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ScienceDirect

Procedia Manufacturing 37 (2019) 627–632

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

9th International Conference on Physical and Numerical Simulation of Materials Processing (ICPNS'2019)

Modelling and design of new stainless-steel welding alloys suitable for low-deformation repairs and restoration processes

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Abstract

The plasticity associated with low-temperature martensitic transformation can be exploited to reduce the stresses developed due to thermal contraction of the weldments. The key feature of stress-mitigating welding alloys is their transformation from austenite to martensite at low temperatures *e.g.* ideally close to ambient temperature. Thermodynamics databases (MTDATA and SGTE) were used to model and design new welding alloys with low martensitic transformation temperatures (Ms) around 200 °C. The modelling, conducted in this work, was based on this assumption that martensitic transformation starts at a certain temperature when the free-energy change for austenite to transform to ferrite reaches a critical value. Since martensitic transformation is a diffusion-less process, the change in free-energy vs. temperature was calculated for the austenite and ferrite phases with the same composition.

Three prototype welding alloys, *CamAlloys 4 & 5* and *OpenAlloy 1*, were successfully designed and made in the University of Cambridge (UK) and the Open University (UK). The design of these alloys was purely based on thermodynamics equations. Comprehensive characterisation, examinations and mechanical tests showed this family of alloys could substantially reduce contraction-induced deformations in stainless steel weldments. One of the applications of these alloys is in the repair and restoration of damaged stainless-steel components.

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2351-9789
10.1016/j.promfg.2019.12.099

Keywords: Residual stress, Stainless steel weld, Phase transformation, Transformation plasticity

1. Introduction

Fusion welding processes are associated with thermal shrinkage when the weldment is cooled to the room temperature. Thermal shrinkage builds up tensile residual stresses within the fusion zone (weld bead) and surrounding base material (heat affected zone). The extent and severity of the residual stresses depend on many parameters including the nature and intensity of the heat source used, *e.g.* electro-discharge arc, flame, laser or electron beam. Nevertheless, the presence of such undesirable residual stresses is inevitable when using conventional filler metals. Previous work showed that martensitic transformation of purpose-designed filler metals can mitigate tensile residual stresses during fusion welding of ferritic as well as austenitic steels [1].

The key criterion, when designing a stress-mitigating filler metal, is to attain an optimum martensite start temperature. High martensitic transformation temperatures would result in an early completion of the transformation, consequently re-generation of residual stresses as the martensitic phase contracts until it reaches ambient temperature. On the other hand, if the martensitic transformation starts below ambient temperature, the strain compensation effect of the filler metal cannot be fully exploited. Thermodynamics databases (MTDATA and SGTE) were used to design new welding alloys with low martensitic transformation temperatures around 200 °C (Ms). *CamAlloy 4* was the first corrosion resistant stainless-steel filler metal which was designed to mitigate residual stresses in large weldment where post-welding heat treatment is not practical [2]. More recently, un upgraded versions of *CamAlloy 4* (*i.e. CamAlloy 5* & *OpenAlloy 1*) have been developed in order to enhance the strain-reducing effect by further reduction in the martensitic transformation temperature. Given the higher amount of costly alloying elements in *CamAlloy 5* & *OpenAlloy* 1, their main application is in low-deformation repairs and restoration processes.

2. Alloy design criteria

CamAlloy 4 and newly designed *CamAlloy 5* & *OpenAlloy 1* should be martensitic stainless-steels with the lowest carbon content possible, in order to prevent formation of intergranular chromium carbide during welding process – also known as "sensitization" which can reduce the toughness and corrosion resistance of the welded stainless-steels. Meanwhile, chromium concentration must not be below 12 wt.% to ensure high corrosion resistance of the filler metal due to the formation of native chromium oxide on its surface. However, reduction in carbon content would substantially push up the martensitic transformation temperature. Therefore, addition of other elements, such as Cr, Ni and Mo, was considered to suppress the transformation temperature. The target transformation temperature was about 190 to 200 °C for *CamAlloy 4* & *CamAlloy 5*, respectively. The effects of alloying elements on the martensitic transformation temperature of these alloys, calculated using thermodynamics databases, are shown in **Figure 1.**

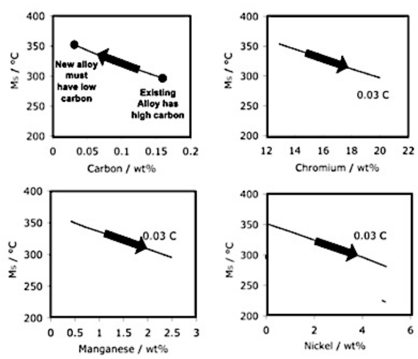

Fig. 1. Martensitic-transformation temperature can be suppressed by addition of Cr, Ni and Mn to ultra-low carbon stainless-steel welding alloys.

