Journal of Materials Processing Technology 243 (2017) 246–257

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Effects of laser cladding on fatigue performance of AISI 4340 steel in the as-clad and machine treated conditions

Youxiang Chew [a], John Hock Lye Pang [b,*], Guijun Bi [a,*], Bin Song [a]

[a] Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, 637662, Singapore
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

ARTICLE INFO

Article history:
Received 30 May 2016
Received in revised form
24 November 2016
Accepted 22 December 2016
Available online 23 December 2016

Keywords:
Fatigue enhancement
Fatigue test
Laser cladding
Additive manufacturing
S-N curve

ABSTRACT

Laser clad specimens were fabricated to characterize the axial fatigue failure behavior of laser clad 4340 steel in the as-clad condition and for specifically designed clad specimens with pre-clad machining and post-clad surface grinding processes. Three types of laser clad fatigue test specimens (Type I, II and III) were tested to study fatigue failure behavior and were compared to the unclad 4340 steel substrate specimen. Type I specimen investigates fatigue failure behavior from the clad toe region of as-clad specimens. Type II specimen evaluates fatigue strength enhancement effects by pre-clad machining of a groove for depositing a clad layer with post-clad surface grinding to process the added clad layer in the groove to be flush with the substrate material. Type III specimen studies clad specimens with extended clad area and surface grinding to promote fatigue failure within the clad region. The fatigue S-N curve for Type I, II and III clad specimens were compared to the S-N curve for the substrate specimens to show the reduction in fatigue strength for as-clad Type I specimens, and machining methods to improve fatigue strength for Type II and Type III specimens. The fatigue strength of all laser-clad specimens was observed to be lower as compared to that of the unclad substrate specimen.

1. Introduction

Laser cladding is increasingly used in laser additive manufacturing applications and can be applied to a metal substrate material in the as-clad condition or employed as part of a remanufacturing process with pre-clad machining of a groove and post-clad surface grinding to meet specific surface requirements. Laser cladding of specimens are examples of emerging laser assisted welding and additive manufacturing applications that require further fatigue performance investigations. Research is needed to characterize the fatigue failure behavior of laser cladded parts in laboratory specimens before they are applied to additive manufacturing and remanufacturing of engineering components. For instance, Sandhu and Shahi (2016) investigated the fatigue performance of AISI 304L austenitic stainless steel with a single layer of Inconel 625 weld cladding using shielded metal arc welding (SMAW) process. They observed better fatigue performances for specimens with higher amount of clad IN625 content and the base substrate, AISI 304L stainless steel exhibiting lowest fatigue strength. Kasperovich and Hausmann (2015) improved the ductility and fatigue resistance of TiAl6V4 specimens by optimizing the selective laser melting parameters employed during the fabrication process. They reported higher fatigue strength for heat-treated specimens even though the tensile strengths were relatively lower. Branza et al. (2009) investigated the fatigue performances of heat-resistant cast steel with multi-pass weld-repair using SMAW process. They highlighted that buttering technique were useful to eliminate weld cracking but reduced the fatigue strength of the repaired parts. Sun et al. (2015) reported detailed evaluations of defect density, microstructure, residual stress, and mechanical properties of laser-deposited AISI 4340 steel coatings on 4140 steel substrate. It was observed that voids and bonding defects in the 4340 steel coating are sites for nucleation and propagation of high temperature oxidation cracks. Microstructural and micro-hardness investigation on 4340 steel laser deposited on rolled mild steel substrate by Direct Metal Deposition (DMD) process was reported by Bhattacharya et al. (2011). Their study showed a decrease in micro-hardness values from the top layer to the alloy layer due to tempering effects of the martensite phases towards the interface. Sun et al. (2014) investigated the fatigue behavior of AISI 4340 and AerMet 100 steel powder clad onto 4340 steel substrate. They demonstrated that using the softer AerMet 100 as the clad material resulted in better fatigue performance compared to AISI 4340 steel as the ductility and toughness

---

* Corresponding author.
E-mail addresses: mhlpang@ntu.edu.sg (J.H.L. Pang), gjbi@simtech.a-star.edu.sg (G. Bi).

http://dx.doi.org/10.1016/j.jmatprotec.2016.12.020

Table 1
Chemical composition of AISI 4340 steel.

Elements	C	Si	Mn	Ni	Cr	Mo	P	S	Fe
Wt. (%)	0.41	0.29	0.76	1.82	0.76	0.26	0.012	0.002	balance

were increased. Recently, Hutasoit et al. (2015) investigated the fatigue life of Stellite 6 and Deloro 40G on AISI 4130 steel substrate under rotary bending fatigue test. They explained that the presence of tensile residual stresses in the clad region reduced the fatigue life compared to substrate of the same size. Chew et al. (2015) reported residual stress simulation results for single and multiple laser clad beads of 4340 steel powder on 4340 steel substrate. This underlines the potential to consider residual stress results in fatigue models for more accurate fatigue life assessments. Tensile and fatigue properties of laser cladded medium carbon steel with two clad layers of Co-Cr alloy were studied by Niederhauser and Karlsson (2003) and it was noted that the residual stress created during cladding had a significant effect on the stress versus number of cycles to failure test results particularly for fatigue tests with small strain amplitudes.

