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# Effect of irradiation dose on mechanical properties and fracture character of Cu//SS joints for ITER

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**Abstract**

Cu//SS type joints are essential for the heat-sink systems of the ITER high-heat flux components. A number of technologies have been proposed for the production of such bimetallic structures, including brazing, friction welding, HIP and cast-copper-to-steel. In this paper, the authors present the results of investigations into the irradiation resistance of GlidCopAl25//316L(N) and CuCrZr//316L(N)-type joints produced by the HIP and cast-copper-to-steel (CC) technologies. Specimens of the joints were irradiated in the RBT-6 reactor in the dose range of $10^{-3}$–$10^{-1}$ dpa at $T_{irr} = 150$ °C. Irradiation causes strengthening of the joint specimens and the uniform elongation drops from 7% in the initial state to 1–2%. However, the total elongation remains at the relatively high level of ~10%. The investigations performed make it possible to recommend joints of CuCrZr//316L(N) (CC) and CuCrZr//316L(N) (HIP) type produced by the cast-copper-to-steel and HIP technologies, respectively, for ITER applications.


## 1. Introduction

Cu//SS type joints are essential for the heat-sink systems of the ITER high-heat flux components. A number of technologies have been proposed for the production of such bimetallic structures, including brazing, friction welding, HIP and cast-copper-to-steel [1–4]. The last two mentioned technologies ensure sufficiently high mechanical properties and a high joint quality, when unirradiated. However, data on the irradiation resistance of joints are scarce.

In 1998–2000, data were obtained on the radiation resistance of the first-generation joints of CuCrZr//316L(N) and GlidCopAl25//316L(N) type as applied for ITER. Irradiation to 0.2–3 dpa at 150 and 300 °C caused significant embrittlement of the joints [5,6]. It was shown that the uniform elongation of the joints is decreased to ~1% even at doses of 0.2 dpa and changed only slightly with further increase in the dose. Physically, loss of ductility saturation is explained by the fact that for copper based alloys hardening and loss of ductility are saturated at doses of ~0.1 dpa [7,8]. As for steel, this dose is about 10 dpa, i.e. much higher. In

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irradiated Cu//SS joints the deformation is localized mainly in the copper part of the specimen, hence the behavior of the joints under irradiation is determined, first of all, by the radiation resistance of the copper based alloy.

In view of the above, it would be reasonable to determine the radiation resistance of the joints in the dose range of $10^{-3}$–$10^{-1}$ dpa, where their properties should change. Such experiments will make it possible to obtain the dose dependence of the main mechanical properties of joints and to estimate the level of their properties at a dose of $\sim 10^{-1}$ dpa, at which the irradiation effects are saturated.

Reasoning from the above, the authors examined radiation resistance of a new-generation Cu//SS joints. Specimens of the GlidCopAl25//316L(N) and CuCrZr//316L(N)-type joints produced by the HIP and cast-copper-to-steel (CC) technologies were irradiated in the RBT-6 reactor in the dose range of $10^{-3}$–$10^{-1}$ dpa at $T_{irr} = 150$ °C.

## 2. Experimental procedure

Three variations of Cu//SS joints were investigated in this work: CuCrZr//316L(N) joints manufactured in the EU by hot isostatic pressing (HIP), GlidCopAl25//316L(N) HIP joints manufactured in the EU and CuCrZr//316L(N) joints manufactured in the RF, by cast-copper-to-steel (CC). Details of the manufacturing technologies are presented in [9,4].

Specimens of Cu//SS joints were irradiated in the RBT-6 reactor in irradiation facilities SMM01-1; SMM01-2; SMM01-3. Flat specimens for tensile testing (1 mm in thickness) (STS type) were irradiated in tight helium-filled subcapsules.

The irradiation doses in the RBT-6 reactor amounted to $10^{-3}$; $10^{-2}$; $10^{-1}$ dpa. Irradiation temperature, as recorded by thermocouples, was $150 \pm 8$ °C. Different doses were attained by varying the irradiation time, i.e. 24 h; 240 h; 1500 h. Average ratio between thermal and fast neutrons in the RBT reactor was $\Phi t_{therm}/\Phi t_{fast} \sim 1.04$. The irradiated and initial specimens were tested in tension ($\varepsilon \sim 1.66 \times 10^{-3}$ s$^{-1}$) at 150 °C. The character of joint fracture was investigated by optical microscopy and SEM.

