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The Effect of Weld Line on the Mechanical Strengths and its Elimination Process in the Zr–4 Resistance Upset Welds

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지르칼로이-4의 저항업셋용접에서 용접선이 기계적성질에 미치는 영향과 그 소멸과정

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Abstract

The objective of this study is to investigate the effect of weld line on the mechanical strengths and the process of weld line elimination in the Zircaloy–4 resistance upset welding for the fabrication of heavy water reactor fuel rods. The weld current and the amount of upset increased linearly with the main heat, in which two relations between them were derived. It was found that the threshold to obtain sound weld was 50% of main heat in terms of weld upset size, mechanical strengths and weld line elimination. The weld microstructure of resistance upset welds of Zircaloy–4 comprsied basketweave, Widmanstätten and martensite respectively by changing the main heats. Dimples on uniaxially fractured surface at weld line in the Zr–4 welds were larger and deeper compared with those on biaxially fractured surface. It was also found that the process of the weld line elimination in the resistance upset weld of Zircaloy–4 could be divided into three stages in terms of the presence of many pores, their shrinkage and elimination, and the shrinkage of the original weld interface with increasing weld currents.

요 약

중수로형 핵연료봉단마개용접부의 품질검사는 금속조직 검사에 따른 용접계면에 존재하는 불연속인 용접선(weld line) 길이가 가장 중요한 검사기준이다. 본 연구에서는 저항용접에서 가장 중요한 변수인 용접열의 변화에 따라 용접계면에서 용접선 소멸과 이 용접선이 용접부에 미치는 영향을 미세조직, 인장 및 파열시험으로 조사하였고, 또 주사전자현미경을 사용하며 파단면을 조사하였다. 용접열(main heat)의 변화에 따라 실제 용접에 사용된 전류와 업셋에 따른 시편길이 감소량은 증가하였으며 이들에 관한 상관관계식을 유도하였다. 용접열 50%는 용접된 용접부의 용접 업셋 크기, 기계적 강도 및 용접선 소멸등을 고려한 결과 이것이 건전한 봉단마개용접을 위한 임계치임을 알았다.

용접열을 50%에서 75%로 변화시킴에 따라 Zircaloy-4 용접부의 미세조직은 basketweave, Widmanstätten과 마르텐사이트로 변했고, 이는 용접시 최고도달 온도에 따라 냉각속도가 크게 변화했기 때문으로 사료된다. 인장시험에 의한 용접선 파단면에서 연성파괴의 dimple 형상은 2축응력에 의해 파열된 파단면의 dimple보다 크고 깊었음이 관찰되었다. 저항업셋용접부에서의 용접전류 증가에 따른 용접선의 소멸과정은 초기용접계면에 기공 존재, 이들의 수축과 소멸 및 초기계면 수축등 3단계로 구분할 수 있었다.

1. Introduction

Pressurized heavy water reactor(PHWR) fuel rods are manufactured by stacking uranium dioxide sintered pellets into zirconium alloy cladding tubes. The sealing process of end caps to tubes is a fundamental part in the design and fabrication of nuclear fuel rods. In order to prevent the escape of fission products and to maintain a good in-reactor performance of the nuclear fuel, it is necessary that tubes containing pellets should be hermetically sealed. Cracks in the end cap weld heat affected zone(HAZ) in a reactor have been found to be related to incomplete welds(1) and power ramp(2).

As far as welding methods of Zircaloys are concerned, fusion welding such as tungsten inert gas (TIG), electron beam welding and laser beam welding has been widely used(3,4,5). However, it has to go through a process of melting the base metal which is altered, and the weld defects such as porosity, lack of fusion, lack of penetration and mismatched joint are inevitable(6).

Resistance upset welding which is a kind of solid state welding is being widely used to seal tubes to end caps in terms of good mechanical and corrosion properties, small heat affected zone and small grains. From the economic standpoint, in addition, it produces nuclear fuel rods in a relative low cost due to its high productivity.

In the fabrication of nuclear fuel rods, quality control of end cap welds is made on the basis of the extent of weld line(or any discontinuity at weld interface) by metallography. The cause of weld line formation in the resistance upset welds is known to be associated with the contamination of parts to be welded, damage of parts to be contacted and improper welding conditions(7,8). However, studies on the effects of weld line in the resistance upset welds are scarce even though the weld line is one of the most important criteria in the process of the evaluation of weld quality.

