test in conventional tensile testing machine

Fig. 3 describes a photograph of the specimen using in the small punch test. The specimens are wire-cut from sheets made of SUS304 steel. Then, the surfaces of specimen are ground by using silicon carbide papers up to 2000 grit in order to reduce the friction between the specimen and the punch head as well as eliminate the influence of surface geometry factors on the mechanical properties of the material during plastic deformation.

The results obtained from the small punch test are discussed based on the relationship between applied force - punch displacement. Fig. 4 shows a typical force - displacement

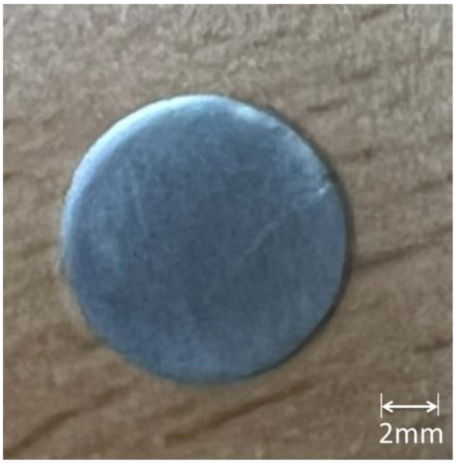


Fig. 3. Specimen using in the small punch test

curve obtained from the small punch test. From this figure, the shape of the obtained curve of the small punch test is very different from that obtained from traditional experiments such as tensile or three-point bending test. According to Abendroth et al. [17], this curve can be divided into 5 zones corresponding to the deformation stages of the material. Zone I is the elastic bending deformation region of the material. Next, zone II shows a transition between elastic deformation and plastic deformation. The third stage of zone III is called the plastic deformation zone. Zone IV corresponds to a less stable deformation and the initial crack might appear in this stage. In the final stage, the applied force will decrease after reaching its maximum value.

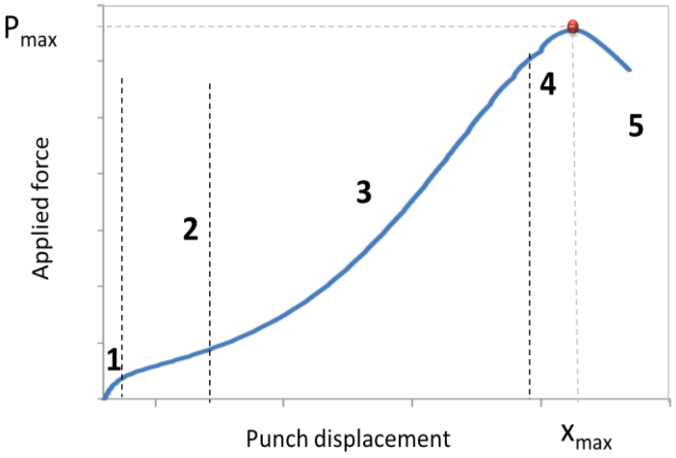
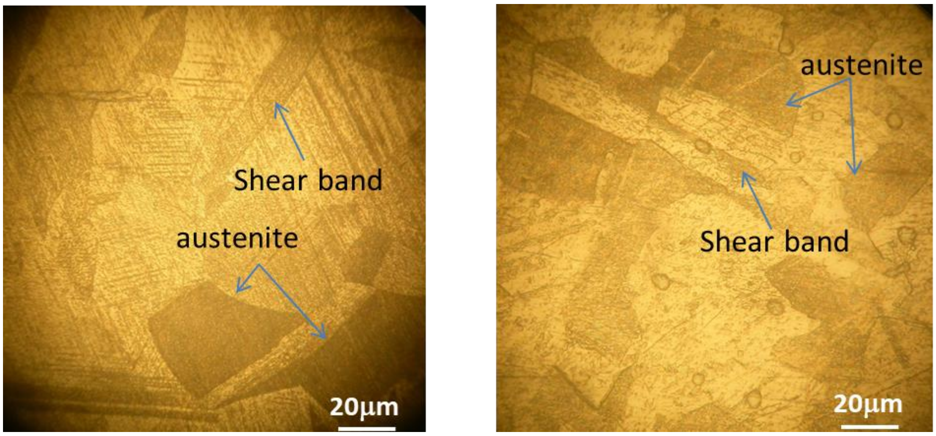


