Accumulation of stress in constrained assemblies: novel Satoh test configuration

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A common test used to study the response of a transforming material to external constraint is due to Satoh and involves the cooling of a rigidly constrained tensile specimen while monitoring the stress that accumulates. Such tests are currently common in the invention of welding alloys which on phase transformation lead to a reduction in residual stresses in the final assembly. The test suffers from the fact that the whole of the tensile specimen is not maintained at a uniform temperature, making it difficult to interpret the data. To eliminate this problem, the authors report here a novel Satoh test in which the material investigated is a part of a composite sample. It is demonstrated that this helps avoid some of the complications of the conventional tests and gives results which are consistent with independent tests.

Keywords: Satoh test, Residual stress, Welding alloys, steels

There has been considerable recent effort to develop weld metals which when used to join steel, are able to exploit the shape deformation due to solid state phase transformations to compensate for the stress that develops as the welded structure cools.[1–18] The method relies on an old experiment carried out by Jones and Alberry,[19] where a steel tensile test sample in its austenitic state is rigidly constrained and then allowed to cool; thermal contraction leads to an accumulation of stress during cooling, but the stress is relieved when bainite or martensite forms (Fig. 1). If the transformation is exhausted before ambient temperature is reached then the stress once again accumulates due to thermal contraction. Thus, the primary design criterion for a compensating weld metal is to suppress the transformation temperature sufficiently so that the sample is left in a state of zero stress once cooling is completed.

Such an experiment is known as a Satoh test.[20] It is necessary to heat the sample in order to conduct the experiment and one difficulty is that the heating is localised on a gauge length so that the temperature is not uniform along the sample depending on the technique used; the sample grips are of course maintained at a low temperature, using water cooling. The material being tested therefore inevitably experiences temperature gradients (Fig. 2) and in consequence, a range of transformation temperatures. The test temperature measured, usually with one thermocouple at the centre of the gauge length, does not therefore reflect the events occurring elsewhere. On the other hand, the recorded load is due to the behaviour of the entire sample. This discrepancy between the recording of stress and temperature is particularly important in the design of welding alloys, where as stated before, a key design parameter is the transformation temperature under the influence of constraint. These difficulties also make it unlikely that Satoh tests conducted using different heating systems give comparable results.

The authors propose in this work a modified Satoh design which overcomes these issues by ensuring a homogeneous temperature and stress within the test material. The concept involves the bonding of two pieces of non-transforming metal to the test material, with the latter being of a length which is smaller than the uniform temperature zone in the test sample used (Fig. 3).

A new martensitic welding alloy has recently been developed for the purposes of mitigating weld residual stresses;[15] this was machined into a disc of 10 mm diameter and 5 mm thickness. Nickel base superalloy IN617 was machined into the two end rods with the same diameter. This alloy has a thermal expansion coefficient of 12×10^{-6} K^{-1}.[21] The faying surfaces of all the samples were cleaned using a gallium assisted polishing method described elsewhere.[22] Solid state bonding was carried out in a vacuum, at 1050°C under 5 MPa for 30 min. There is no interlayer used for solid state bonding so the test material composition remains unaffected by the bonding process. Three 1·5 mm diameter Satoh samples were then electrodischarge machined out of the bonded bimetallic specimen.

A thermomechanical fatigue testing machine was used as illustrated in Fig. 2. The sample was heated by induction to 800°C for 2 min. The machine was programmed to keep the load at zero by compensating for the thermal expansion of the sample during heating. The grips were then locked just before switching off the heating system. The results are illustrated in Fig. 4 for two cases, one where the entire sample is made using the weld alloy, and the other with the bimetallic configuration where the slice of the test material itself is fully immersed in the

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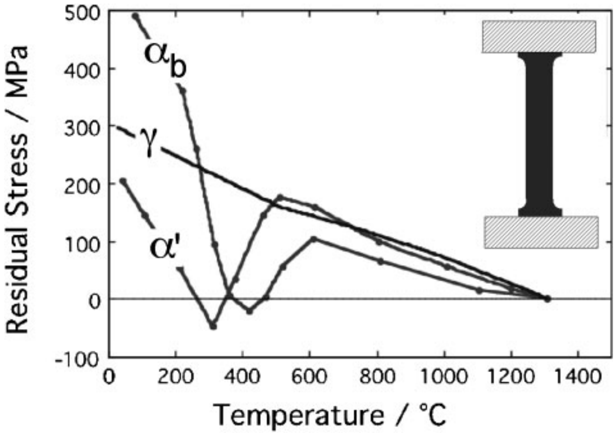
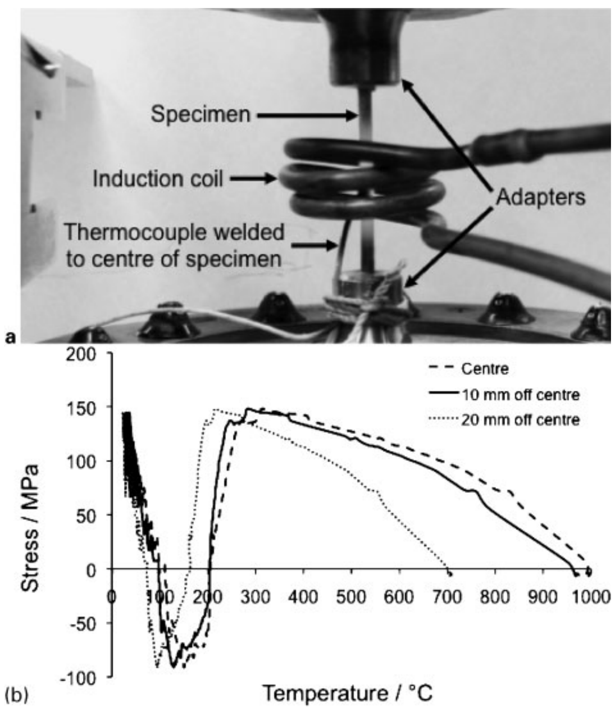
Published by Maney on behalf of the Institute
Received 22 March 2009; accepted 24 May 2010
DOI 10.1179/136217110X12731414739998