The purpose of the present study is to investigate the process of weld line elimination and the effect of weld line on the mechanical strengths of Zr–4 resistance upset welds in terms of tensile and burst tests, the shape of weld flash(or upset) and microhardness measurement. Microstructural change due to the welding currents by different setting of main heats was also examined.

2. Experimental Method

2.1 Materials and weld procedure

2.1.1 Materials

Zircaloy–4 tubes, typical of current heavy water reactor fuel cladding, with a nominal outer diameter of 13.08mm and a wall thickness of 0.42mm, 20cm long were used. They were stress–relieved at about 510–520℃ for 2 h. On the other hand, end caps were prepared by Zircaloy–4 rod which was fully annealed at 700℃ for 2h.

Two electrodes were used in the end cap welding. One electrode holding an end cap during welding was a Cu–Be alloy of RWMA (Resistance

Welder Manufacturers' Association) class 3 while the other electrode(or collet) clamping a tube was a Cu–30%W alloy of RWMA Class 12.

2.1.2 Welding equipment

A semi–automatic resistance upset welder equipped with a microprocessor which controls weld current, sequence and mechanical operation was used. The sequence of welding was performed by moving a weld head containing an end cap toward a tube at a very high deformation rate by a diaphram actuated by air cylinder. Thus, the high-velocity impact caused plastic deformation and the formation of weld upset. The amount of upset due to the formation of weld flash was measured by linear variable differential transducer (LVDT).

2.1.3 Welding conditions and specimen preparation

Fig.1 shows a schematic diagram of a straight butt joint design for end cap welding, in which ① represents a leg on the end cap and ② denotes a groove to accommodate the weld upset. In order to obtain uniform contact in a circumference between end cap and tube of unequal thickness during welding, the tube end was machined with 120° projection whereas the tip of end cap to be contacted with it was machined flat. All materials such as end cap, tube and electrodes were thoroughly cleaned with aceton and rinsed with water prior to welding to get rid of any contaminants which could affect the weld quality.

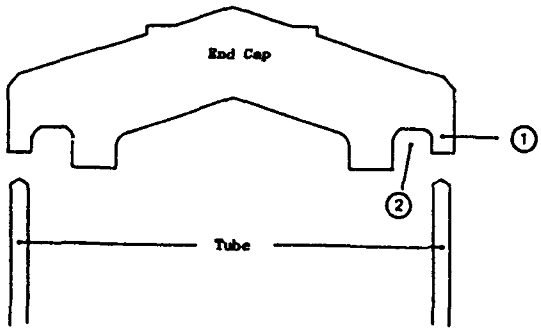


Fig.1 Schematic diagram of end cap welding design.

The welding cycle in the resistance welding consisted basically of such four phases as squeeze, preheating, main weld(or heat) and hold cycles as shown in Fig.2. The alternating 30 heating and cooling cycles were used to preheat the weld joint and 30 cycles of hold time was used to cool down the weld as well. In order to investigate the generation of weld line other welding parameters except main heat were fixed, in which only current was varied by setting the phase shift for heat control in the welding machine between 40% and 75%. To protect the weld from oxidation, helium gas was purged during welding and a weld squeeze force of 72KPa(10.5psi) was used.

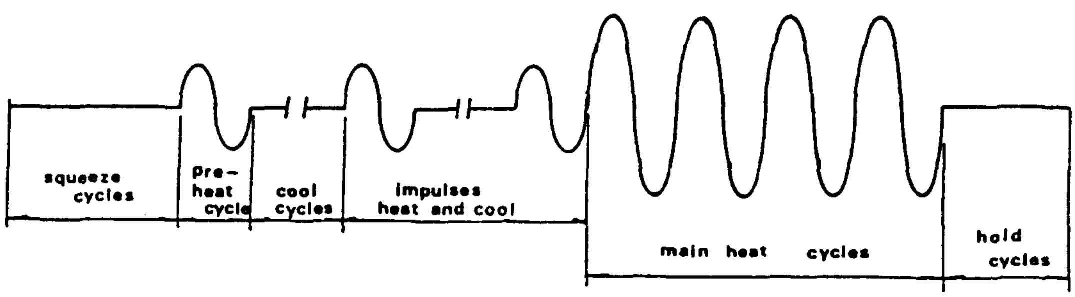


Fig.2 Weld cycle for end cap resistance upset weld.

