Title	Toughness Improvement of the HAZ for Machine Structural Carbon and Low Alloy Steels (Report 1) : Effect of Cooling Time and Isothermal Heating Treatment on Medium and High Carbon Steels(Materials, Metallurgy & Weldability)
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Toughness Improvement of the HAZ for Machine Structural Carbon and Low Alloy Steels (Report 1)†

— Effect of Cooling Time and Isothermal Heating Treatment on Medium and High Carbon Steels —

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Abstract

In fusion welding processes for medium and high carbon steels. two problems are often experienced. One is, high susceptibility to cold cracking and the other is poor resistance to toughness.

This paper has been investigated for the toughness of the simulated HAZ using "Gleeble 1500" with commercial plain carbon steels from 0.24 to 0.89% carbon content.

Main conclusions obtained are as follows:

(1) In the case of changing cooling time ($\Delta t_{1073\text{-}773K}$: Δt_C) in continuous cooling method. S25C(0.24% C) is fairly. S35C and S40C are merely and S55C. SKV70 and SK5 are barely improved in absorbed energy with increasing Δt_C.

(2) By an use of isothermal heating treatment method during weld heat cycle, ductility of these all steels can be fairly improved in comparison with the results of continuous cooling method, although the degree of improvement is depeneded on carbon content in steel. Increasing isothermal holding temperature up to 823K increases ductility of these steels.

KEY WORDS : (Toughness), (Fusion Welding), (Heat-Affected Zone), (Medium. High carbon Steel), (Cooling time), (Preheating)

1. Introduction

Although low carbon steel for machinary use is soundly welded with various fusion welding processes, welding of medium and high carbon steels with or without alloying elements is often confronted with some difficulties, for example, cracking and poor ductility in the HAZ. The weldability of medium and high carbon steels for machinary use has not been clear yet perfectly.

However, in the recent advance of welding process these steels are expected in machinary industries to be welded not only with arc but also with electron-beam and laser-beam processes.

Therefore the investigation of weldability for these steels is required to be clear more.

One of the authors has recently investigated for cold quenching cracking of medium and high carbon steels with or without alloying elements[1]. Then a part of weldability concerning cracking during welding has been made clear.

Consequently, the authors wish to investigate here the ductility in toughness of weldment of these steels in relation to cooling condition during welding and isothermal treatment during welding.

Usually welding of these steels is done after entire preheating or in the hot box which is held to a constant preheat temperature. Therefore the authors have investigated for the ductility of the simulated HAZ by Gleeble with changing of cooling time during continuous cooling to room temperature and isothermal holding temperature and time during a weld heat cycle.

2. Steels Used and Experimental Procedures

2.1 Steels used

Medium and high carbon steel bars of JIS S25C, S35C, S40C, S55C, SKV70 and SK5 were used as base metal. All of these are commercial steel bars whose chemical compositions are given in **Table 1**.

2.2 Experimental procedures

The shape and size of the simulated round bar impact specimen is shown in **Fig 1**, the center of specimen which has a circular notch. The shape and dimension of the notch is according to the JIS standard charpy impact specimen.

Simulated weld thermal cycle is given by a dynamic

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Table. 1 Chemical compositions and impact value of base metal of commercial carbon steels used

Steels	Chemical			Composition (wt. %)							Impact Value (J)*
	C	Si	Mn	P	S	Ni	Cr	Mo	N	O	
S25C	0.24	0.20	0.39	0.018	0.018	0.04	0.04	0.01			55.9
S35C	0.33	0.24	0.69	0.018	0.018	0.02	0.03	0.01			35.1
S40C	0.39	0.25	0.70	0.026	0.028	0.02	0.12	0.01			37.6
S55C	0.54	0.26	0.69	0.022	0.011	0.05	0.19	0.02			16.2
SKV70	0.72	0.22	0.75	0.025	0.023	0.07	0.22	0.01	0.0096	0.002	12.1
SK5	0.89	0.24	0.29	0.022	0.020	0.04	0.12		0.0043	0.001	15.2

* As received base metal. Size of specimen is the same as shown in Fig. 1.

