Laser Welding Unit for Intersection Line Welding of Spacer Grid Inner Straps and its Application

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A spacer grid assembly is one of the most important structural components in a Pressurized Water Reactor fuel assembly. The spacer grid assembly, which supports nuclear fuel rods laterally and vertically with a friction grip, is an interconnected array of slotted grid straps welded at the intersections to form an egg-crate structure. From a structural point of view, the spacer grid assembly is required to have enough crush strength under lateral loads so that the nuclear fuel rods are maintained in a coolable geometry, and that control rods are able to be inserted. The capacity of a spacer grid assembly to resist lateral loads is usually characterized in terms of its crush strength. Zircaloy is prevailing as the material of a spacer grid because of its low neutron absorption characteristic and its extensive successful in-reactor use. One of the primary considerations is to provide a Zircaloy spacer grid with crush strength sufficient enough to resist design basis loads, without significantly increasing the pressure drop across the reactor core. Based on the fact that the crush strength of a spacer grid assembly is known to be proportional to a weld penetration at the intersections of the slotted grid straps, a laser welding unit which is able to weld along the intersection line of spacer grid inner straps was proposed, and spacer grid specimens were fabricated using the proposed laser welding unit in this study. Also, a crush strength test and analysis of the spacer grid specimens were carried out to confirm the effect of the resultant crush strength enhancement.

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1. Introduction

A fuel assembly in a Pressurized light Water Reactor (PWR) consists of spacer grid assemblies, fuel rods, a top nozzle, a bottom nozzle, guide tubes, and an instrumentation tube as shown in Fig. 1. Among them the spacer grid assembly is one of the most important structural components in a PWR fuel assembly. General roles of a spacer grid assembly should be maintained under design basis loads as in the following: (1) providing lateral and vertical support for fuel rods (2) maintaining a fuel rod space under accidental and operational loading conditions (3) keeping the guide tubes straight so as not to impede a control rod insertion under any normal or accidental conditions.

A spacer grid assembly, which supports nuclear fuel rods laterally and vertically with a friction grip, is an interconnected array of slotted grid straps welded at the intersections to form an egg-crate structure as shown in Fig. 2. Zircaloy is prevailing as the material of a spacer grid because of its low neutron absorption characteristic and its extensive successful in-reactor use. Currently, a commercially available Zircaloy spacer grid assembly is fabricated by spot-welding the intersections between the grid straps arranged in a matrix array by a TIG welding, laser beam welding (LBW) or electron beam welding (EBW) method.

From a structural point of view, the spacer grid assembly is required to have enough crush strength under lateral loads so that the nuclear fuel rods are maintained in a coolable geometry, and that control rods are able to be inserted. The capacity of a spacer grid assembly to resist lateral loads is usually characterized in terms of its crush strength. One of the primary considerations is to provide a Zircaloy spacer grid with crush strength sufficient enough to resist design basis loads, without significantly increasing the pressure drop across the reactor core. The crush strength of a spacer grid assembly is closely related with a buckling of the grid straps composing the spacer grid assembly. However, it is very difficult to set a marginal deformation limit for a grid strap buckling which enables us to meet a design concern. Therefore, an incipient buckling is considered as the design failure criterion for a spacer grid during a design stage [1].

It has been reported that the crush strength of a spacer grid assembly is proportional to a weld penetration at the intersections of the slotted grid straps [2]. Therefore, it is necessary to increase a weld penetration at the intersections or the weld line length along the intersections in order to meet the higher crush strength requirements of a spacer grid assembly. Such a spacer grid can be achieved by changing the welding method or improving the weld quality at the intersections. However it has been reported that by a conventional spot welding method there are some limitations to increasing the weld penetration to some extent because of a spattering [3].

In this study, a LASER beam welding unit and a method for an inner strap welding have been proposed to obtain a longer and finer weld line and a smaller weld bead size for a spacer grid assembly. Also, a crush strength test and analysis of the spacer grid specimens were carried out to confirm the effect of the resultant crush strength enhancement.

