

METHOD TO CALCULATE ULTRASONIC WAVE VELOCITY BY USING CHEMICAL COMPOSITION OF AUSTENITIC STAINLESS STEELS

METODE IZRAČUNAVANJA BRZINE ULTRAZVUČNIH TALASA KORIŠĆENJEM HEMIJSKOG SASTAVA AUSTENITNOG NERĐAJUĆEG ČELIKA

Originalni naučni rad / Original scientific paper

UDK / UDC: Weld World (2014) 58:491–497;

DOI 10.1007/s40194-014-0132-0

Rad primljen / Paper received:

Jun 2017.

Prevod izvornog rada na srpski jezik: Milica Antić, dipl.ing

Key words: *Austenitic Stainless Steel, Density, Young's Modulus, Poisson's ratio, Ultrasonic wave velocity, Lattice Parameter*

Abstract

Various kinds of austenitic stainless steel have been used in oil refinery and chemical plant, and a value of ultrasonic wave velocity is necessary for not only thickness measurement but also evaluation of material deterioration. Although ultrasonic wave velocity depends generally on chemical composition, material structure, grain size etc., it is hard to study the influence of all factors for calculating ultrasonic wave velocity. Therefore, we noticed chemical composition of materials only.

Since ultrasonic wave velocity depends generally on parameter such as density ρ , Young's modulus E and Poisson's ratio ν , we calculated these parameters by using material data of respective elementary substances. Then, we have investigated the relationship between the calculated values of ultrasonic wave velocity and the experimental ones measured by ultrasonic testing.

1. Introduction

In measuring thickness of various kinds of austenitic stainless steels using in oil refinery and chemical plant, it is hard to find out the velocity except for a typical type of stainless steel (for example, AISI type 304 and 347) in a public handbook. Especially, an accurate value of longitudinal wave velocity is necessary for thickness measurement by using ultrasonic pulse echo technique. Also, for estimating deterioration of material, it is useful to examine a deviation in ultrasonic wave velocity such as longitudinal or transverse wave velocity. Longitudinal wave velocity C_L and transverse wave velocity C_S are given by the following equations (1) respectively

Adresa autora / Author's adresse :

¹ *Sankyu Incorporated, Fukuoka, Japan*

² *Kyushu Institute of Technology, Fukuoka, Japan*

Ključne reči: austenitni nerđajući čelik, gustina, Jungov modul, Poasonov odnos, brzina ultrazvučnog talasa, parametar rešetke

Rezime

Razne vrste austenitnih nerđajućih čelika koriste se u rafinerijama nafte i hemijskim postrojenjima, a vrednost brzine ultrazvučnog talasa je potrebna, ne samo za merenje debljine, već i za ocenjivanje propadanja materijala. Iako brzine ultrazvučnog talasa uglavnom zavise od hemijskog sastava, strukture materijala, veličine zrna itd, teško je proučavati uticaj svih faktora za izračunavanje brzine ultrazvučnog talasa. Stoga smo razmatrali samo hemijski sastav materijala.

Dok brzina ultrazvučnog talasa uglavnom zavisi od parametara, kao što su ρ gustina, Jungov modul E i Poasonov odnos ν , izračunali smo ove parametre pomoću podataka za materijale od odgovarajućih osnovnih supstanci. Zatim smo istraživali odnos između izračunate vrednosti brzine ultrazvučnog talasa i eksperimentalno dobijenih ultrazvučnim ispitivanjem.

1. Uvod

Pri merenju debljine raznih vrsta austenitnog nerđajućeg čelika koji se koriste u rafinerijama nafte i hemijskim postrojenjima, teško je naći u raspoloživim priručnicima brzinu, osim za tipične vrste nerđajućeg čelika (na primjer, AISI tip 304 i 347). Posebno, precizna vrednost brzine longitudinalnog talasa je potrebna za merenje debljine pomoću ultrazvučne impuls-eho tehnike. Takođe, za procenu pogoršanje materijala, korisno je ispitati odstupanje brzine ultrazvučnog talasa, kao što su brzine longitudinalnog ili transverzalnog talasa. Brzina longitudinalnog talasa C_L i transverzalnog talasa C_S date su jednačinama (1)

$$C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (1)$$

$$C_S = \sqrt{\frac{E}{2\rho(1+\nu)}} \quad (2)$$

where E is Young's modulus, ν is Poisson's ratio and ρ is density.