Following welding, the outer weld flashes of all specimens were removed for mechanical tests.

2.2 Weld evaluation

2.2.1 Tensile and burst tests

A hole was drilled on end cap of closed-end tube and a 8cm long and 7mm in diameter screw bolt was inserted inside tube to be gripped on the tension machine. A solid steel rod was also inserted inside a tube not to be collapsed when it was gripped on tension test.

A 20cm-long closed-end burst test specimen was sealed with Swagelock pressure fitting and was then connected to the oil pressurization system. Internal pressurization was applied at a speed of 0.23MPa/sec until the specimen ruptured. Five specimens per weld condition were prepared for both tensile and burst tests.

2.2.2 Metallography and hardness test

In order to examine the shape of weld flash and weld line as a function of weld current, specimens were cut, etched in the chemical solution of 50% H_2O, 47% HNO_3, 3% HF(vol.%) and measured the unsound weld along the weld interface by a light microscope at 100 magnification and microstructure was examined. Fracture surfaces failed at the weld line and weld microstructure were also examined by a scanning electron microscope. Specimens for the metallography were also used to investigate the hardness variation of the weld heat affected zone(HAZ) by Knoop microhardness test with 500g load.

3. Results and discussion

Fig.3 shows the current variation and amount of upset as a function of the main heat by using the phase shift. The welding current increased with increasing main heat. The change of phase shift from 40% to 75% resulted in a current variation from 3.5KA to 10KA. A linear relationship between main heat, welding current and upset increment is clearly seen in Fig. 3. An increase of welding current also increased the weld upset which resulted in a decrease of specimen length.

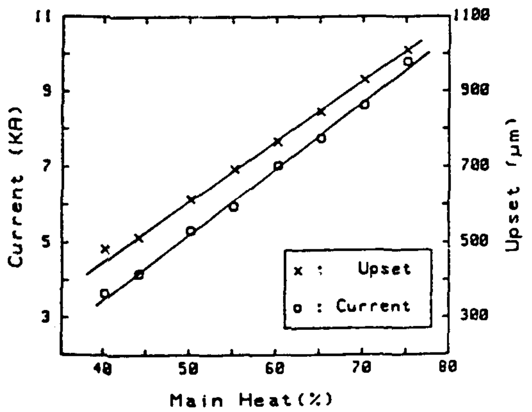


Fig.3 Effects of main heat on the weld current and the amount of upset.

In practice, it is very important for welding operators that proper welding currents should be chosen to make sound welds by adjusting welding parameters in the resistance upset welding. Based on data obtained from Fig.3, the effect of main heat on the weld current variation and upset reduction can be expressed as the following relationships.

$$I=0.17X-3.3 \quad (1)$$

$$L=15.8X-135 \quad (2)$$

where I is the actual weld current(KA), X is the main heat by phase shift(%) and L is the amount of upset(μm).

Fig. 4 shows the effect of main heat conditions on the sound weld in the end cap welds. The extent of weld line decreased drastically with increasing the main heat and was entirely eliminated at about 50% of it. The amount of sound weld increased continuously with the main heat, because the heat generation at weld zone was increased with the welding current by the following formula.

$$Q = I^2 Rt \qquad (3)$$

where Q=heat generated, joules, I=current, ampere, R=resistance of the work, ohms and t=time of current flow, seconds.

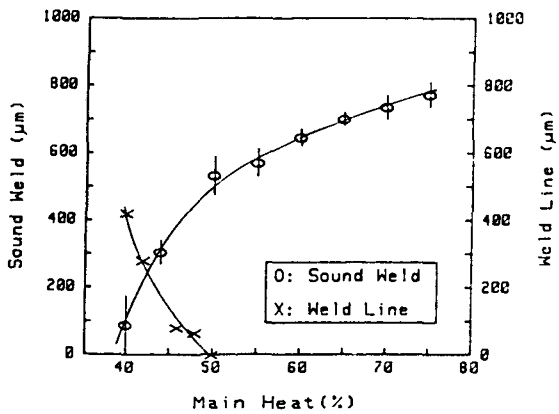


Fig.4 Effects of main heat on the sound weld in the end cap welding.