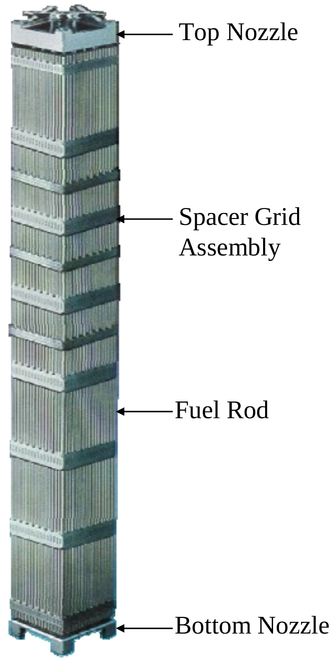

Fig. 1 PWR fuel assembly.

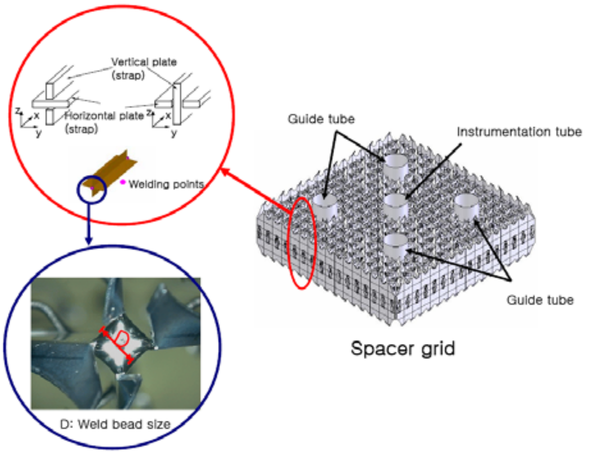

Fig. 2 Schematic diagram of a spacer grid assembly.

2. Outline of a Spacer Grid Welding

Two kinds of spacer grid assembly prevail for the PWR fuel assembly. One is an Inconel spacer grid assembly made of Inconel straps because of its high strength and high corrosion resistance. The other is a Zircaloy spacer grid assembly made of Zircaloy straps because of its high neutron economy. Brazing is used for a joining of the Inconel straps, while a TIG welding, EBW, or LBW are used for a joining of the Zircaloy straps. Nowadays, an LBW is prevailing for most of the Zircaloy spacer grid manufacturing vendors, for the purpose of a smaller bead size and a larger weld penetration at the welding parts. A spacer grid assembly with a smaller bead size leads to a smaller pressure drop of the coolant flowing along the fuel assembly, which consequently leads to a reduction in the load on a reactor coolant pump. In addition, a spacer grid assembly with a deeper weld penetration results in a larger crush strength of a spacer grid assembly, which is very important for the seismic resistance of a nuclear fuel assembly. However, a conventional laser spot welding with a high energy input at the intersection points usually results in spattering and larger bead size, which is a demerit for a spacer grid assembly performance in reactors. Hence, a seam welding method could be proposed as one of the alternatives to solve these demerits. Figure 3 shows the bead shapes at the intersection points and intersection line welded by a conventional spot welding technique and a seam welding technique, respectively.

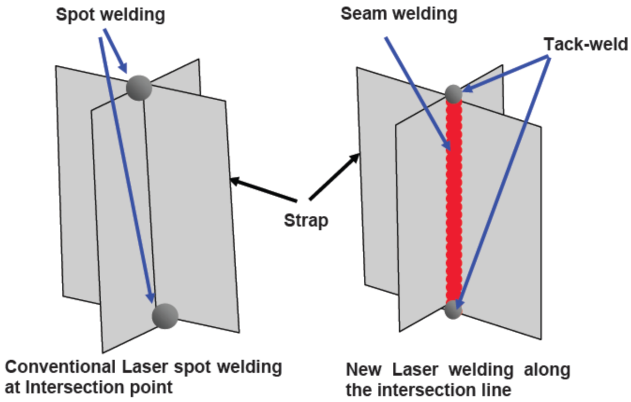

Fig. 3 Bead shapes for the conventional and the proposed welding technique.