If parameters such as E , ν and ρ can be estimated by using material data of respective elementary substances of austenitic stainless steel, it will be possible to calculate ultrasonic wave velocity.

When measured longitudinal wave velocity C_L (m/s) and transverse wave velocity C_S (m/s), E (GPa), and ν can be calculated as follows.

$$E = \frac{\rho C_S^2 (3C_L^2 - 4C_S^2)}{C_L^2 - C_S^2} \quad (3)$$

$$\nu = \frac{1}{2} \left(1 - \frac{1}{(C_L/C_S)^2 - 1} \right) \quad (4)$$

In order to simulate a deviation in ultrasonic wave velocity, we set that one of these factors was variable and others were constant.

2. Materials Used for Calculating Ultrasonic Wave Velocity

We measured E , ν and ρ of T.P. No.1-1~1-6 in Table 1, and these materials were goods on the market, which were produced by solution treatment in accordance with Japanese Industrial Standard.

Data of other materials listed in Table 1 were based on those by H.M.Ledbetter^{2)~5)}, because he had measured both E and ν of AISI type 304, 304L, 316 and 310S stainless steel by measuring both C_L and C_S . The data of T.P. No.1-1~1-6 in Table 1 shows both figures of mill-sheet issued by fabricator and the results by fluorescent x-ray analysis (FXA). Carbon and sulfur of T.P.No.1-1~1-6 were analyzed by equipment for analyzing carbon and sulfur simultaneously, because it is hard to analyze these elements by FXA.

We used figures of mill-sheet, because the difference between mill-sheet and FXA were negligibly small.

3. Experimental Method

3.1 Measurement of Lattice Parameter and Density

Lattice parameter d of T.P. No.1-1 ~ 1-6 were measured by X-ray diffraction method to investigate a deviation in density caused by lattice parameter. Since the relation between $\cos^2\theta$ and d is represented by a straight line, d was obtained by extrapolating to $\cos^2\theta = 0^6)$, where θ is Bragg angle.

$$C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (1)$$

$$C_S = \sqrt{\frac{E}{2\rho(1+\nu)}} \quad (2)$$

gde je E Jungov modul, ν Poissonov odnos i ρ je gustina.

Ako se parametri kao što su E , ν i ρ mogu se proceniti pomoću podataka za materijale odgovarajućih osnovnih supstanci austenitnog nerđajućeg čelika, onda je moguće izračunati brzine ultrazvučnog talasa.

Kada se meri brzina longitudinalnog talasa C_L (m/s) i brzina transverzalnog talasa C_S (m/s), E (GPa), može se izračunati ν kako sledi

$$E = \frac{\rho C_S^2 (3C_L^2 - 4C_S^2)}{C_L^2 - C_S^2} \quad (3)$$

$$\nu = \frac{1}{2} \left(1 - \frac{1}{(C_L/C_S)^2 - 1} \right) \quad (4)$$

Kako bi simulirali odstupanje u brzini ultrazvučnog talasa, postavili smo da jedan od tih faktora varira a ostali su bili konstantni.

2. Materijali se koristi za izračunavanje brzine ultrazvučnog talasa

Merili smo E , ν i ρ od T.P. No.1-1~1-6 u tabeli 1, a ovi materijali su roba na tržištu, i proizvedeni su rastvarajućim tretmanom u skladu sa japanskim industrijskim standardima.

Podaci o drugim materijalima navedenim u tabeli 1 su na osnovu tih po H.M.Ledbetter^{2)~5)}, zato što je mereno i E i ν nerđajućeg čelika tipa AISI 304, 304L, 316 i 310S merenjem i C_L i C_S . Podaci za T.P. No.1-1~1-6 u tabeli 1 pokazuju obe slike valjaoničkih podataka koje izdaje proizvođač i rezultate dobijene fluorescentnom analizom x-zracima (FXA). Ugljenik i sumpor u T.P.No.1-1~1-6 su analizirani opremom za analizu ugljenika i sumpora istovremeno, jer je teško analiziranje ovih elemenata pomoću FXA.