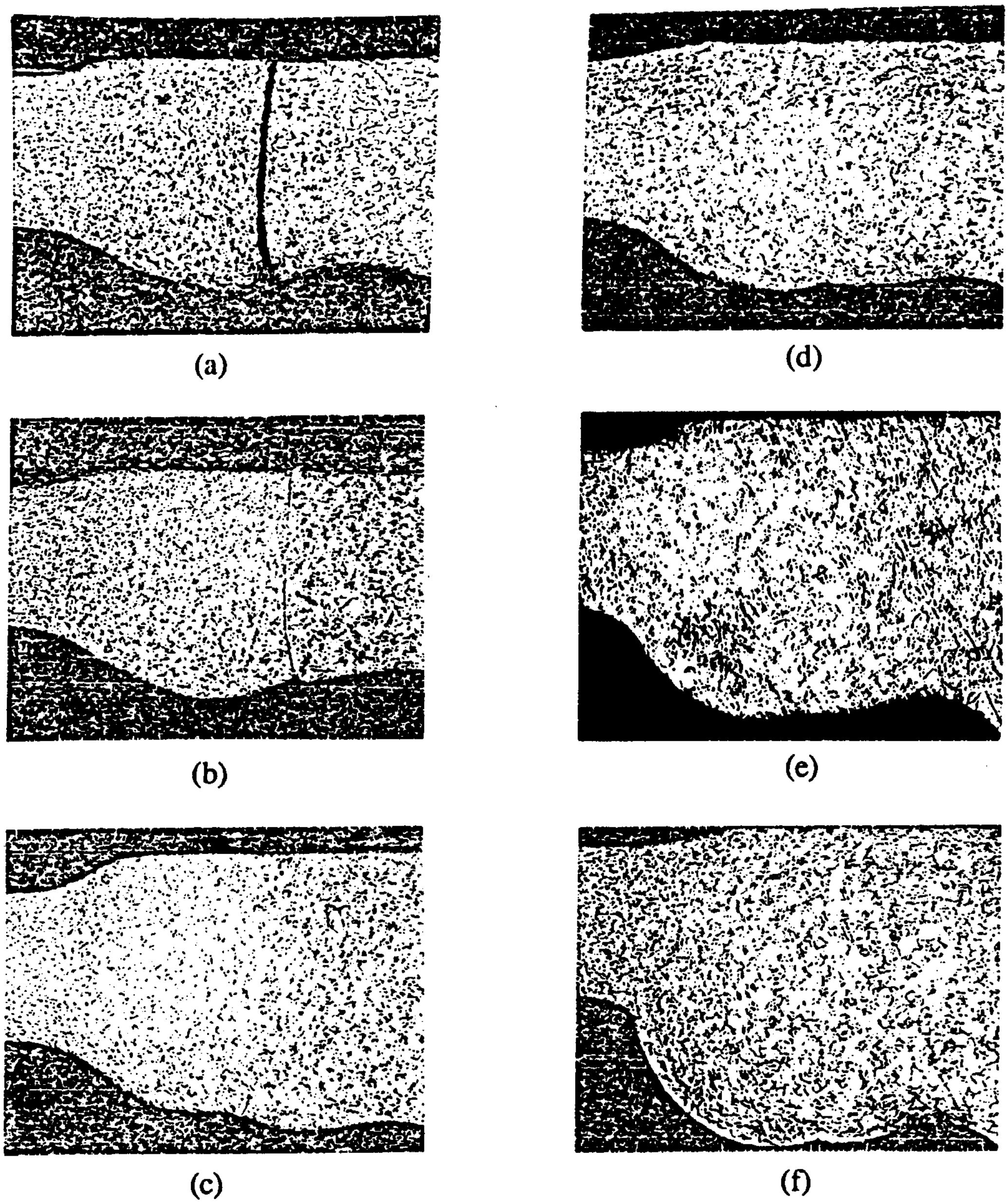
In general, the resistance upset weld is done in a very short time, much less than one second. From eq.(3), it is easily understood that weld current has a greater effect on the heat generation than either resistance or time. As the heat generation increases with increasing weld current, it can be expected that weld interface movement and void elimination at weld interface will be taken place by active atoms movement across weld interface and more plastic deformation will occur as well. This will be discussed later.