3. Proposed LASER Welding Technique

The conventional spot welding method of a spacer grid assembly can give rise to spattering phenomenon and a thermal deformation in order to obtain a deep weld penetration. Thus, a fine welding is impossible, therefore the bead size for an intersection in a spacer grid is large, and thus the flow resistance of a coolant is increased. Ultimately, the pressure drop level of the coolant is increased, which in turn is responsible for increasing the load on a reactor coolant pump. In order to increase the structural strength of a spacer grid assembly and to decrease the pressure drop level of a coolant, a new method for welding a spacer grid assembly must be developed. To this end, it is critical to develop a new welding technique and a welding unit in the case of using the same LASER welder (Miyachi ML-2550A) of for a conventional spot welding. The welding speed of a new welding technique is 1 mm/s.

In this study, a new LBW technique is proposed by tilting the LASER beam along the intersection line of the spacer grid assembly in order to obtain a longer weld line and a smaller weld bead size. Tilting the LASER beam is achieved by using the apparatus as shown in Fig. 4 [4]. Weld lines for the new LASER welding technique are illustrated in Fig. 5 in the case of a continuous seam weld and an intermittent seam weld, respectively.

Welding conditions for manufacturing the spacer grid specimens are shown in Table 1 for the conventional spot welding technique and the proposed new welding technique using 99.999% Argon as a shielding gas. The specifications of Miyachi ML-2550A are listed in Table 2.

Table 1. Welding conditions for the spacer grid specimens

	peak power	pulse width	repeat	No. of shots
Current spot welding	3.20 *kW*	6 *ms*	17	6
Proposed new welding	0.87 *kW*	6 *ms*	4	84

Table 2. Specifications of LASER welder

Maximum rated output	400 W
Maximum output energy	80 Joule/pulse
Maximum peak power	8 kW
Oscillator type	Nd:YAG
Wave length	1064 nm

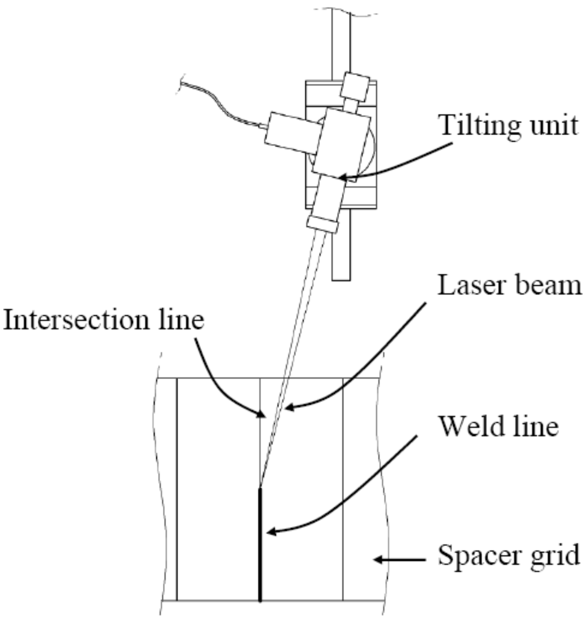

Fig. 4 Proposed LASER welding techniques (Tilting unit).

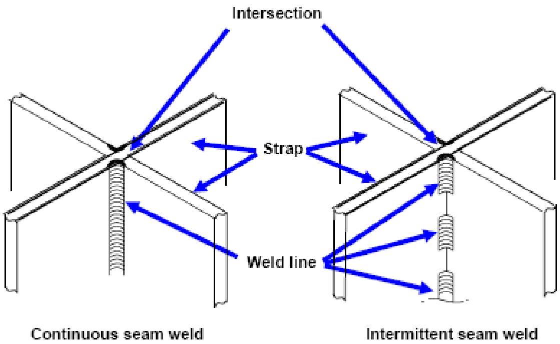

Fig. 5 Weld line for the proposed LASER welding techniques.

4. Spacer Grid Specimen made by the Proposed LASER Welding Technique

A sub-sized (7x7 type) spacer grid assembly with a side-length of 90.2 mm was fabricated by the proposed LASER welding technique as shown in Fig. 6. Crush test and analysis for the sub-sized spacer grid assembly were performed for various weld line lengths. The crush strength of the spacer grid welded by the new LBW technique was enhanced by up to 30 % when compared to that by the conventional spot welding method. Figure 7 shows the continuous weld line of the specimen welded by the proposed LASER welding technique, where the crush strength increases up to a maximum of 34 % compared with that of the specimen welded by the conventional spot welding.