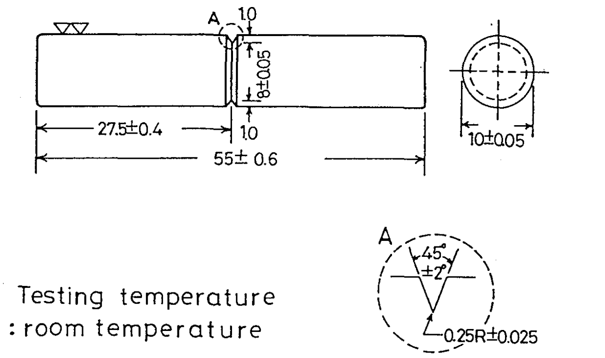


Fig. 1 Shape and size of the simulated round bar impact specimen.

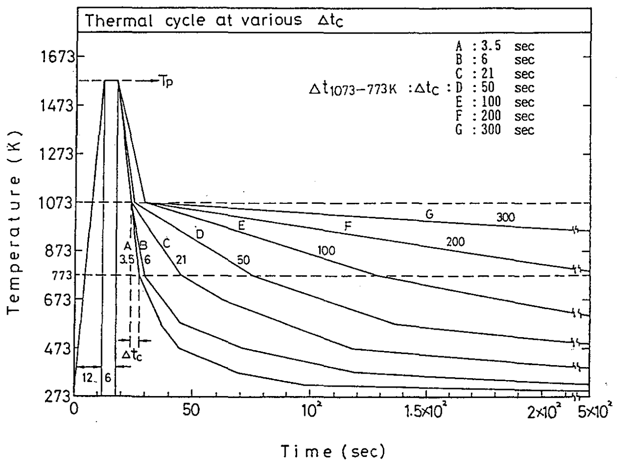


Fig. 2 Thermal cycle for simulated toughness test as continuous cooling method.

testing machine (Gleeble 1500) which is based on resistance heating.

In this investigation, two kinds of thermal cycle were used. The first is shown in **Fig. 2**, which is defined as Continuous Cooling Method. Time for heating from room temperature (≒ 293K) to grain boundary liquation temperature (peak temperature. T_P)[2] is 12sec, and for holding at the T_P is 6sec. T_P for S25C, S35C, S40C, S55C, SKV70 and SK5 was given 1643, 1633, 1623, 1583, 1558 and 1548K respectively. Then, cooled to room

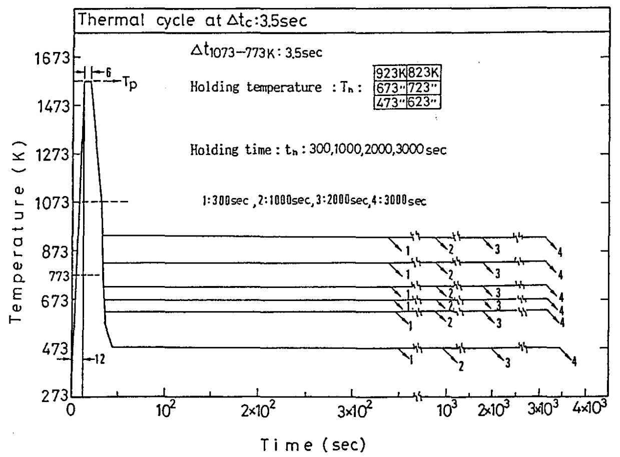


Fig. 3 Thermal cycle for simulated toughness test as isothermal heating treatment.

temperature. On the cooling cycle, cooling time from 1073 to 773K ($\Delta t_{1073\text{-}773K}$: Δt_C) was changed to 5 levels of 3.5, 6, 21, 50, 100sec.