Fig. 4. Typical curve of applied force - punch displacement in the small punch test

3. RESULTS AND DISCUSSION

Fig. 5 shows microstructure observation of SUS304 steel before and after heat treatment. From this figure, the difference in the microstructure of steel before and after heat treatment cannot be seen clearly. The microstructure mostly shows a homogeneous austenite phase similar to the typical microstructure of SUS304 stainless steel. The appearance of shear bands can be observed because of plastic deformation of the surface layer of the specimen during grinding and polishing for metallurgical observation. According to previous studies [11], although phase transformation during quenching cannot be obtained, the austenite phase of the steel might become less stable and this phase might transform into martensitic phase during plastic deformation. Moreover, the hardness of investigated material is 55HRA before heat treatment and 52HRA after heat treatment, respectively. It can be considered that an improvement of hardness of the material as well as a considerable change of the microstructure due to heat treatment cannot be observed. However, as above discussion, the case of heat treatment with more unstable austenitic phase might increase probability for martensitic transformation by plastic deformation during the small punch test. Therefore, it is expected that the mechanical properties of the steel will be improved by heat treatment in the small punch test.



(a) Before heat treatment (b) After heat treatment

Fig. 5. Microstructure of SUS304 steel before and after heat treatment

Fig. 6 presents a photograph of specimen after the small punch test. A local deformation can be seen from this figure. During the experiment, when the force is applied via vertical direction, the part in contact with the punch head is deformed into a concave shape with a hat-shaped profile. Meanwhile, the part of specimen that is clamped between the upper and lower dies might not be deformed. In the final stage of deformation, a crack on one side of the specimen initiates and expands, leading the fracture of the specimen. The obtained result of morphology of the deformed specimen is very similar to the typical deformation of the specimen in the small punch test.

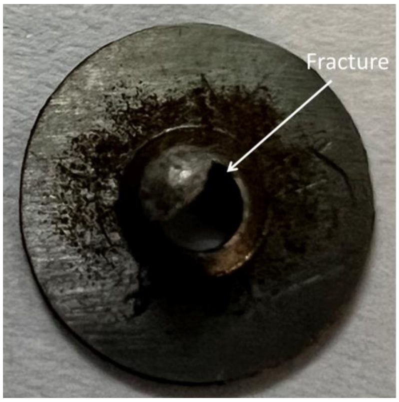
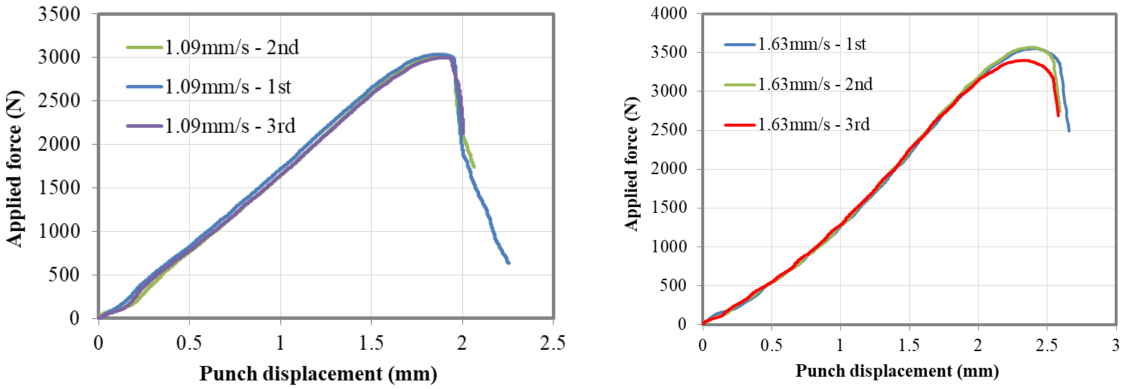
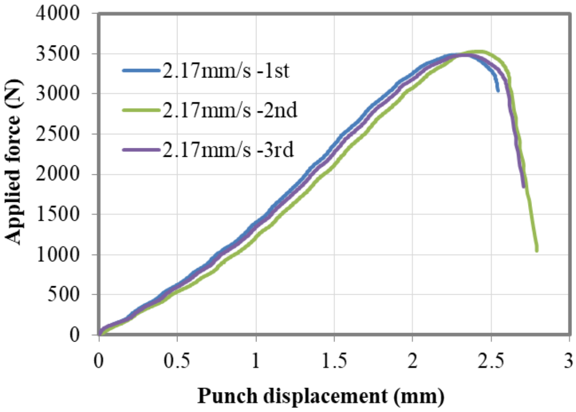