## 3. Results

Fig. 1 shows the yield strength (a) and total elongation (b) of joints as a function of the testing temperature. For comparison purposes, Fig. 1 presents the properties of CuCrZr and GlidCopAl25 base alloys produced on samples cut directly from the joints.

It is evident that the GlidCopAl25 base alloy is characterized by higher strength and ductility than the GlidCopAl25//316L(N) joints. The CuCrZr base alloy has much higher ductility and lower strength than the CuCrZr//316L(N) joints. On the whole, all joints have demonstrated sufficiently high strength properties $\sigma_u > 200$ MPa and satisfactory plastic properties $\delta_{tot} > 7\%$. Study of the fracture character of unirradiated joints revealed that all joints fail only in the copper part of a specimen at a distance of 2–3 mm from the joint line (see Fig. 1(a)). The fracture is of ductile transcrystalline character.

Study of the joint structure by the optical microscopy revealed (Fig. 2(a) and (b)), that HIP and CC technology cause considerable grain growth in the CuCrZr alloy (to $\sim$200 μm at HIP and 400 μm at CC). In GlidCopAl25//316L(N) joints no grain growth was observed in GlidCopAl25. An average grain size in 316L(N) steel in the joint is $\sim$80 μm. Study of deformed specimens of the joints revealed that plastic deformation is obtained in the copper and steel parts of specimens (Fig. 2(c) and (d)) and, what is particularly important, the deformation proceeds through the joint line zone. As a result, the joint line is free of cracks (Figs. 2(e) and (f)). In the CuCrZr alloy a noticeable contribution of intergranular sliding to deformation is observed even at $T_{test} = 150$ °C (Fig. 2(d)), causing massive grains to rotate relative to each other. Twins are also observed in the structure of CuCrZr alloy (Fig. 2(d)).

On the whole, the results of the studies of the unirradiated state allow the conclusion to be made that new-generation joints produced by HIP and CC technologies have a good level of strength and ductility and, what is important, good properties in the joint zone. Even at considerable plastic deformation more than 15% and high stresses $\sigma > 200$ MPa no detachment occurs in the joint zone and fracture is localized at a sufficient distance from the joint line.

### 3.1. Irradiated condition

Fig. 3 presents typical engineering stress–strain curves for CuCrZr//316L(N) and GlidCopAl25//316L(N) joints, when unirradiated and irradiated