Fig. 5 shows the variation in the weld upset contour as a function of main heat from 40% to 75%. It is clearly seen that weld line exists up to 46% of main heat but suprisingly it disappears a great deal at 50% of main heat. It also shows that inner weld upset size increases with increasing main heat. It is, however, noted that the notch type contour at the boundary of weld HAZ/heat unaffected sheath as shown in Fig. 5 becomes smaller of its radius of curvature with increasing the main heat. Such a geometry of weld flash in the end cap weld would act as a stress raiser. We had also found that incipient cracks at the boundary of the weld HAZ/heat unaffected sheath of inner upset of weld occurred frequently in the process of manufacturing of end cap welds(9). It was found that the increase of welding current increased the amount of weld upset when other welding parameters were being equal.

The amount of sound weld of 420 μm corresponding to the nominal sheath thickness as shown in Fig.3 was obtained at 50% of main heat, in which weld line was almost disappeared as shown in Fig.5(c). Therefore, it was found that the main heat at 50% was threshold to obtain sound weld larger than wall thickness of sheath from Figs. 3,4 and 5.

Figs. 6 and 7 show the mechanical strengths of weld specimens as a function of main heat in terms of tensile and burst tests. Although the values of strength were different between two tests due to different modes of loading, they showed similar fashion in the curves that strength increased rapidly up to 50% of main heat, in which specimens ruptured at weld interface, but specimens ruptured in the heat unaffected sheath above 50% of main heat. Based on the results of mechanical strengths, it can be said that the weld heat to obtain good quality of sound weld should be above 50% of main heat and weld line along the weld interface also disappeared at the main heat as mentioned earlier.

As a result of the resistance upset welding, the weld upset became thicker than the wall-thickness of heat unaffected sheath due to the plastic deformation. Therefore, it was understandable that the weld upset could support higher loads than the heat unaffected sheath because it had a larger load supporting area. Specimens welded at the main heat below 50% were failed at the weld interface by both tensile and burst tests. This was resulted from a small portion of welded area



(a) 40% (b) 46% (c) 50%

(d) 55% (e) 65% (f) 75%

Fig.5 The varation of the weld upset contour with main heat.

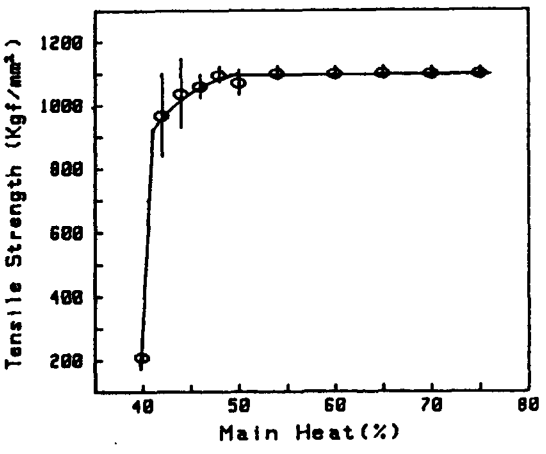


Fig.6 Tensile strength as a function of main heat.

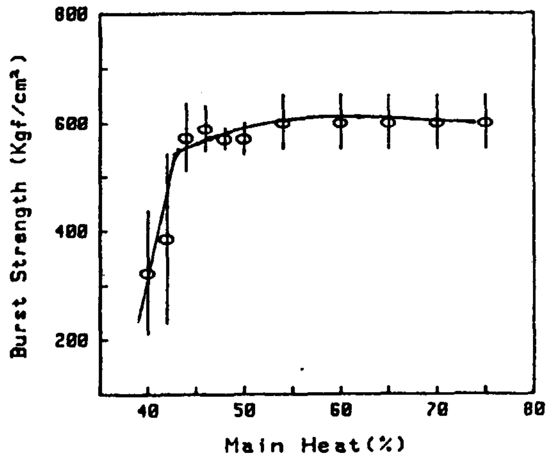


Fig.7 Burst strength as a function of main heat.