Besides, in order to fully exploit transformation plasticity, the alloy must be capable of becoming fully austenitic at high temperatures. This imposes an additional restriction on the use of ferrite-stabilizing elements such as chromium. Initial calculations showed that the chromium content should not exceed 13% despite its desirable effect on reducing martensitic transformation temperature.

Vulnerability of welds to hot-cracking depends on the solidification mode and the impurity content (*e.g.* S, P). If the liquid weld solidifies to austenite rather than ferrite, the tendency to cracking increases substantially. Hence, the fourth and yet important criterion is to ensure the new welding alloy solidifies to ferrite first. This condition imposes a limit on the amount of austenite-stabilizing elements, *e.g.* Ni, which can be added to the welding alloy.

3. Optimization and fabrication of new alloys

Based on the above-mentioned criteria a number of welding alloys were designed but only 3 physical samples were fabricated using the vacuum casting facilities in the University of Cambridge.

CamAlloys 1 & *2* were designed based on the thermodynamic modeling but they were not fabricated. *CamAlloy 3* was the first new welding alloy, which was made after the theoretical calculations proved it would meet all required criteria. **Figure 2** shows the calculated phase diagram of *CamAlloy 3* which had a composition similar to *CamAlloy 4* but with a lower nickel content. It is clear that *CamAlloy 3* solidifies into ferrite phase before fully transforming to austenite and finally retaining a ferrite/martensite structure. Based the microstructural examinations, conducted on *CamAlloy 3*, the nickel and molybdenum contents were slightly increased in the subsequent *CamAlloy 4* and *CamAlloy 5* to ensure archiving fully martensitic structures in the as-welded condition.

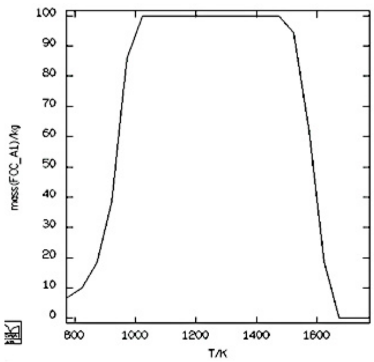

Fig. 2. Phase diagram of *CamAlloy 3* calculated using thermodynamics equations.

The details of modelling and the specific considerations taken in account when designing the first generation of these alloys are given elsewhere [2]. The measured compositions of prototyped alloys are given in Table 1.

Table 1. Actual composition (wt.%) of stress-mitigating weld alloys designed using thermodynamics modelling (balance Fe, S & P <0.01%).

Alloy Name	C	Cr	Ni	Mn	Mo	Si
CamAlloy 4	0.01	12.66	5.24	1.36	0.10	0.74
CamAlloy 5	0.01	12.90	5.84	1.64	1.03	0.64
OpenAlloy 1	0.01	13.22	6.12	1.91	1.02	0.01

Figure 3 shows a stainless-steel bar which was welded using *CamAlloy 5*. The initial examination showed that the welded bar hardly suffered any distortion unlike when using conventional non-transforming austenite welding alloys. This is consistent with the already reported behaviour of *CamAlloy 4* [1,2]. *OpenAlloy 1* with a composition similar to *CamAlloy 5* but without any silicon is still in the preparation stage. Unlike *CamAlloys 4* & *5*, *OpenAlloy 1* will be used for laser welding under a shielding gas.

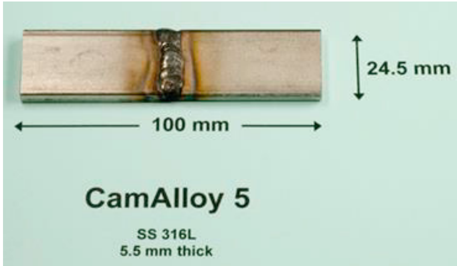

Fig. 3. Near-zero distortion was found in the stainless-steel bar after deposition of *CamAlloy 5* using a conventional TIG welding torch.

4. Comparative Satoh testing of *CamAlloys*

Satoh tests are used to assess the residual stresses, which accumulate within a constraint alloy due to its thermal shrinkage during cooling. **Figure 4** shows the specimen setup used for Satoh testing and more details are given elsewhere [3]. As expected, the thermal contraction of both *CamAlloys* lead to the accumulation of tensile stress during cooling until martensitic transformation started around 200 °C. The transformation-induced "expansion" not only annihilated the tensile residual stress but also built up compressive stress within the sample temporarily. As soon as the transformation is completed, tensile residual stress started to build-up again. **Figure 5** shows the results of Satoh tests conducted on *CamAlloys* under the same conditions. The experimental results clearly verify the effect of having a higher amount of molybdenum in *CamAlloy 5* on the transformation start temperature - as predicted by the theoretical modelling. About 50 °C lower transformation temperature of *CamAlloy 5* compared to *CamAlloy 4* reduced the final residual stresses at ambient temperature noticeably.