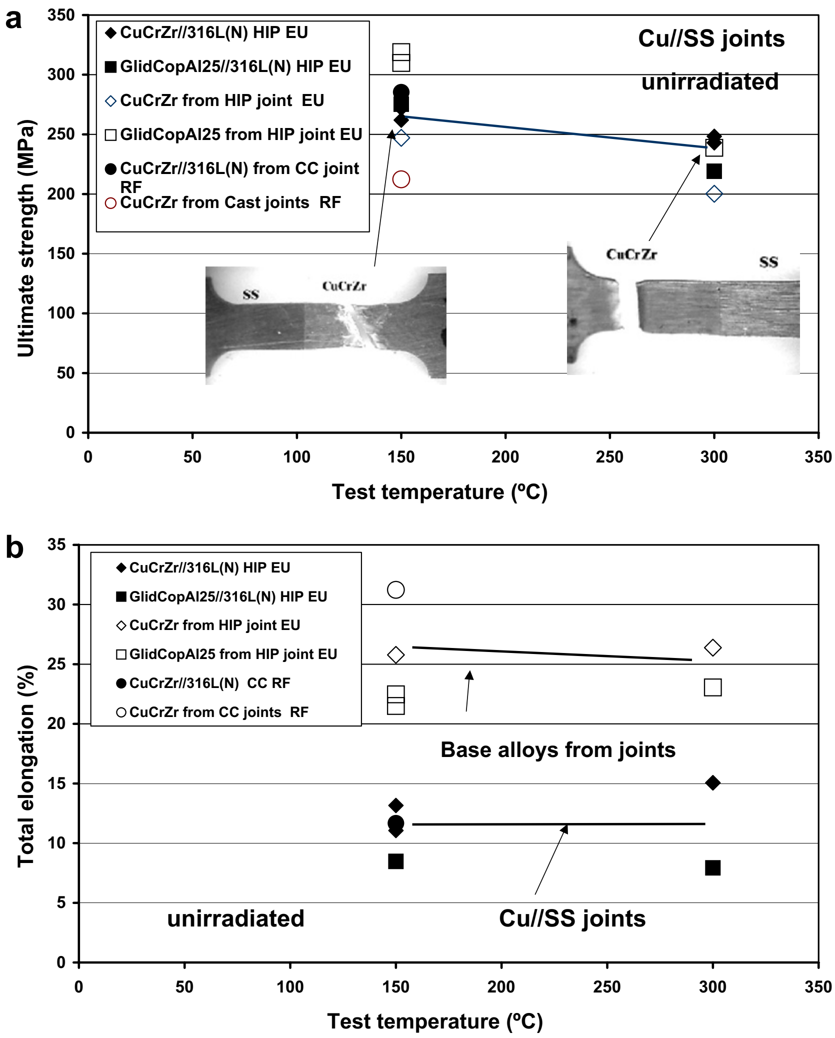


Fig. 1. Ultimate strength (a) and total elongation (b) versus test temperature for CuCrZr//316L(N) HIP EU, CuCrZr//316L(N) CC RF and GlidCopAl25//316L(N) HIP EU joints, unirradiated condition.

by neutrons. For comparison purposes, these figures present the stress–strain curve for CuCrZr and GlidCopAl25 base alloys produced on specimens cut from the joints.

### 3.2. CuCrZr//316L(N) joints

CuCrZr//316L(N) joints have half as much ductility as that of the base alloy and a higher strength. This is evidence that the processes occurring in the stronger steel part of a specimen contribute to hardening of the Cu//SS joints, as seen in Fig. 2(c). An increase in the irradiation dose results in hardening of the joints and a considerable reduction in their uniform elongation. The total elongation is also decreased but substantially less.

### 3.3. GlidCopAl25//316L(N) joints

GlidCopAl25//316L(N) joints, when unirradiated, show much lower strength and ductility than GlidCopAl25 base alloy (Fig. 3(b)). The reason is that 316L(N) steel has much lower yield strength and, hence, the deformation in GlidCopAl25//316L(N) joints sample starts in steel. To investigate geometry effects, a base alloy specimen was cut along the joint plane and a joint specimen across the joint plane. As reported earlier [10] for