Fig. 6. Photograph of specimen after experiment at punch displacement rate of 2.17 mm/s

To ensure the reliability of the experimental results the experiments at each displacement rate were repeated at least three times. Then, the obtained results of applied force punch displacement relationship at different rate of punch displacement are shown in Fig. 7 for the unheated treatment specimens. It can be seen that the applied force punch displacement curves are quite similar to the typical applied force punch displacement curve obtained from the small punch test as shown in the past studies [9]. The deformation stages of the material are quite corresponding to those shown in Fig. 4. From these results, it can be seen that the small punch was successfully set up and the obtained results from this experimental arrangement might be reliable.



(a) Displacement rate of 1.09 mm/s (b) Displacement rate of 1.63 mm/s



(c) Displacement rate of 2.17 mm/s

Fig. 7. Relationship of applied force - punch displacement at various punch displacement rate for unheated-treatment specimens

Next, force-displacement curve for SUS304 steel under the small punch test at different displacement rate is described in Fig. 8. The influence of the punch displacement rate can be seen clearly. According to Cao et al. [18], the total consumption energy in the small punch test can be calculated from the area under the applied force - punch displacement curve until the maximum value of applied force. Thus, from Fig. 8, it can be observed that total energy consumption is higher at higher displacement rate in the investigated range of displacement rate of the punch from 0.82 to 1.63 mm/s. To obtain same value of displacement in the plastic deformation stage (zone III), two cases of lower displacement rate indicate higher levels of force compared to the cases of higher displacement rate. Meanwhile, the values of maximum force as well as displacement at the maximum force increase with an increase of displacement rate from 0.82 mm/s to 1.63 mm/s. However, the value of maximum force at 2.17 mm/s is slightly smaller than that at 1.63 mm/s.