A fully arrayed (16x16 type) spacer grid assembly with a side-length of 206.8 mm was fabricated by the proposed LASER welding technique as shown in Figs. 8 and 9. Figures 10 and 11 show the weld beads of the conventional spot welding technique and the weld line of the proposed welding technique, respectively. As shown in Fig. 10, the bead size of the proposed welding technique is smaller than that of the conventional welding technique (~56 % of the bead size of the conventional spot welding). Also, the weld line of the proposed welding technique is by far larger than that of the conventional welding technique as shown in Fig. 11.

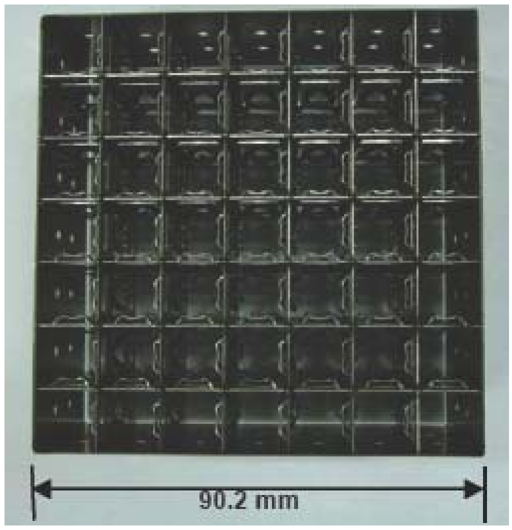

Fig. 6 Sub-sized (7x7) Spacer Grid Specimen.

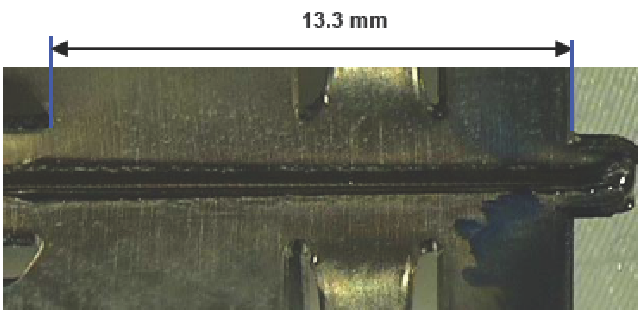

Fig. 7 Continuous weld line of the specimen welded by the proposed LASER welding method.

5. Crush Strength Test

A pendulum type impact tester as shown in Fig. 12 was used to perform the impact test of the spacer grid assembly [5]. It is intended to simulate the type of load and impact velocities anticipated under a seismic disturbance. This tester is composed of a structural body, an impact hammer, a data acquisition system and a furnace. The impact hammer is composed of a sphere type impact tip for a dynamic loading and two sensors, which are two force transducers and one accelerometer, for gathering the dynamic data. An angular transducer is attached at the hinge point of the impact hammer in order to detect the initial angle of the hammer and to obtain continuous data on the angle of it. The data acquisition system consists of a magnetic controller, two dynamic signal amplifiers, and a temperature controller. The impact hammer moves with the guidance of the four guide rods. The impact hammer is made of mild steel, which mass corresponds to the mass of one span of the spacer grid assembly. The manipulator at the hinge point of the impact hammer is made for an accurate impact point regardless of a specimen's size. The general test setup consists of the floor, hammer weight, force transducer, dynamic accelerometer, and mounting fixtures. The specimen is fixed to the holding fixture by two screws. The impact hammer is held by a magnetic holder and released when a release signal on the controller is activated.

Fig. 8 Fully arrayed (16x16) spacer grid specimen welded by the proposed LASER welding method (without guide tubes).