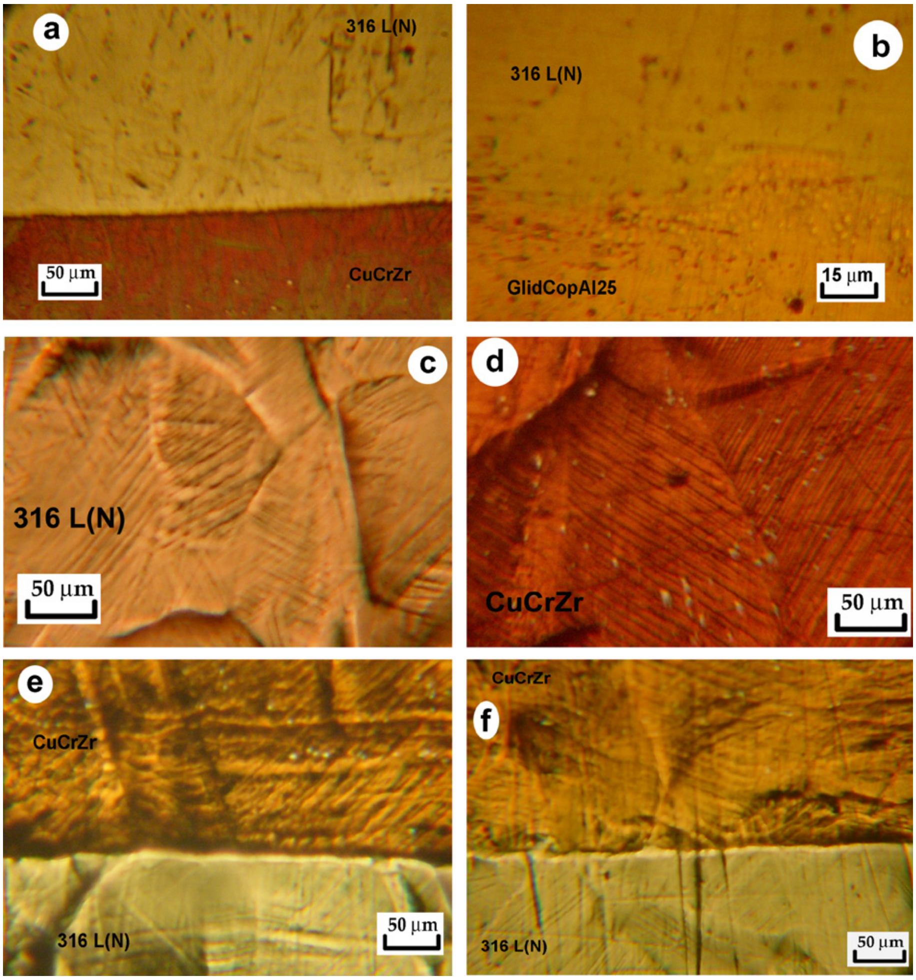


Fig. 2. Structure of CuCrZr//316L(N) (a) and GlidCopAl25//316L(N) (b), HIP EU joints, deformation processes in Cu part and SS part of samples of CuCrZr//316L(N) HIP EU joints, $T_{test} = 150$ °C (c)–(f), unirradiated condition.

GlidCopAl25, these directions, i.e. along and across the cross-rolled direction, differ in $\sigma_u$ by about 50 MPa, as seen in Fig. 3(b).

Irradiation leads to hardening and a decrease in both total and uniform elongation of GlidCopAl25//316L(N) joints. At the maximum irradiation doses the strength properties of the GlidCopAl25//316L(N) joints is appreciably higher (by 30 MPa) than in CuCrZr//316L(N) joints.

Fig. 4(a) and (b) show the dose dependence of the ultimate stress, as well as the total elongation for all joints investigated in our work.

The ultimate stress of the joints (Figs. 4(a) and (b)) rises monotonically with the dose, and radiation hardening reaches ~80 MPa at a dose of 0.07 dpa. This value coincides with that of hardening for CuCrZr alloy observed under the same conditions [11]. The uniform and total elongation of all joints is monotonically decreased with increasing the dose to the values $\delta_{unif} > 0.5\%$, $\delta_{tot} > 4\%$.

The fracture character of irradiated joints is, on the whole, similar to that for unirradiated joints. The irradiated joints fail, as a rule, in copper alloy well apart (1–3 mm) from the joint line (Fig. 4(a)). But in irradiated CuCrZr//316L(N) CC, the joints fracture was sometimes observed in the joint zone at $T_{test} = T_{irr} = 150$ °C.

Study of the fracture surface of the tested irradiated joints of CuCrZr//316L(N) and GlidCopAl25//316L(N) type revealed that they fracture, on the whole, in a ductile transcrystalline way (Fig. 4(b)).

A comparison between the fracture character of the joints based on CuCrZr and GlidCopAl25