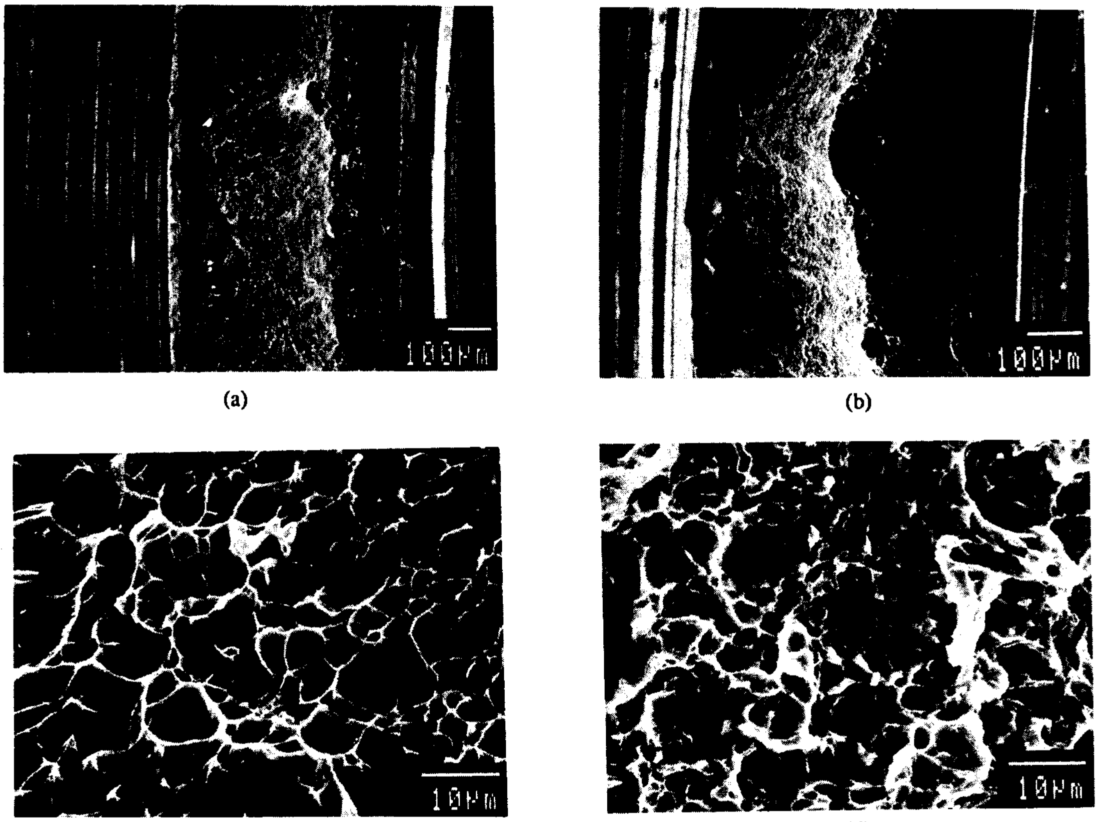
along the weld interface in a circumference. It was evident that such partially welded joints failed at lower tensile and burst strengths than those of heat unaffected sheath.

Fractographs in Figs. 8(a) and (b) show the partially welded HAZ in the weld joint at main heat below 50% in terms of tensile and burst tests. Both fractured surfaces show the ductile fracture of microvoid coalescence as shown in FIgs. 8(c) and (d). Dimples on uniaxially fractured specimen in Fig. 8(c) are larger and deeper compared with the biaxially fractured specimen in Fig.8(d). It was reported that HCP metals such titanium and zirconium were generally unaffected by the state of stress(10). It was, however, found in this study that the size and depth of dimple in the Zircaloy-4 resistance upset welds were decreased under a biaxial state of stress.

Fig. 9 shows the microstructure of weld joints at different main heats of 50%, 60% and 75%, respectively, in which any fusion zone is not observed in the weld. Fig. 9(a) shows weld microstructure at main heat of 50%. Small non-parallel α-plates appeared but they did not grow much because the peak temperature was low due to a low heat generation.

In the weld microstructure at main heat of 60% as shown in Fig.9(b), the weld HAZ comprised a mixed structure of paralled α-plates of Widmanstätten structure and non-parallel α-plates of basketweave structure in prior β grains, in which Widmanstätten structure was predominant. α-plates became larger due to a higher heat generation than the weld at 50% of main heat.

Fig. 9(c) shows needle-like martensitic α' and fine α-plates of Widmanstätten in prior β grains. A SEM micrograph shows clearly the mixed microstructure of both in Fig. 10. Judging from the weld microstructure, the peak temperature at main heat of 75% which could reach the upper region of β-phase field(>1400K) was higher than those of welded joints shown in Fig. 9(a) and (b), in which the peak temperature range would be a lower region of β-phase field(>1260 K)(11). Thus the cooling rate was also faster than other weld joints. The cooling rate from β phase of Zircaloy-4 in the resistance welding was reported to be approximately the order of 10^3 ℃/sec(12) even though we did not measure the heating and cooling rates. The weldment was heated above the β phase and was cooled over a range of cooling rates due to different main heats, so that different phase transformation products could be resulted in basketweave, Widmanstätten and mar-



(a) (b)

(c) (d)

Fig.8 SEM photographs showing weld joints failed at weld interface by (a) tensile, (b) burst tests and fracture surfaces by (c) tensile, (d) burst tests.

tensitic type of microstructures.