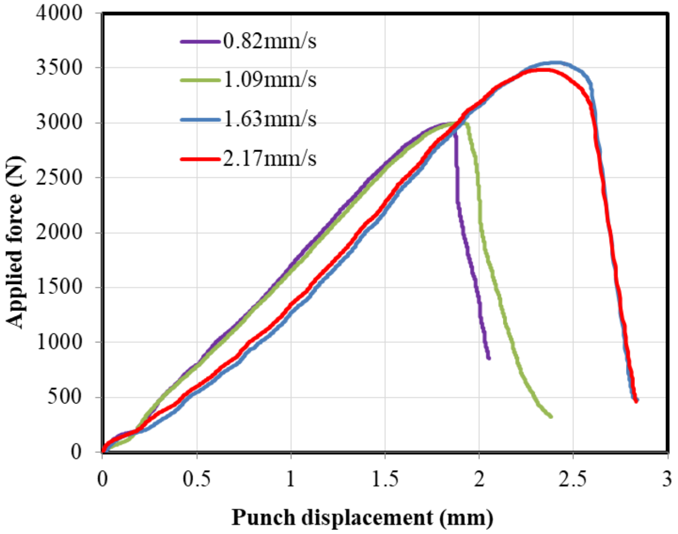
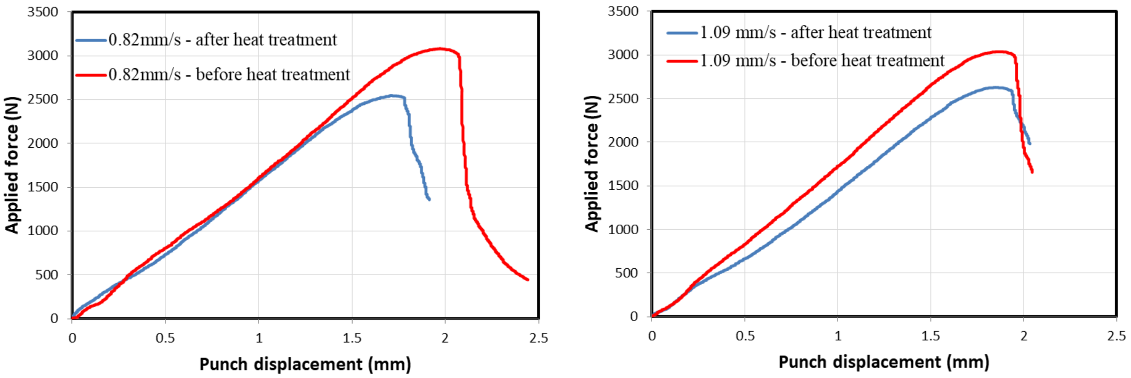
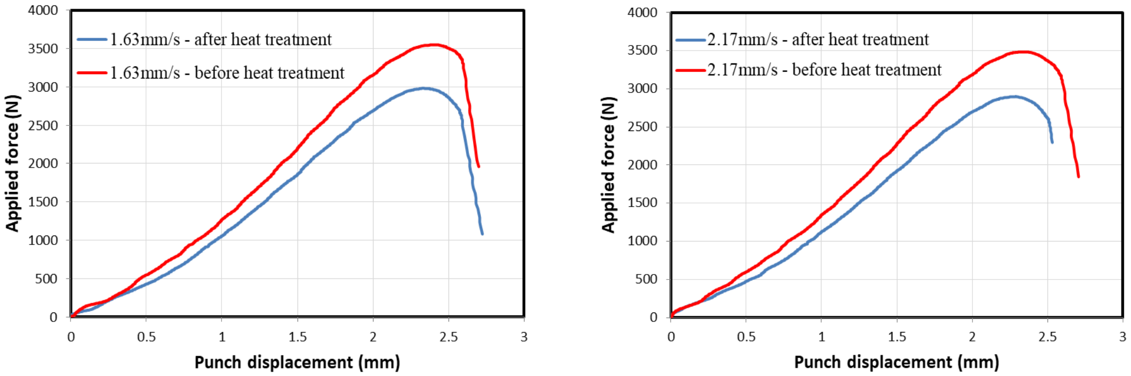


Fig. 8. Force - displacement curve at various punch displacement rate before heat treatment

Fig. 9 describes the effect of heat treatment on the force - displacement curve obtained from the small punch test for SUS304 steel at different displacement rate in quasi-static condition. A considerable influence of heat treatment can be seen. At low displacement rate of 0.82 mm/s, the values of maximum applied force and displacement at the maximum force decrease after heat treatment. At higher displacement rate in the investigated range, except for the elastic deformation stage, a decrease in the value of force can be seen in the case of heated treatment in the plastic deformation stage. As above mention, the value of maximum force obtained in the small punch test can be used to calculate the ultimate strength of material. As a result, it can be considered that the heat treatment has a considerable effect on the ultimate strength of material in the investigated range of displacement rate. An improvement of the ultimate strength cannot be achieved by heat treatment. Furthermore, in the case of 0.83 mm/s, a reduction in the displacement at the maximum force due to heat treatment might induce a decrease in the fracture toughness of the material.



(a) Displacement rate of 0.82 mm/s (b) Displacement rate of 1.09 mm/s



(c) Displacement rate of 1.63 mm/s (d) Displacement rate of 2.17 mm/s

Fig. 9. Effect of heat treatment on force - displacement curve at different punch displacement rate

The relationship of applied force - punch displacement at various punch displacement rate in the case of heat treatment is presented in Fig. 10. Although, the heat treatment process strongly affects the force - displacement curve as shown in Fig. 9, the tendency of mechanical properties of material in the case of heated treatment is quite similar to that of the unheated treatment case. Also, a higher value of total consumption energy in the small punch test can be obtained at higher rate of punch displacement in the range from 0.82 mm/s to 1.63 mm/s.