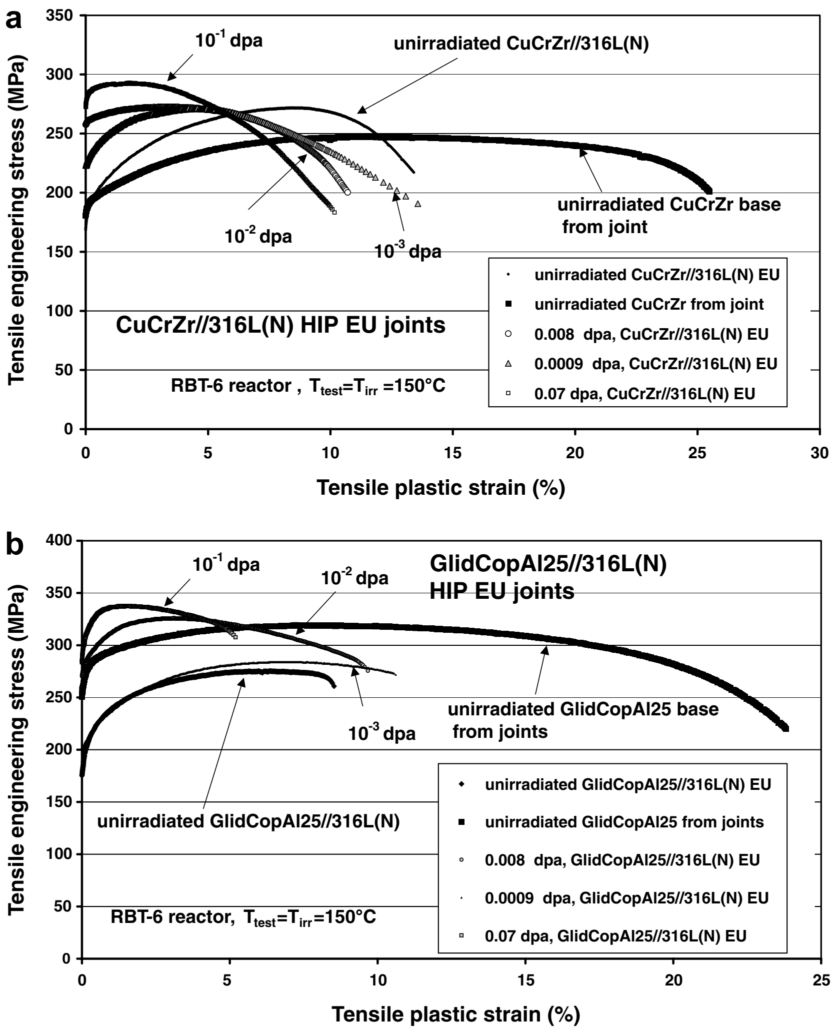


Fig. 3. Effect of neutron irradiation on engineering stress–strain curves of CuCrZr//316L(N) HIP EU joints (a) and GlidCopAl25//316L(N) HIP EU joints (b), $T_{test} = T_{irr} = 150$ °C.

shows that CuCrZr//316L(N) joint is characterized by a considerable neck developing in the copper part of a specimen. Considerable plastic deformation is observed on the fracture surface. An average diameter of a dimples is ~5–10 μm (Fig. 4(b)).

The irradiated GlidCopAl25//316L(N) joints are characterized by fracture with little necking. Plastic deformation of the fracture surface is less. An average diameter of dimples is about 2–3 μm (Fig. 4(b)). By and large, the CuCrZr-based joints fail in a more ductile manner than those based on GlidCopAl25.

## 4. Discussion

The data obtained make it possible to compare the radiation resistance of the CuCrZr//316L(N) and GlidCopAl25//316L(N) joints. At first glance, both types of joint behave quite similarly under irradiation. The yield strength and ultimate stress of the joints increase with increasing irradiation dose, and the total and uniform elongation is decreased (Fig. 3). But close inspection of the fracture character of CuCrZr//316L(N) and GlidCopAl25//316L(N) joints shows differences. The SEM microscopy of tested specimens confirms that in the CuCrZr//316L(N) joints a marked neck is formed and RA is ~60–80%. In GlidCopAl25//316L(N) joints the neck is practically absent and RA is ~10–30% (Fig. 4(b)).

Previously, when analyzing the effect of the GlidCopAl25 alloy texture on the mechanical properties, the authors reported that the alloy has very low