The second thermal cycle is shown in **Fig. 3**, which is defined as Isothermal Heating Treatment during weld heat cycle. The heating cycle is same as the above-mentioned heating cycle. But on the cooling cycle Δt_C is fixed as 3.5sec and after cooled to each holding temperature (T_h : 623, 723 and 823K) the specimen was kept for 3 kinds of holding time (t_h : 300, 1000 and 2000sec) as an isothermal heating treatment. Further, cooling to the room temperature after the treatment was let by cooling rate of 275.5K/sec.

Charpy impact testers of 5Kgfm and 50Kgfm were used to evaluate ductility of the specimen as absorbed energy (E) at room temperature (≒293K)

After charpy testing the specimen was cut axially and polished for metallographic investigation. Then the maximun hardness and metallographic microstructure were evaluated. In order to prevent the surface distortion of the specimen in polishing, electrolytic polishing method was adopted. The compositions of electrolytic polishing solution are the solution mixed of 5ml distilled water, 225ml acetic acid and 20ml perchloric acid. In order to

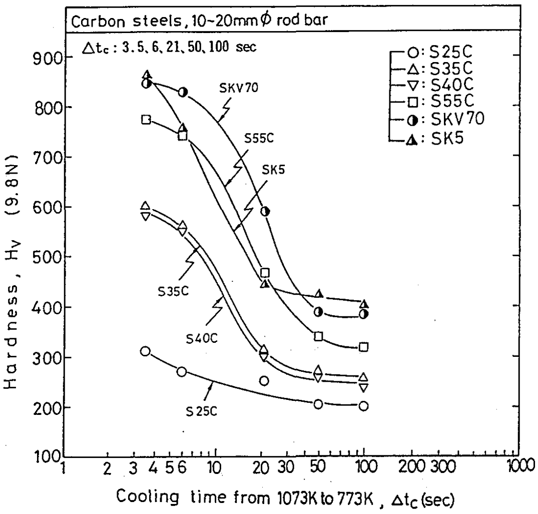


Fig. 4 Effect of cooling time on hardness of carbon steels.

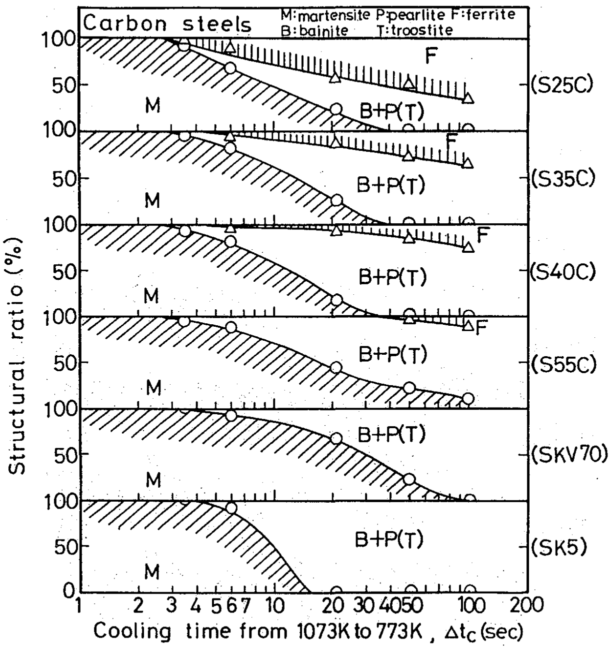


Fig. 5 Schematic illustration of relationship between cooling time and microstructure ratio of carbon steels.

evaluate clearly grain boundary ferrite and ferrite side plate in medium carbon steels or ferrite sawteeth in higher carbon steels, there was used 2% Nital + 2% Picral mixture etchants for etching.