From the results of force - displacement curve in Figs. 8 and 10, the rate - sensitivity of applied force in the low range of displacement rate is achieved as presented in Fig. 11. In detail, Fig. 11(a) presents a negative rate - sensitivity of applied force value at displacement of 1 mm. However, a positive rate - sensitivity of maximum force in the investigated range of displacement rate in quasi-static test is indicated in Fig. 11(b). This means that the steel might possess more excellent mechanical properties at lower displacement rate in both cases with and without heat treatment during the plastic deformation stage of the small punch test. On the other hand, a positive rate - sensitivity of maximum force is shown in Fig. 11(b), leading an improvement of the ultimate strength at higher deformation rate.

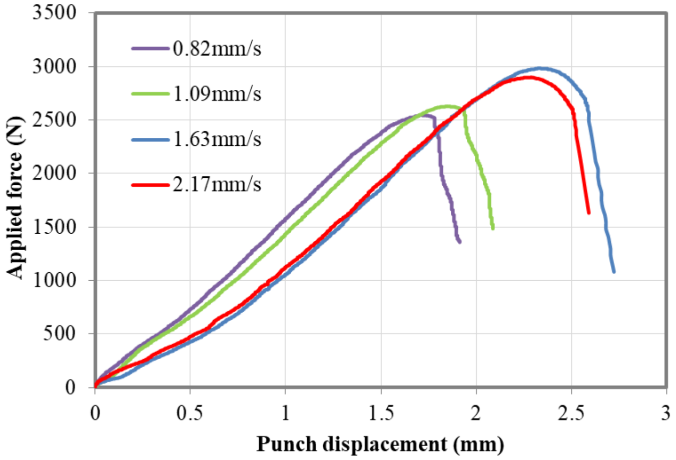
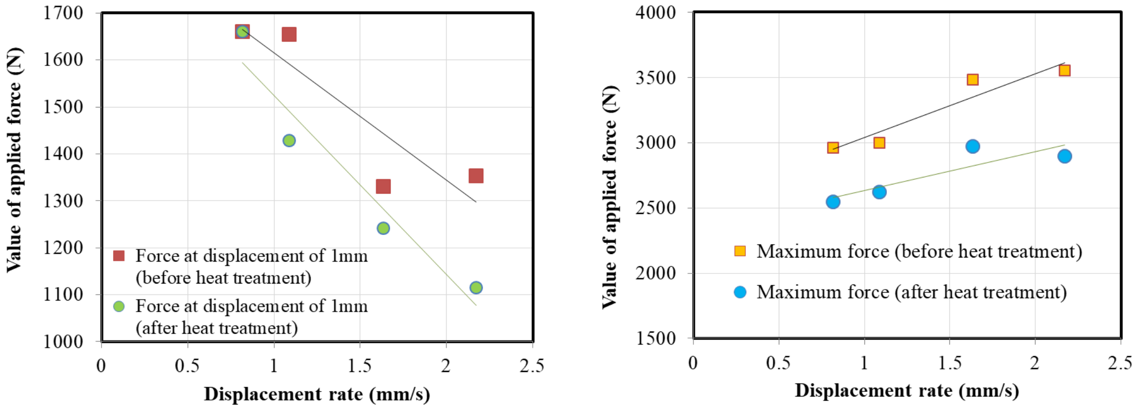


Fig. 10. Force - displacement curve at various displacement rate after heat treatment



(a) Rate - sensitivity of applied force at displacement of 1 mm

(b) Rate - sensitivity of maximum force

Fig. 11. Rate - sensitivity of applied force in the cases of with and without heat treatment

Fig. 12 shows rate - sensitivity of displacement at the maximum applied force in the cases of with and without heat treatment. Both cases with and without heat treatment indicate a positive rate - sensitivity of displacement of the punch at the maximum applied force. According to previous study [19], fracture toughness of material might indicate a correlation with the equivalent fracture strain that can be evaluated from results of the displacement at the maximum force. From results of Fig. 12, it might be said that the material shows higher value of equivalent fracture strain at higher displacement rate in the investigated range of displacement rate. This tendency is consistent with the results on J-integral for determine fracture toughness as reported in Pham et al. [20] for the same material. As a result, a correlation between equivalent fracture strain in the small punch test and fracture toughness of the material can be obtained in the small range of displacement rate in quasi-static condition.