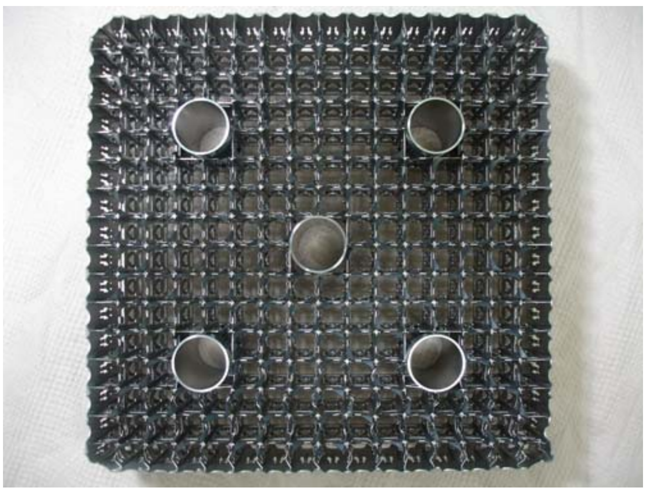

Fig. 9 Fully arrayed (16x16) spacer grid specimen welded by the proposed LASER welding method (with guide tubes).

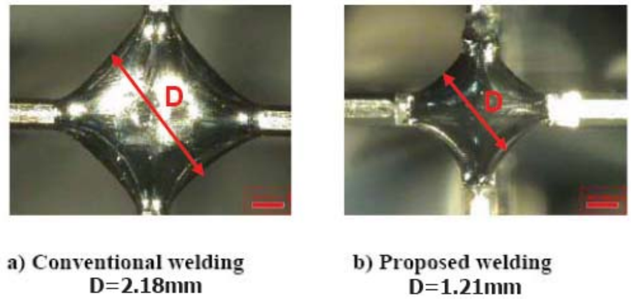

Fig. 10 Weld bead by the conventional and the proposed welding technique.

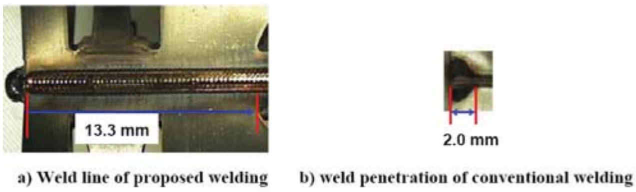

Fig. 11 Weld line by the conventional and the proposed welding technique.

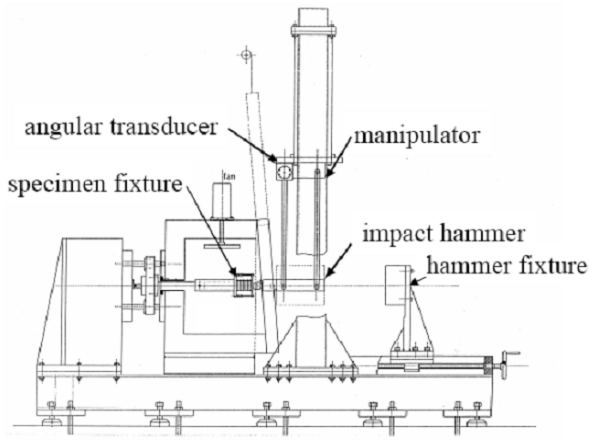

Fig. 12 Crush strength tester.

6. FE Modeling

6.1 Geometric Data and Material Properties

Since we are dealing with the plastic buckling phenomena, the mechanical property of the material has to be considered by the elastic-plastic characteristic curve from the uni-directional tensile test according to the ASTM procedure [6]. The elastic-plastic material properties of Zircaloy-4 are summarized in Ref. 7.

6.2 Finite Element Model

The finite element (FE) models for the sub-sized (7x7 type) and the fully arrayed (16x16 type) spacer grid assembly for the impact analysis were created using I-DEAS [8]. The 4-node shell elements were used for the inner/outer straps and the 4-node tetrahedral solid elements were used at the welded intersections as shown in Fig. 13. Since the slot width for the inner straps is wider than the inner strap thickness, there may be a gap at the interconnected parts. So, surface-to-node contact elements were used at these interconnected parts to simulate the gap conditions as shown in Fig. 13.