3. Experimental Results and Discussions

3.1 Continuous cooling method

Figure 4 shows the relationship between Δ t_C and hardness for continuous cooling simulated HAZ for each steel used. Generally, increasing Δt_C shows a decrease in hardness in each steel, although the variation of hardness is larger in higher carbon steel as the hardness of

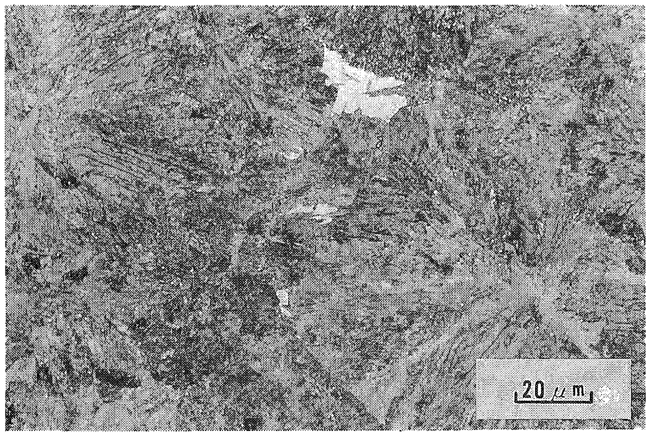


Fig. 6 Microstructure of SK5 on $\Delta t_{1073\text{-}773K}$: 21sec.

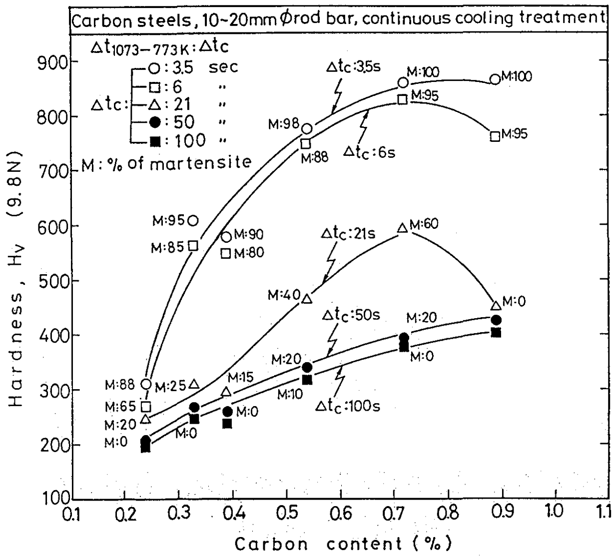


Fig. 7 Relationship between carbon content and hardness of various cooling time of carbon steels.

martensite is higher in higher carbon steel. It is estimated that between Δ t_C : 3.5 and about 30sec there is a big microstructural change from martensite to fully ferrite and pearlite or fully bainite structures.

Figure 5 shows the relationship between Δt_C and ratio (%) of each microstructure in metallographic microscope in the simulated HAZ for each steel. M, F and B + P(T) shows martensite, ferrite and bainite and pearlite (including troostite) structure, respectively. As a result, it is shown that martensite structure is easy to remain due to increase in C content except SK5. Further, the formation of ferrite is difficult according to the increasing in C content up to S55C(0.54% C). In SKV70(0.72% C) and SK5(0.89% C) steels the formation of ferrite is not seen even in longer Δt_C up to 100sec. These results well agree with those of Inagaki et al[3] which were introduced from F_e-C binary alloys.

In SK5 the formation of martensite is strongly

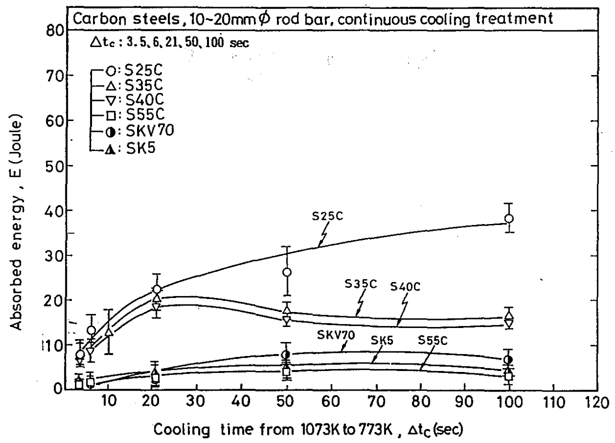


Fig. 8 Effect of various cooling time on absorbed energy of carbon steels.