Koristili smo valjaoničke podatke, jer je razlika između valjaoničkih lista i FXA su zanemarljiva.

3. Eksperimentalna metoda

3.1 Merenje parametra rešetke i gustine

Parametar rešetke d za T.P. No.1-1 ~ 1-6 meren je metodom difrakcije x zraka radi istraživanja odstupanja u gustini uzrokovanog parametrom rešetke. S obzirom da je odnos između $\cos^2\theta$ i d predstavljen ravnom linijom, d je dobijen ekstrapolacijom do $\cos^2\theta = 0^6)$, gde je θ Bragg-ov ugao.

Density ρ of T.P. No.1-1~1-6 was obtained by measuring the mass of the test piece in air and water to compare experimental values with ones calculated by using d .

Densities of other materials were referred from the papers by H.M.Ledbetter^{2)~5)}.

Gustina ρ za T.P. No.1-1~1-6 je dobijena merenjem mase ispitnog komada u vazduhu i vodi radi upoređenja eksperimentalnih vrednosti sa onima izračunatim preko d .

Gustine drugih materijala su uzete iz radova H.M.Ledbetter^{2)~5)}.

T.P.No.	AISI No.	Analysis	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	N	Ref.No.
1-1	304	Mill-sheet	0.060	0.47	0.85	0.030	0.003	8.07	18.13	—	—	—	—
		FXA	0.059	0.59	0.94	0.032	0.005	7.54	18.09	0.20	0.372	—	
1-2		Mill-sheet	0.050	0.51	0.92	0.032	0.003	8.05	18.13	—	—	—	
		FXA	0.054	0.76	1.02	0.034	0.004	7.45	18.20	0.14	0.211	—	
1-3		Mill-sheet	0.040	0.53	0.92	0.036	0.002	8.06	18.08	—	—	—	
		FXA	0.034	0.72	1.01	0.034	0.006	7.52	18.18	0.15	0.278	—	
1-4	304L	Mill-sheet	0.017	0.37	1.32	0.029	0.004	9.07	18.12	—	—	—	
		FXA	0.023	0.64	1.41	0.029	0.006	8.41	18.25	0.25	0.332	—	
1-5	310S	Mill-sheet	0.040	0.71	0.9	0.022	0.001	19.20	24.91	—	—	—	
		FXA	0.035	0.86	1.01	0.026	0.001	17.89	24.95	0.05	0.088	—	
1-6	316	Mill-sheet	0.060	0.55	0.84	0.027	0.000	10.06	16.06	2.09	—	—	
		FXA	0.059	0.69	0.92	0.051	0.001	9.37	16.35	2.07	0.250	—	
2-1	304	—	0.028	0.50	1.57	0.021	0.019	10.10	18.30	0.200	0.210	0.039	2
2-2			0.058	0.50	1.57	0.021	0.019	10.10	18.30	0.200	0.210	0.039	
2-3			0.089	0.50	1.57	0.021	0.019	10.10	18.30	0.200	0.210	0.039	
2-4			0.037	0.57	1.50	0.022	0.017	9.91	18.00	0.205	0.197	0.120	
2-5			0.067	0.57	1.50	0.022	0.017	9.91	18.00	0.205	0.197	0.120	
2-6			0.094	0.57	1.50	0.022	0.017	9.91	18.00	0.205	0.197	0.120	
2-7			0.030	0.55	1.42	0.024	0.016	9.97	20.30	0.195	0.200	0.240	
2-8			0.057	0.55	1.42	0.024	0.016	9.97	20.30	0.195	0.200	0.240	
2-9			0.085	0.55	1.42	0.024	0.016	9.97	20.30	0.195	0.200	0.240	
3-1	304	—	0.025	0.53	1.02	0.022	0.013	8.68	18.19	0.32	0.30	0.11	3
3-2			0.025	0.60	1.19	0.023	0.015	7.81	19.36	0.32	0.28	0.19	
3-3			0.028	0.63	2.00	0.021	0.013	8.66	18.10	0.31	0.28	0.11	
3-4			0.022	0.64	2.01	0.023	0.013	7.89	19.35	0.32	0.30	0.19	
3-5			0.025	0.59	3.85	0.023	0.013	8.70	18.22	0.31	0.29	0.11	
3-6			0.024	0.65	3.85	0.022	0.014	7.84	19.25	0.31	0.29	0.19	
3-7			0.023	0.62	4.03	0.023	0.014	8.22	18.71	0.31	0.30	0.15	
3-8			0.024	0.61	5.79	0.024	0.014	7.83	19.48	0.31	0.30	0.21	
3-9			0.031	0.62	5.80	0.024	0.014	8.29	18.42	0.31	0.30	0.15	
3-10			0.021	0.64	5.81	0.023	0.014	8.62	18.06	0.33	0.30	0.11	
4-1	316	—	0.021	0.30	1.05	0.002	0.004	13.80	18.50	2.05	0.00	0.180	4
4-2			0.024	0.30	1.00	0.003	0.004	12.00	18.00	2.06	0.00	0.188	
4-3			0.022	0.30	1.02	0.002	0.005	14.00	18.20	2.98	0.00	0.188	
4-4			0.023	0.29	1.01	0.002	0.005	11.80	18.00	3.00	0.00	0.200	
4-5			0.022	0.30	1.00	0.002	0.004	14.20	17.90	4.02	0.00	0.196	
4-6			0.020	0.28	1.03	0.002	0.005	12.10	18.20	4.08	0.00	0.204	
5-1	304	—	0.048	0.38	1.88	0.019	0.024	9.49	18.65	0.52	0.07	0.120	5
5-2	310S		0.080	0.70	1.70	0.020	0.020	20.80	24.80	0.10	0.10	—	
5-3	316		0.062	0.56	1.77	0.030	0.020	12.93	17.46	2.20	—	—	