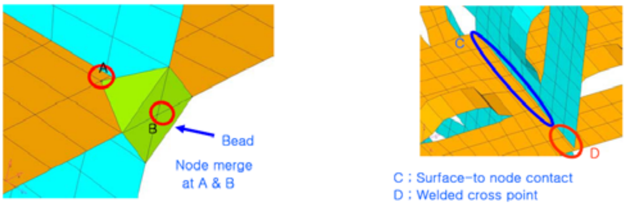

Fig. 13 Finite elements node merge.

6.3 Boundary and Loading Conditions

Figures 14 and 15 show the FE models for the sub-sized and the fully arrayed spacer grid assembly. The impact hammer was modeled as a rigid element, which had an equivalent mass of the hammer. An external impact load was modeled for the initial impact velocity at the reference node of the upper rigid surface, which was located in the centre of the upper rigid surface. In the FE analysis model, a rigid and mass element was used for the impact hammer as shown in Figs. 14 and 15. An external force was modeled by applying the initial impact velocity at the center node of the rigid surface, and the output values (acceleration) for the initial impact velocity could be obtained at this node. The impact force of the grid was evaluated by multiplying the maximum acceleration of the model by the mass of the impact hammer. The applied boundary condition simulated the actual test condition. All degrees of freedom were fixed at the rigid surface of the bottom side as shown in Figs. 14 and 15.

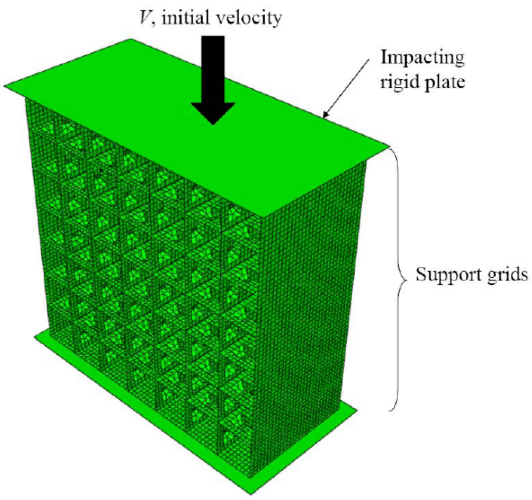

Fig. 14 Boundary and loading conditions for the sub-sized spacer grid assembly.

7. Results

7.1 Effects of a Weld Penetration on the Spacer Grid Strength for a 7x7 sub-sized grid assembly

It is known that a welding penetration depth affects the crush strength of a spacer grid assembly to some extent [9]. Crush test and FE analysis for the sub-sized (7x7 type) spacer grid assembly shown in Fig. 6 were performed. Table 3 shows the geometric data for the sub-sized specimen and Table 4 shows the test and analysis results for the sub-sized specimen. The test results were obtained from an average of 5 or 13 specimens. According to Table 4, the tendencies of a crush strength increase from the analysis are in good agreement with those from the test. The discrepancy between the test and analysis results is attributed to the manufacturing dimensional tolerances and a local thinning of the strap thickness around the welded parts as shown in Fig. 16, whereas fixed dimensions were assumed in the analysis. We found that the crush strength was enhanced by up to 34 % with an increase of the weld line when compared with that of the conventional spot welding method for the 7x7 sub-sized spacer grid specimen.

7.2 Effects of a Weld Penetration on the Spacer Grid Strength for a fully arrayed grid assembly

Figure 17 shows the normalized crush strength enhancement for the fully arrayed spacer grid assembly with guide tubes from the test and FE analysis with an increase of the normalized weld line length. The crush strength enhancement has a good linear relation with a weld line length as shown in Fig. 17 from the finite element analysis and test.

Figure 18 shows the normalized crush strength enhancement for the fully arrayed spacer grid assembly without guide tubes from the test and FE analysis with an increase of the normalized weld line length. The crush strength enhancement also has a good linear relation with a weld line length as shown in Fig. 18 from the finite element analysis and test, even though there is some discrepancy between the analysis and test results. It seems that the discrepancy is attributed to the effect of the guide tubes on the crush strength of the spacer grid assembly.