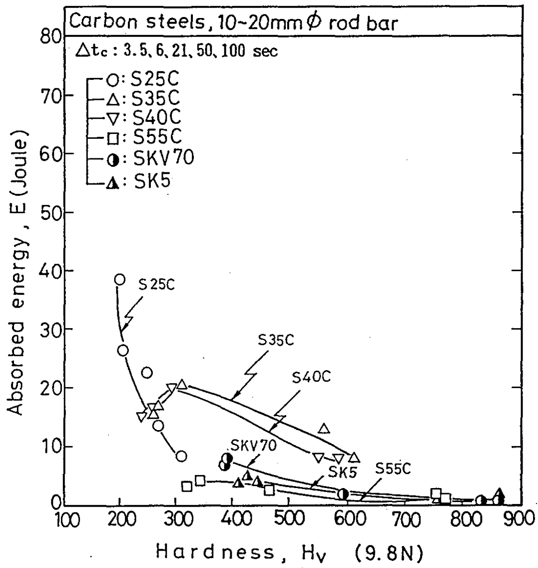


Fig. 9 Relationship between hardness and absorbed energy on various cooling time of carbon steels.

suppressed between Δt_C : 10 and 21sec which is shown in Fig. 5. As shown in **Fig. 6** almost pearlite structure was formed at the time of Δt_C : 21sec in SK5.

Figure 7 shows hardness change against carbon content for five different Δt_C (3.5, 6, 21, 50 and 100sec). In each hardness the ratio (%) of martensite M in microstructure is shown. As a result, the hardness increases with C content in Δt_C : 3.5sec, but the maximun hardness shows at about 0.72% C of SKV70 in Δt_C : 6 and 21sec. Martensite ratio in 0.89% C of SK5 in Δt_C : 21sec is about 0%, while martensite ratio of 60% exists still in case of 0.72% C. Easier transformation of martensite in 0.89% C steel shows a lower value in hardness in 6 to 21sec of Δt_C than 0.72% C steel. However, the hardness of fully annealed structure more than 50sec of Δt_C is gradually increased with C content.

The relationship between Δt_C and absorbed energy for

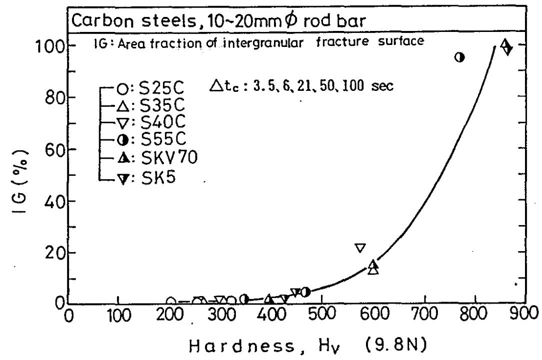


Fig. 10 Relationship between hardness and the ratio of intergranular fracture surface with various Δt_C of carbon steels.

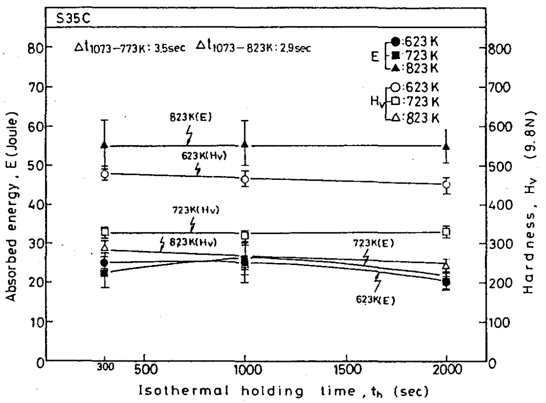
each steel is shown in **Fig. 8**. With increasing Δt_C the absorbed energy is improved fairly in only S25C, merely in S35C and S40C, and barely in S55C, SKV70 and SK5. By means of adoption of initial preheating or increase in weld heat input in welding we usually expect to improve the ductility as well as crack susceptibility in the HAZ. However, from the result of Fig. 8 it is estimated that the improvement of ductility of the HAZ is expected only for the steels whose carbon content is less than 0.3%. For higher carbon containing steel than 0.3% C slow cooling in continuous cooling method is not useful for improvement of the HAZ ductility.