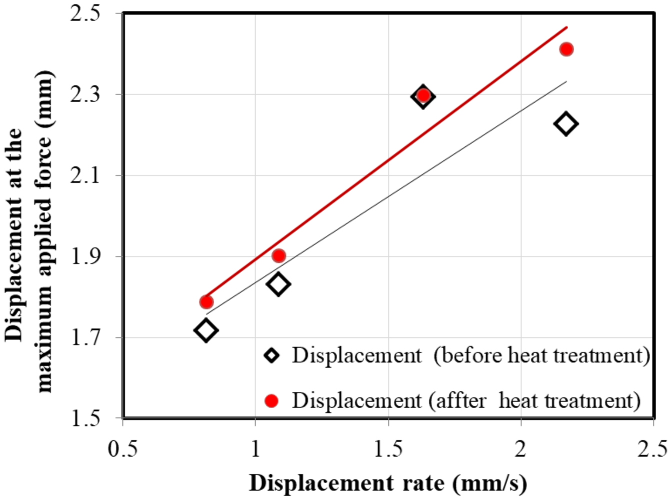


Fig. 12. Rate - sensitivity of displacement at the maximum applied force in the cases of with and without heat treatment

4. CONCLUDING REMARKS

The small punch tests are performed to evaluate the mechanical properties of SUS304 steel at different displacement rates of the punch in quasi-static loading condition in the case of with and without heat treatment. The obtained results show that although heat treatment has an insignificant effect on the microstructure and the hardness of the material, the ultimate strength of the material determined in the small punch test is greatly reduced after heat treatment. However, the tendency of the rate - sensitivity of the applied force - displacement curve in the cases with and without heat treatment is quite similar. In the stable plastic deformation zone, the value of applied force value needs to be higher to obtain the same displacement value at low displacement rate However, in the stage of unstable plastic deformation then leading to fracture, the applied force increases at higher displacement rate In the examined displacement rate range, a positive - rate sensitivity of displacement at the maximum force. Therefore, a correlation between equivalent fracture strain and fracture toughness of the material can be achieved.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] M. P. Manahan. *The development of a miniaturized disk bend test for the determination of post-irradiation mechanical behavior*. PhD Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, (1982).

[2] J. Zhong, T. Xu, K. Guan, and J. Szpunar. A procedure for predicting strength properties using small punch test and finite element simulation. *International Journal of Mechanical Sciences*, **152**, (2019), pp. 228–235. https://doi.org/10.1016/j.ijmecsci.2019.01.006.

[3] T. E. García, C. Rodríguez, F. J. Belzunce, and C. Suárez. Estimation of the mechanical properties of metallic materials by means of the small punch test. *Journal of Alloys and Compounds*, **582**, (2014), pp. 708–717. https://doi.org/10.1016/j.jallcom.2013.08.009.

[4] E. Fleury and J. S. Ha. Small punch tests to estimate the mechanical properties of steels for steam power plant: I. mechanical strength. *International Journal of Pressure Vessels and Piping*, **75**, (9), (1998), pp. 699–706. https://doi.org/10.1016/s0308-0161(98)00074-x.

[5] E. Martínez-Pañeda, I. I. Cuesta, I. Peñuelas, A. Díaz, and J. M. Alegre. Damage modeling in Small Punch Test specimens. *Theoretical and Applied Fracture Mechanics*, **86**, (2016), pp. 51–60. https://doi.org/10.1016/j.tafmec.2016.09.002.

[6] T. Y. Doan, H. T. Pham, K. Q. Le, T.-H.-N. Nguyen, and V. Van Nghiem. Experimental evaluation of fracture properties of aluminum alloy 1050-H14 by small punch test. *Strength, Fracture and Complexity*, **16**, (2023), pp. 61–72. https://doi.org/10.3233/sfc-230003.

[7] R. K. Guduru, K. A. Darling, R. Kishore, R. O. Scattergood, C. C. Koch, and K. L. Murty. Evaluation of mechanical properties using shear–punch testing. *Materials Science and Engineering: A*, **395**, (2005), pp. 307–314. https://doi.org/10.1016/j.msea.2004.12.048.