(Note) FXA means Fluorescent X-ray Analysis.

Table 1: Chemical composition of materials used

Tabela 1: Hemijski sastav korišćenih materijala

Mill-sheet –valjaonička lista

FXA znači analiza fluorescentnim X zracima

3.2 Measurement of Young's modulus and Poisson's ratio

Both E and ν were measured by using both strain gauge method and ultrasonic method.

3.3 Ultrasonic Test Instrument and Size of Test Piece for Measuring Ultrasonic Wave Velocity

Table 2 shows ultrasonic instrument and probes for measuring longitudinal and transverse wave velocity of T.P.No.1-1 ~ 1-6.

Size of test piece is shown in Table 3.

3.2 Merenje Jungovog modula i Poasonovog odnosa

I E i ν mereni su metodom merila naprežanja i ultrazvučnom metodom.

3.3 Ultrazvučni ispitni instrument i veličina ispitnog komada za merenje brzine ultrazvučnog talasa

Tabela 2 prikazuje ultrazvučni instrument i sonde za merenje brzine longitudinalnih i transverzalnih talasa za T.P.No.1-1 ~ 1-6.

Veličina ispitnog komada prikazana je u tabeli 3.

Ultrasonic test instrument	Model USN 58L, GE Inspection Technology, Inc.
Probe for longitudinal wave	Model V109 (5MHz) Panametrics-NDT, Inc.
Probe for shear wave	Model 5Z10X10N-S, Japan Probe Co, Ltd.

Table 2: Ultrasonic test instrument and probes
Tabela 2: Ultrazvučni ispitni instrument i sonde

T.P. No.	AISI No.	Size (mm)
1-1 ~ 1-4	304, 304L	1200×w 50×t 15
1-5 ~ 1-6	310S, 316	1200×w 50×t 9

Table 3: Size of test piece
Tabela 3: Veličina ispitnog komada

3.4 Measurement of Transverse Wave Velocity Ratio

To investigate acoustic anisotropy of T.P. No.1-1~1-6, ratio of transverse wave velocity at rolling direction of material to that at vertical direction was measured.