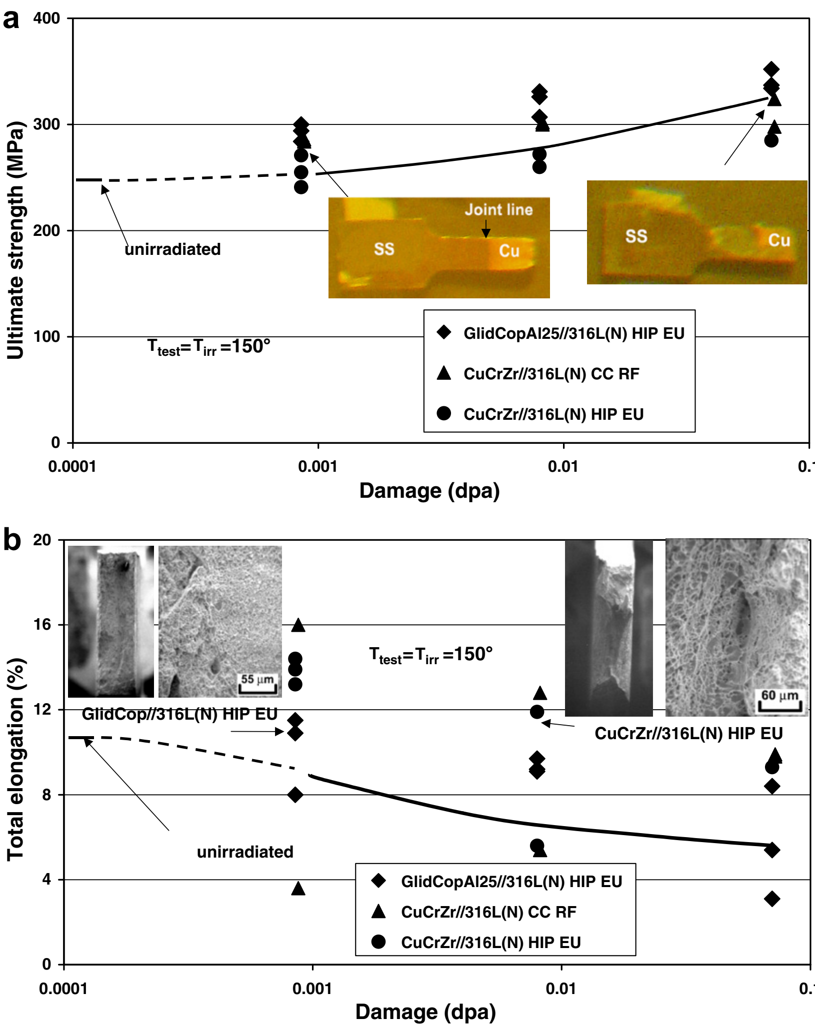


Fig. 4. Dose dependence of ultimate strength (a) and total elongation (b) of CuCrZr//316L(N) HIP EU joints, CuCrZr//316L(N) CC RF joints and GlidCopAl25//316L(N) HIP EU joints, $T_{test} = T_{irr} = 150$ °C.

local deformation in the cross-rolled direction [10]. It is likely to be associated with peeling microcracks open under stress. Specimens of the joints are cut precisely in this direction (normal to cross-rolled). In specimens cut along the rolling direction (base alloy specimens) these cracks do not grow, as they are aligned with the acting stress.

A weak capability for local deformation usually correlates with a low fracture toughness and the GlidCopAl25 alloy ranks below CuCrZr alloy in fracture toughness as shown by Tathinen et al. [12].

Thus, the behavior of CuCrZr//316L(N) and GlidCopAl25//316L(N) joints under irradiation is similar, on the whole, to that of copper base alloys. In this case the texturing of the GlidCopAl25 alloy determined by the manufacturing technology results in a decrease in the total elongation and limited deformation in the neck of the GlidCopAl25//316L(N) joint.

A three-dimensional simulation of the stress–strain state of the joints shows that during a tensile test the stresses are concentrated in the joint line zone. But the high strength properties of the joint zone cause the localization of deformations and fracture not in the joint line but in the copper part of the specimen at a distance of 1–3 mm from the joint line.

A comparison between the radiation resistance of the joints produced by HIP and CC methods shows that the joints produced by the CC technology are stronger and less ductile than those produced by the HIP technology.

## 5. Conclusions

The studies carried out have shown that recent joints of CuCrZr//316L(N) and GlidCopAl25//316L(N) type produced by the HIP and CC methods have high strength properties and satisfactory ductility after neutron irradiation to doses of $10^{-3}$–$10^{-1}$ dpa at $T_{irr} = T_{test} = 150$ °C. The Cu//SS joint is high-quality and does not fracture at a total specimen deformation of ~15%. In this case, the deformation proceeds in both parts of bimetallic specimens and in the joint line zone itself.

Neutron irradiation results in hardening and embrittlement of joints qualitatively and quantitatively similar to those observed in copper base alloys. Radiation resistance of joints of CuCrZr//316L(N) HIP and GlidCopAl25//316L(N) HIP type is nearly the same. Joints of CuCrZr//316L(N) HIP type are advantageous in their capability for high local deformation in the neck, including in the irradiated condition. The lower capability of GlidCopAl25//316L(N) HIP joints for local deformation is associated with anisotropy of the properties of this base alloy.

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