[8] J. A. Rodríguez-Martínez, A. Rusinek, R. Pesci, and R. Zaera. Experimental and numerical analysis of the martensitic transformation in AISI 304 steel sheets subjected to perforation by conical and hemispherical projectiles. *International Journal of Solids and Structures*, **50**, (2013), pp. 339–351. https://doi.org/10.1016/j.ijsolstr.2012.09.019.

[9] H. T. Pham and T. Iwamoto. An evaluation of fracture properties of type-304 austenitic stainless steel at high deformation rate using the small punch test. *International Journal of Mechanical Sciences*, **144**, (2018), pp. 249–261. https://doi.org/10.1016/j.ijmecsci.2018.05.056.

[10] D. Kaoumi and J. Liu. Deformation induced martensitic transformation in 304 austenitic stainless steel: In-situ vs. ex-situ transmission electron microscopy characterization. *Materials Science and Engineering: A*, **715**, (2018), pp. 73–82. https://doi.org/10.1016/j.msea.2017.12.036.

[11] H. T. Pham, T. Y. Doan, and T.-H.-N. Nguyen. A study on effect of heat treatment on strain-induced martensitic transformation in type-304 austenitic stainless steel. In *Proceedings*

of the International Conference on Advanced Mechanical Engineering, Automation, and Sustainable Development 2021 (AMAS2021), Springer International Publishing, (2022), pp. 584–591. https://doi.org/10.1007/978-3-030-99666-6_84.

[12] D. Sunjaya, T. Wei, R. Harrison, and W. Y. Yeung. Finite element modelling of small punch test on 304H stainless steel. *Key Engineering Materials*, **345–346**, (2007), pp. 1165–1168. https://doi.org/10.4028/www.scientific.net/kem.345-346.1165.

[13] R. Mahmudi and M. Sadeghi. Correlation between shear punch and tensile strength for low-carbon steel and stainless steel sheets. *Journal of Materials Engineering and Performance*, **22**, (2012), pp. 433–438. https://doi.org/10.1007/s11665-012-0256-6.

[14] S. Yang, J. Zhou, X. Ling, and Z. Yang. Effect of geometric factors and processing parameters on plastic damage of SUS304 stainless steel by small punch test. *Materials & Design*, **41**, (2012), pp. 447–452. https://doi.org/10.1016/j.matdes.2012.05.029.

[15] P. Kubík, F. Šebek, J. Petruška, J. Hůlka, N. Park, and H. Huh. Comparative investigation of ductile fracture with 316L austenitic stainless steel in small punch tests: Experiments and simulations. *Theoretical and Applied Fracture Mechanics*, **98**, (2018), pp. 186–198. https://doi.org/10.1016/j.tafmec.2018.10.005.

[16] Y. Fan, B. L. Yang, T. G. Liu, and Y. H. Lu. Effect of inhomogeneous microstructure on the deformation and fracture mechanisms of 316LN stainless steel multi-pass weld joint using small punch test. *Journal of Nuclear Materials*, **538**, (2020). https://doi.org/10.1016/j.jnucmat.2020.152239.

[17] M. Abendroth and M. Kuna. Determination of deformation and failure properties of ductile materials by means of the small punch test and neural networks. *Computational Materials Science*, **28**, (2003), pp. 633–644. https://doi.org/10.1016/j.commatsci.2003.08.031.

[18] B. Cao, S. Yoshida, T. Iwamoto, and H. T. Pham. Development of impact small punch test for investigating energy absorption. *International Journal of Mechanical Sciences*, **208**, (2021). https://doi.org/10.1016/j.ijmecsci.2021.106675.

[19] X. Mao, T. Shoji, and H. Takahashi. Characterization of fracture behavior in small punch test by combined recrystallization-etch method and rigid plastic analysis. *Journal of Testing and Evaluation*, **15**, (1987), pp. 30–37. https://doi.org/10.1520/jte11549j.

[20] H. T. Pham and T. Iwamoto. An experimental investigation on rate sensitivity of fracture-mechanical characteristics in 304 austenitic stainless steel under bending deformation. *ISIJ International*, **55**, (12), (2015), pp. 2661–2666. https://doi.org/10.2355/isijinternational.isijint-2015-397.