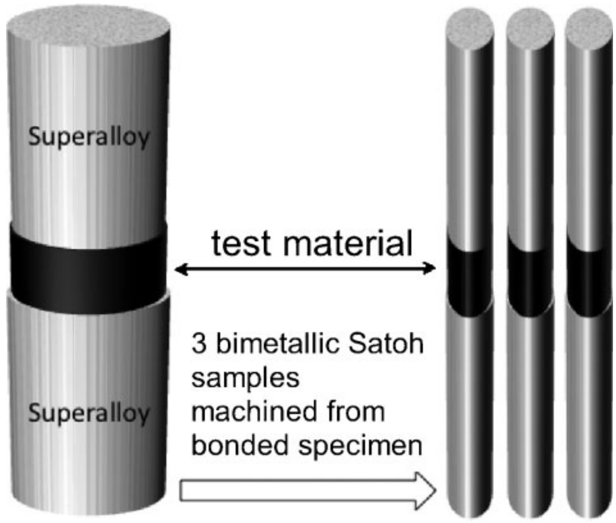
1 **Development of stress as tensile test sample which is austenitic at high temperatures is constrained (inset) and then allowed to cool:[19] sample labelled γ remains austenitic (γ) at all temperatures, whereas other two transform either into bainite (α_b) or (α')**

uniform hot zone whereas the gradients in temperature exist only in the non-transforming superalloy.

Both samples show the evolution of stress as they cool under constraint, with the stress being relieved as the weld alloy undergoes martensitic transformation. It is interesting that the monolithic sample apparently begins to transform at a temperature a little in excess of 300°C, but this is a reflection of the fact that the colder regions of the sample transform first whereas the temperature is measured in the centre of the hot zone. The independently measured martensite start temperature of the alloy is in fact 216±2°C,[15] which is consistent with the onset of stress relief in the bimetallic sample at temperatures in the range 225–230°C (Fig. 4).



2 ***a* Satoh test in progress: gradient of colour along length of sample is due to variations in temperature; these gradients compromise relationship between recorded stress and temperature, and *b* variations along length of sample**



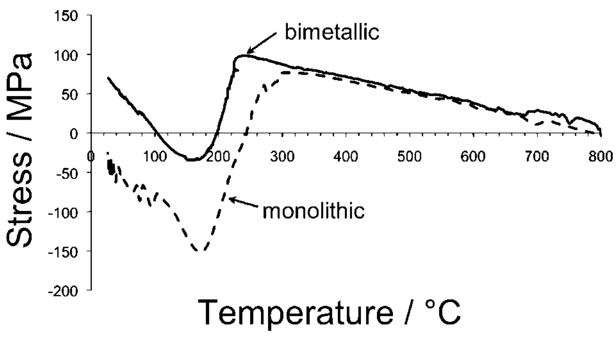
3 **Bimetallic specimen made by diffusion bonding non-transforming nickel superalloys to test material (steel weld metal) followed by electrodischarge machining into three Satoh samples**

The bimetallic sample shows a greater level of stress at room temperature, primarily because the transforming material is a fraction of the entire sample and of the region which experiences heating. The superalloy component which is the greater proportion contributes only to an increase in stress through thermal contraction. This is why both specimens behave almost identically until the onset of phase transformation.

There are other variants of the new configuration which could be explored in the future. The end rods could be made of Invar[23] which has a zero thermal expansion coefficient so that only the effect of the test material (e.g. a welding alloy) is manifested in the output. In simulating a real weld, the end rods could be made from the plates intended for welding, and the test material of the weld metal. This may give a more realistic simulation of the development of stress in practice, although it is appreciated that the sample geometry here is simple in comparison.

Acknowledgement

The authors are grateful for support from the UK. Ministry of Defence and also thank Dr L. Karlsson of ESAB AB in Sweden for the provision of the welding alloy.



4 **Satoh tests on martensitic weld alloy[15] using bimetallic sample, and one manufactured entirely from test alloy**

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