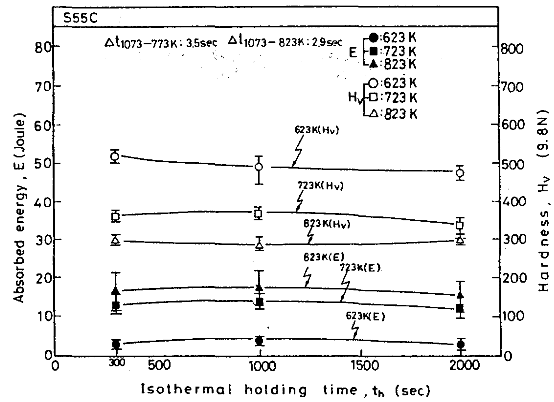
Figure 9 shows the ductility change against hardness of the HAZ. S25C sharply decreases with increase in hardness, but S35C and S40C merely and the other high carbon steels insensitively. Absorbed energy does not show a simple relation with hardness of the HAZ even in carbon steels.

The relationship between the hardness and the ratio of intergranular fracture surface with various Δt_C for all steels is shown in **Fig. 10**. Intergranular fracture surface is abruptly increased when the hardness of the HAZ exceeds more than 500 to 600 (H_V), and is reached to almost 100% in case of hardness of 800 (H_V) irrespective of type of steel.

3.2 Isothermal heating treatment

On the continuous cooling of Δt_C : 3.5sec the specimen is stopped to cool at three different temperature as 823, 723 and 623K and held up to 2000sec. Accurate Δt_C is expressed as 2.9sec in case of 823K holding. **Figure 11(a),(b)** and **(c)** show the relationship between the absorbed energy (E) and the hardness (H_V), and isothermal holding time t_h for three different temperatures for S35C, S55C and SKV70 steels. As a result of Fig. 11(a), (b) and (c), an increase in holding temperature generally decreases the hardness and increases the





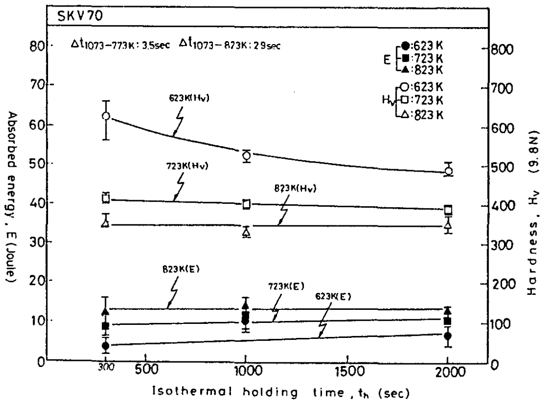


Fig. 11 Relationship between the absorbed energy and hardness and isothermal holding time for three different holding temperature.
(a) S35C (0.33% C)
(b) S55C (0.54% C)
(c) SKV70 (0.72% C)

absorbed energy, the degree of which is depending on carbon level of steel. Moreover, holding time from 300 to 2000sec does not obviously influence in the changes of the hardness and the absorbed energy. According to TTT curves (S curve) in the reference[4], it is considered that bainitic transformation would be completed within about 300 to 1000sec for these steels in isothermal heating treatment.

Figure 11(a) for S35C shows that holding temperature of 823K was useful for improvement of the ductility and the hardness of the HAZ, although those of 723 and 623K did not so beneficial for the ductility.

Figure 11(b) and (c) for S55C and SKV70 show that, even if the holding temperature is raised to 823K, the ductility of the HAZ is not so improved for high carbon steel although the hardness is decreased with temperature.