3.5 Method to Calculate Ultrasonic Wave Velocity

3.5.1 Method to calculate lattice parameter and density

In calculating ρ by using chemical composition, it is indispensable to estimate d . Although Fig. 1 shows the relation between d and carbon content C in austenitic stainless steel⁷⁾, original data are for the range where carbon content is more than 0.275%C. Since carbon content of materials used was from 0.017%C to 0.094%C, we extrapolated the original data to $C=0$ for estimating lattice parameter corresponding to respective carbon content of materials used.

W.C.Leslie⁸⁾ studied a deviation in lattice parameter of iron and its dilute substitutional solid solutions. He reported that the lattice parameter in BCC (body-centered cubic lattice) depended on atomic percent solute of dilute substitutional solid solutions. According to his study, Mn, Ni and Cr didn't cause a deviation in the lattice parameter because of negligibly small size-misfit of atom. Furthermore, Si and P decreased the lattice parameter a little.

Assuming that a deviation in lattice parameter of FCC (face-centered cubic lattice) would be similar to that in BCC, Eq. (5) was used for estimating d (nm) based on paper⁸⁾.

$$d = 0.3555 + 0.0045C - 0.000035Si - 0.00010P + 0.000067Mn + 0.00007Ni + 0.000055Cr \quad (5)$$

Density ρ (kg/m³) was calculated by Eq. (6)⁹⁾,

$$\rho = \frac{4}{Nd^3} \left(\sum_{i=1}^n M_i a_i + \frac{A}{1-A} M_c \right) \quad (6)$$

3.4 Merjenje odnosa brzina transverzalnog talasa

Da bi istražili akustičnu anizotropiju za T.P. No.1-1~1-6, izmeren je odnos brzine transverzalnog talasa u smeru valjanja materijala nasuprot brzini u vertikalnom smeru

3.5 Metoda za izračunavanje brzine ultrazvučnog talasa

3.5.1 Metoda za izračunavanje parametara rešetke i gustine

U obračunu ρ pomoću hemijskog sastava, neophodno je proceniti d . Iako sl. 1 prikazuje odnos između d i sadržaj ugljenika C u austenitnom nerđajućem čeliku⁷⁾, originalni podaci su za opseg gde je sadržaje ugljenika veći od 0.275%C. s obzirom da je sadržaj ugljenika u materijalu koji se koristi od 0.017%C do 0.094%C, ekstrapolirali smo originalne podatke za $C=0$ za procenu parametra rešetke, koji odgovara odgovarajućem sadržaju ugljenika u materijalu.

W.C.Leslie⁸⁾ je proučavao odstupanje u parametru rešetke železa i njegovim razređenim supstitucijskim čvrstim rastvorima. On je saopštio da parametar rešetke u BCC (zapreminski centrirana kubna rešetka) zavisi od atomskog procenta razređenja supstitucijskih čvrstih rastvora. Prema ovoj studiji, Mn, Ni i Cr ne uzrokuju odstupanje u parametru rešetke zbog zanemarljivo male veličine-neprikladosti atoma. Osim toga, Si i P smanjuju malo parametar rešetke.

Pod pretpostavkom da je odstupanje u parametru rešetke FCC (površinski centrirana kubna rešetka) slično onom kod BCC, jednačina. (5) je korišćena za procenu d (nm) na osnovu rada⁸⁾.

$$d = 0.3555 + 0.0045C - 0.000035Si - 0.00010P + 0.000067Mn + 0.00007Ni + 0.000055Cr \quad (5)$$

Gustina ρ (kg/m³) je izračunata prema jednačini (6)⁹⁾,

$$\rho = \frac{4}{Nd^3} \left(\sum_{i=1}^n M_i a_i + \frac{A}{1-A} M_c \right) \quad (6)$$

where N is Avogadro constant [$=6.02 \times 10^{23}$], d is lattice parameter, M_i is atomic weight except carbon, a_i is atomic fraction except carbon, A is atomic fraction of carbon, and M_c is atomic weight of carbon.

gde je N Avogadrova konstanta (broj) [$=6.02 \times 10^{23}$], d je parametar rešetke, M_i je atomska težina sem ugljenika, a_i je atomska frakcija osim ugljenika, A je atomska frakcija ugljenika, i M_c je atomska težina ugljenika.