Hardness measurements across the sections of welds demonstrate that the hardness values of weld HAZ is higher than that of heat unaffected base metal as shown in Fig. 11. Even though there is some scatter in the hardness number as a function of main heat, the hardness of weld HAZ also increases with increasing main heat because a higher weld current generates a higher heat from the equation 3, and induces a faster cooling rates as mentioned earlier. Martensite and finer α –plates of Widmanstätten structures of weld HAZ at 75% of main heat raised its microhardness compared with that of the basketweave structure at 50% of main heat. The width of weld HAZ also increased with main heat because the weld HAZ at a given weld squeeze force was more deformed with increasing weld current.

The nature of the solid state welding process is, in essence, the coalescence of two solid surfaces. If the two solid surfaces are atomically flat and clean, these solids are welded spontaneously due to the interatomic force by elimination of the original weld interface. However, initial contact surfaces are rough and covered with thin oxide layer, so that cavities or pores remain along the original

(a)

(b)

(c)

Fig.9 Microstructures of Zircaloy-4 resistance upset welds as a function of main heat (X500).
(a) 50%, (b) 60%, and (c)75%

weld interface. Some workers have already proposed the solid state welding mechanism in terms of decreasing process of the interfacial energy caused by coalescence in the pressure welding(13) and the diffusion welding(14). In the resistance upset welding, however, the time of welding is very short and force is applied with a very high

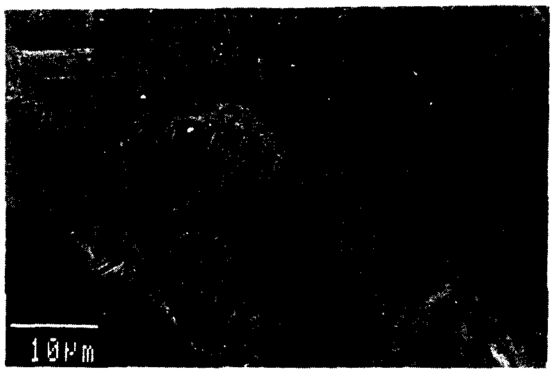
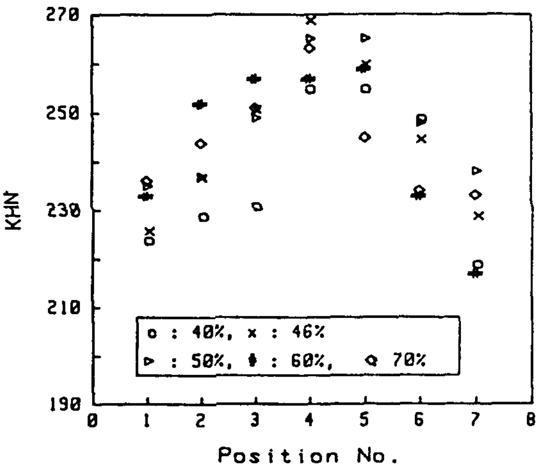


Fig.10 A SEM micrograph showing martensitic type and Widmanstätten microstructure in prior β grains.



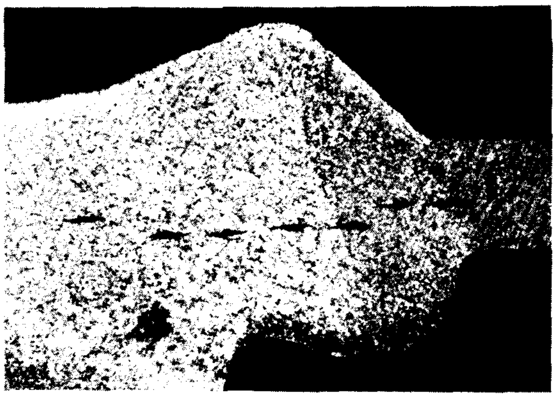


Fig.11 The variation of Knoop Hardness Number across a weld joint as a function of main heat.

deformation rate compared with the diffusion and pressure welding.