According to Figs. 17 and 18, a considerable crush strength enhancement, i.e. up to 60-80 %, was achieved by the proposed welding method compared to that by the conventional spot welding method

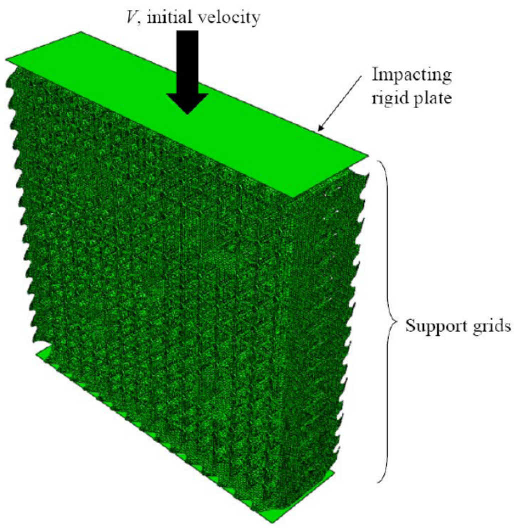

Fig. 15 Boundary and loading conditions for the full-arrayed spacer grid assembly.

Table 3. Geometric data for the Type A and Type B specimens

Specimen	Strap thickness (mm)		
	Outer strap A	Outer strap B	Inner strap
Type A	0.664	0.457	0.457

Table 4. Buckling strength increase ratio based on the value of a welding point at an intersection for the sub-sized specimen

Weld penetration (mm)	Analysis (A)	Test (B)	Difference (B-A)	Remark
Point welding (2.0)	1.000	1.000	0.000	Conventional weld
9.275	1.145	1.154	0.009	
13.280	1.337	1.373	0.036	
17.200	1.344	1.377	0.033	

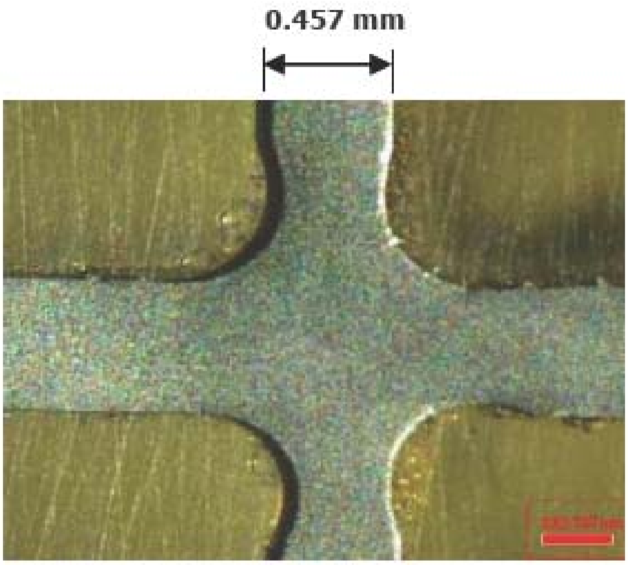

Fig. 16 Local thinning of the straps for the proposed welding technigue.

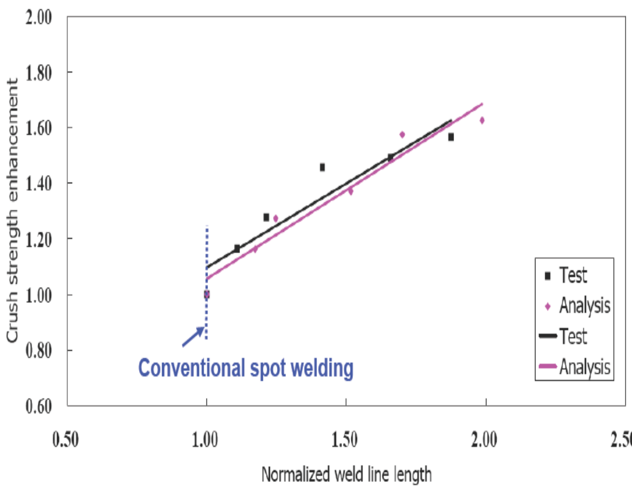

Fig. 17 Crush strength enhancement for the fully arrayed spacer grid assembly with guide tubes.