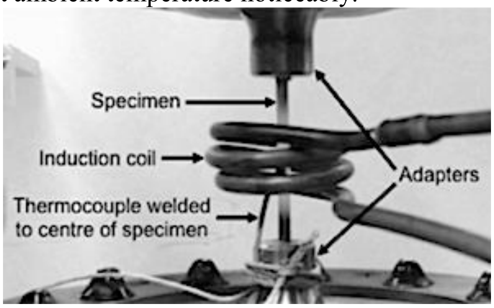

Fig. 4. Specimen setup in Satoh test where an induction coil is used to heat the sample.

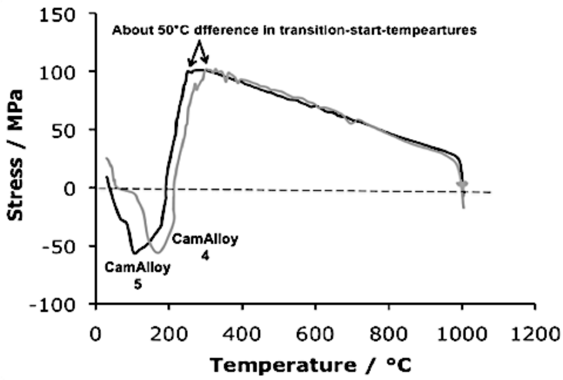

Fig. 5. Satoh test results show the lower martensite transformation temperature of *CamAlloy 5* resulted in less residual tensile stresses compared to *CamAlloy 4* once the alloy reached ambient temperature.

5. Microstructure and hardness of *CamAlloys*

Microstructures of both *CamAlloys* proved to be fully martensitic with very limited and dispersed delta ferrites – see **Figure 6**. The retained ferrite does not form continuous networks in the final microstructure, leading to a very high toughness [2]. Despite having similar microstructures, the average hardness of *CamAlloy 5* was slightly lower than its predecessor *CamAlloy 4*, *i.e.* 310 and 340 VHN, respectively. This could be due to the variations in the welding parameters particularly when it is carried out manually.

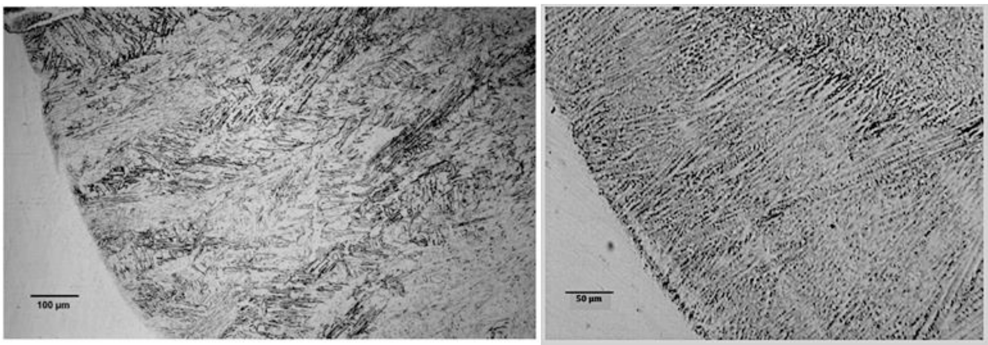

Fig. 6. Optical micrographs of *CamAlloy 4* (left) and *CamAlloy 5* (right) in the as-welded condition show the presence of martensite and limited amounts of delta ferrite (the latter only observable in higher magnifications).

6. Development of *OpenAlloy 1*

Currently, *OpenAlloy 1* with a composition similar to *CamAlloy 5* but slightly higher Mn and without Si is under examination. The exclusion of Si will allow to make a more precise comparison between the theoretical values and experimental data. This is because, as previous work showed, including silicon in the calculations using the thermodynamic databases led to a gross over-estimation of the ferrite content [2]. Therefore, silicon had to be neglected in the calculations of all *CamAlloys*.

Silicon is normally added to welding filler as a deoxidizer. Since *OpenAlloy 1* is designed to be used under a shielding gas for low volume dispositions, it is of interest to find out if the presence of Si is needed at all. The results are expected to be published by the end of 2019.

7. Conclusions

Based on purely theoretical modelling and using thermodynamics calculations, a number of stress-mitigating welding alloys were designed. The fact that the prototyped welding alloys exhibited very desirable properties, underpins the valuable role of such modelling approaches in engineering applications.

The development of *CamAlloys* has led to further research on this family of welding alloys both in academia and welding industry. A major producer of welding consumables in Europe, adopted the composition of *CamAlloy 4* and branded it as a new commercial welding alloys capable of reducing residual stresses.

The plasticity associated with martensitic transformation during the cooling stage of fusion welding, proved to be adequate to reduce the residual stresses, and hence observed near-zero distortion in the weldments.

More work is in progress to further improve the properties of such alloys and also replace the costly elements with more economical substitutes in order to make them more viable for mass production.

Acknowledgements

The author is grateful for the award received Santander University Network and the support from Guangdong Innovative and Entrepreneurial Research Team Program (Project No. 2016ZT06G025).

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