Figure 12 collectively shows the absorbed energy change after isothermal holding treatment at three temperatures against C content in steel. Compare the improvement of three solid lines (for different temperatures) to broken line as continuous cooling to room temperature by Δt_C : 3.5sec. As a result, isothermal holding treatment improves the ductility of the HAZ and generally higher the temperature held, more improvable the ductility. However, degree of improvement is changed depending on carbon content of steel. Steels less than 0.35% C are improved fairly but steels more than 0.4% C are not so enough even in 823K. Moreover generally the difference between 823K and 723K is not clear for more than 0.4% C steel.

In actual welding operation of high carbon steel we usually adopt welding in the furnace which is kept a preheating temperature. In this sequence heat cycle of the weldments in welding is similar to that in this experiment. Therefore as a result of the ductility in this experiment in comparison with those of base metals welding is recommended to do in the hot box heating on 723K for S25C, 723 to 823K for S35C and 823K or more for S40C, S55C, SKV70 and SK5.

4. Conclusion

This papar has treated the variations of hardness, structure and ductility of the simulated HAZ for high carbon steels between 0.24 and 0.9% C. Two different

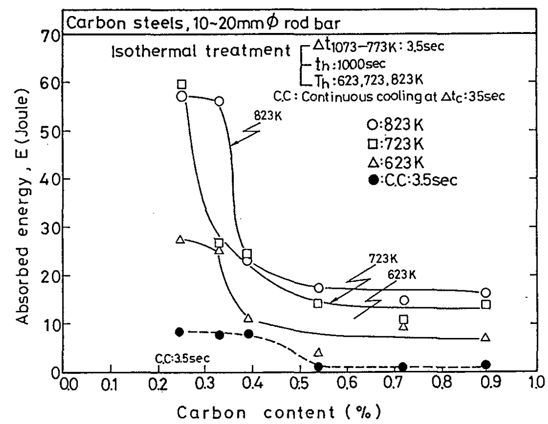


Fig. 12 Relationship between carbon content and absorbed energy change after isothermal holding treatment at three temperature of carbon steels.

experiments were done using Gleeble 1500, one is continuous cooling method to room temperature change cooling time Δt_C between 1073 to 773K, and the other is isothermal heating treatment at 623, 723 and 823K during continuous cooling in Δt_C : 3.5sec.

Main conclusions obtained are as follows

(1) In continuous cooling method, the hardness of the HAZ decreases with the increase in Δt_C for each steel depending on carbon content. Higher the carbon content in steel, the higher the hardness of the HAZ at 3.5sec of Δt_C which shows almost martensitic structure. More than 50sec of Δt_C the hardness of each steel constant value which is expressed in order to carbon content.

(2) Increasing carbon content in steel prolongs the formation of martensite and decreases amount of ferrite in structure except SK5. In SK5 (0.89% C), the formation of martensite is suppressed to form in lower Δt_C, therefore the hardness of the HAZ is also softened in lower Δt_C in comparison with SKV70 steel (0.72% C).

(3) Concerning the improvement of absorbed energy with Δt_C, there are a fair in S25C, a mere in S35C and S40C and scarece in S55C, SKV70 and SK5. As a result, the improvement of the ductility of the HAZ is generally difficult with an increase in Δt_C for high carbon steel containing more than 0.35% C. Especially for carbon steel more than 0.5% C the improvement is not expectable.

(4) Absorbed energy of various steels was not represented by a simple relation with the hardness of the HAZ.

Intergranular fracture surface mode is abruptly increased when the hardness of the HAZ exceeded more than H_V: 600.

(5) In isothermal holding treatment, holding at the temperature up to 823K shows a fair improvement for the steel less than 0.35% carbon content but not so enough for the steels more than 0.4% C, although the hardness is gradually decreased. Moreover holding time is not so influence for these carbon steels.

(6) From the standpoint for improvement of the HAZ ductility for S25C steel(0.24% C) holding temperature is recommended at 723K and for S35C(0.33% C) at 723 to 823K. Moreover, for higher carbon steels more than 0.4% C high holding temperature as 823K is recommended although the improvement of the ductility is not satisfactory.

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