(a)
(b)
(c)

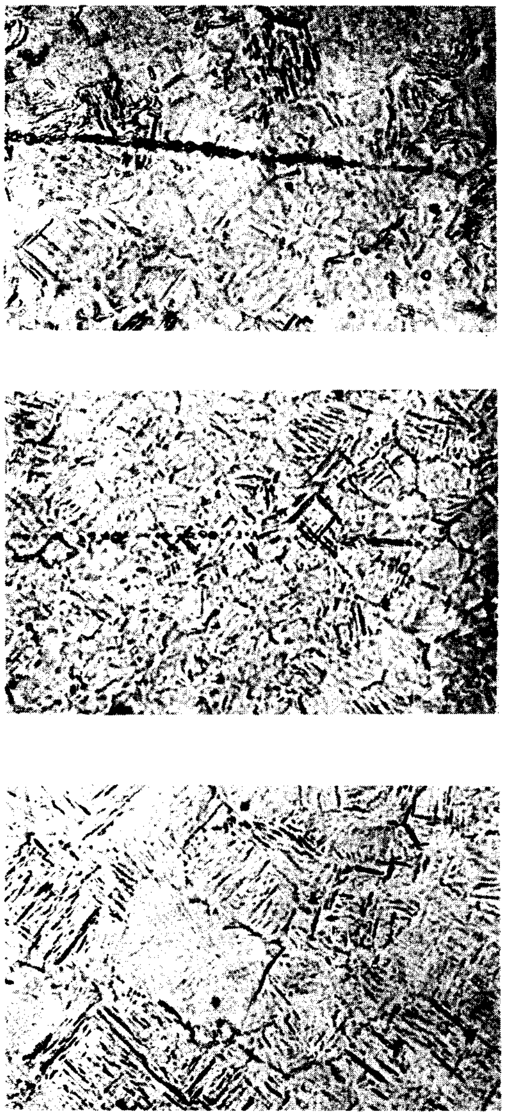


Fig.12 The elimination process of weld line in the Zircaloy–4 resistance upset welds as a function of main heat (X500).
(a) First stage(at 40%),
(b) Second stage(at 50%) and
(c) Third stage(at 70%)

The process of solid state welding we observed in this study consisted of the following three stages. Fig.12(a) shows the first stage of welding at main heat of 40%, in which many pores remain along the original interface resulting from the deformation of surface asperities. Some area of the surface to be welded is still not in contact because of the initial surface roughness, so that pores remain along the original weld interface. In the second stage shown in Fig.12(b), the shrinkage and the elimination of pores occurred simultaneously. In this stage, it seems that atoms move more actively across weld interface due to higher heat generated at a main heat of 50% but some pores still remain along the weld interface. In the third stage shown in Fig.12(c), at main heat of 75%, all pores on the original weld interface shrink and most of them are eliminated due to more active atom movement and grain boundary migration. We did, however, not observe the grain boundary migration at a squeeze force because the weld time was very short. When a sufficient plastic deformation occurs, during the upsetting operation in the resistance welding, as a combination of welding current and squeeze force, the two original contact areas including many pores are squeezed out to the weld flash and the extent of weld line drastically decreases with weld current as shown in Figs.5 (a), (b), and (c). But pores caught in the weld interface shrink and are eventually eliminated by the diffusion–controlled process in a similar way with the solid state welding process(13,14). Also, the weld line elimination process could be activated by the diffusion along dislocation due to the plastic deformation.

Conclusions

1. In the resistance upset welding, the weld current and the amount of upset increased linearly with increasing welding main heat from 40% to 75%, in which two relations between them were derived.
2. The threshold of main heat to obtain sound

weld was 50% in terms of weld upset size, mechanical strengths and elimination of weld line.

3. Fracture surfaces of Zircaloy-4 resistance upset welds failed at weld line by uniaxial tensile mode showed larger and deeper dimple rupture than those by biaxial burst loading mode.
4. Zicaloy-4 welds showed a variety of microstructure of basketweave, Widmanstätten and martensitic type as a function of main heat. This was due to the different peak temperatures and cooling rates of weld joints.
5. The process of weld line elimination in the resistance upset welding was similar with those of pressure and diffusion welding in spite of a very short welding time and a very high deformation rate.

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