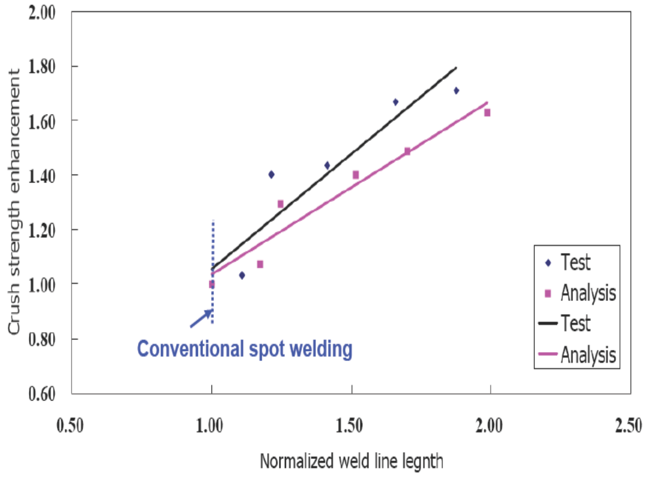

Fig. 18 Crush strength enhancement for the fully arrayed spacer grid assembly without guide tubes.

7.3 Why does the weld line length affect the crush strength enhancement?

It is known that the crush strength of a spacer grid assembly is strongly related to the buckling strength of the spacer grid straps constituting the spacer grid assembly [10]. Based on the fact that the critical load (P_{cr}) is proportional to the moment of inertia (I) of the grid strap, P_{cr} can be enlarged by increasing the plate thickness (t) and the effective strap height (B_e) as shown in Fig. 19 and Eq. 1. B_e refers to the part in a strap where a load passes, which is smaller than the height of a strap (B_1+G+B_2). Fig. 19 shows a simple case where there are no dimples and springs, and we can improve P_{cr} by increasing B_e or reducing the slit (gap) length (G). Reducing the slit length by means of increasing the weld line length by the proposed new welding method was investigated in this study. Therefore, increasing the effective height including the weld line length by maintaining the total height of the grid straps, could increase the bucking strength of the grid straps, consequently, also the crush strength of the spacer grid assembly without increasing the pressure drop of a coolant.

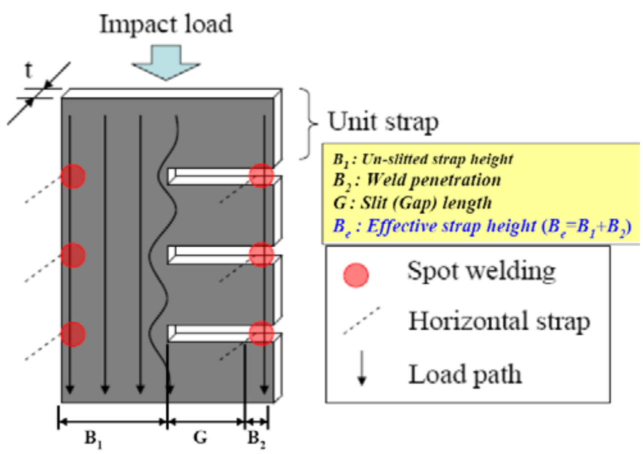

Fig. 19 Effective height of a grid strap

$$p_{cr} \propto \frac{EI}{L^2} \propto B_e \bullet t^3 \qquad (1)$$

8. Conclusions

1. A LASER welding unit and method were proposed for the welding of a nuclear fuel spacer grid assembly. A longer weld line, smaller weld bead size (～56 % of weld bead size of the conventional LASER spot welding), and a lesser occurrence of a spattering were achieved from the proposed LASER welding unit and method.

2. Crush strength of the spacer grid welded by the proposed LASER welding method was increased by up to 60-80 % when compared to that of the conventional LASER spot welding method for the fully arrayed spacer grid assembly.

3. The crush strength enhancement has a good linear relation with a weld line length from the finite element analysis and test. Therefore, it was found that a finite element model is very effective for estimating the crush strength enhancement of a spacer grid assembly.

Acknowledgments

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