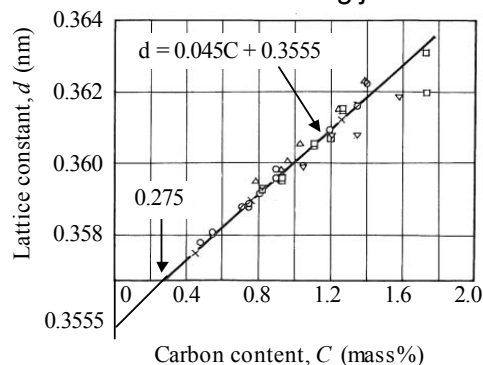


Fig. 1 Relation between lattice parameter and carbon content in austenitic steel⁸⁾
Sl. 1. Odnos između parametra rešetke i sadržaja ugljenika kod austenitnog čelika⁸⁾
 (lattice constant- konstanta rešetke; carbon content-sadržaj ugljenika)

3.5.2 Method to calculate Young's modulus and Poisson's ratio

Since S.Nishikawa¹⁰⁾ reported that Young's modulus of solid-solution type alloy in two component system was roughly proportional to each atomic percent, we assumed that Young's modulus in pluralistic componentsystem would be given by Eq. (7):

$$E = \sum_{i=1}^n a_i E_i \quad (7)$$

where, a_i is atomic fraction and E_i is Young's modulus of an elementary substance. Similarly, we assumed that ν in pluralistic component system would be given by Eq. (8):

$$\nu = \sum_{i=1}^n a_i \nu_i \quad (8)$$

where ν_i is Poisson's ratio of an elementary substance.

The atomic fraction a_i was calculated using weight fraction and atomic weight.

Both E and M of the respective elementary substances are listed in Table 4.

C_L was calculated by substituting values in Eq. (6), (7) and (8) into Eq. (1). Similarly, C_S was calculated by substituting values in Eq. (6), (7) and (8) into Eq. (2).

3.6 Method to Simulate Behavior of Deviation

3.6.1 Deviation in ultrasonic wave velocity and density

We examined the influence of the deviation in each parameter in Eq. (1) and (2) on ultrasonic wave velocity and also the deviation in lattice parameter in Eq. (6) on density.

3.5.2 Metode izračunavanja Jungovog modula i Poasonovog odnosa

S obzirom da je S.Nishikawa¹⁰⁾ saopštio da je Jungov modul kod dvokomponentnih legura tipa čvrstog rastvora, približno proporcionalan svakom atomskom procentu, pretpostavili smo da je Jungov modul u pluralističkom sistemu komponenta dat izrazom. (7):

$$E = \sum_{i=1}^n a_i E_i \quad (7)$$

gde je a_i atomska frakcija i E_i je Jungov modul elementarne supstance.

Isto tako, pretpostavili smo da ν u pluralističkom sistemu komponenta bilo dato izrazom. (8):

$$\nu = \sum_{i=1}^n a_i \nu_i \quad (8)$$

gdje ν_i Poasonov odnos osnovne supstance

Atomska frakcija a_i je izračunata korišćenjem frakcije težine i atomske težine.

I E i M su odgovarajuće elementarne supstance navedene u tabeli 4.

C_L je izračunat zamenom vrednosti u jednačini. (6), (7) i (8) u jed. (1). Slično tome, C_S je izračunat zamenom vrednosti u jednačini. (6), (7) i (8) u jed. (2).

3.6 Metoda za simuliranje ponašanja odstupanja

3.6.1 Odstupanje u brzine ultrazvučnog talasa i gustine

Analizirali smo uticaj odstupanja svakog parametra u jednačini. (1) i (2) na brzine ultrazvučnog talasa kao i odstupanje parametra rešetke u jednačini. (6) na gustinu.

-Kraj 1. dela NASTAVAK U SLEDEĆEM BROJU