Borrego et al. (2007) performed constant amplitude axial cyclic loading on tool steels substrate with pre-machined U–notch and overfilling with laser welding H13 steel filler material to emulate repair applications. The repaired specimens showed significant reduction in fatigue strength compared to substrate specimen due to the presence of high tensile residual stresses and initiation of numerous cracks from defects in the clad region. Koehler et al. (2012) clad Stellite 21 alloy powder on cylindrical substrates of X5CrNi18-10 and 42CrMo4 and obtained the fatigue S-N curve of the specimens under cyclic 4-point bending loading. Cladding was performed at the centre parallel section and maintains a clad thickness of approximately 1.28 mm after grinding. It was reported that both types of clad specimens exhibited lower fatigue strength with the 42CrMo4 clad specimens having more markedly reduced fatigue performance due to tensile residual stresses. They also demonstrated in their numerical model that inclusion of cladding residual stresses in the computation yielded fatigue limit predictions that were closer to experimental results. In another work, Koehler et al. (2011) machined flat specimens from crankshaft made of AISI 4140 steel and clad with Stellite 21 for cyclic axial loading. Grooves of width 65 mm, 0.9 mm radii and depth 1 mm were cut before filling with overlapping clad tracks. The clad specimen was observed to exhibit lower fatigue performance compared to unclad specimen. Fatigue crack initiation from laser clad deposits were investigated by Alam et al. (2013) and their studies showed that for as-clad specimens the overlapping clad traces generate wavy surfaces with sharp notches. It was observed that multiple surface fatigue cracks initiated from clad surface pores. Fatigue studies on laser-clad specimens of Stellite 21 on AISI 316L stainless steel with pre-cladding machined cavity by Ganesh et al. (2010) show superior fatigue strength under rotating bending loading, as fatigue crack nucleation in all specimens took place in the substrate. The presence of the clad layer can suppress fatigue crack initiation from the surface and improve fatigue performance. Tuominen et al. (2015) investigated the fatigue performance of 42CrMo4 steel bar clad with Inconel 625 and S355 structural steel clad with Stellite 21 under four point bending and torsion fatigue test. The clad specimen generally exhibited reduced fatigue strength except for Inconel 625 clad specimen at higher applied stress. The lower fatigue lives were attributed to high tensile residual stress measured by hole-drilling and the presence of defects such as inclusions and porosity. Post-weld heat-treatment was also found to have insignificant impact on fatigue performance for both clad-substrate material pairs.

From the literatures discussed, the fatigue strength of clad specimens is dependent on many factors such as clad-substrate pair, specimen design, process parameters, residual stresses and microstructural details. Experimental fatigue characterization is important to assess fatigue behavior of specimens specially designed for laser cladding applications in this work as there are no standard specimen designs for fatigue testing of laser cladded specimens. Hence, fatigue characterization of laser clad specimens is an important area that needs further research. In this study, the fatigue strength investigation was extended from the fatigue characterization of laser clad 4340 steel powder onto 4340 steel substrate specimens in the as-clad condition reported in Chew and Pang (2016). The laser clad specimen in the as-clad condition with clad-toe failure referred to as Type I specimen in this work, will be used as the base case for further fatigue strength enhancement studies on laser clad AISI 4340 steel specimens. This is achieved by employing carefully designed fatigue test specimens with pre-clad machining of a groove filled for cladding and post-clad surface grinding to a flush smooth surface to enhance fatigue performance.

2. Experimental methods

The fatigue test specimen for 4340 steel substrate conforms to the specimen requirements in ASTM E466-07 (Standard, 2007) and will be denoted as unclad or substrate specimen. Type I specimens are laser cladded fatigue specimens tested in the as-cladded condition. Type II specimens involve pre-clad machining of a groove, laser clad overfilling of the groove, and post-clad grinding the clad material back to a flush surface with the substrate material. Type III specimens are designed with extended clad surface with post-clad grinding treatment over the fatigue test specimen gage area to observe specific fatigue failure behavior where fatigue cracks initiate and propagate to failure within clad region. In this paper, fatigue S-N curve test results for Type I, II, and III specimens are presented and compared to the substrate S-N curve test result. The Type II and III test results will characterize the fatigue strength enhancement methods used for demonstrating the benefits of employing pre-clad machining and/or post-clad grinding processes to improve the fatigue performance of laser cladded 4340 steel specimens.

2.1. Fatigue specimen designs for laser cladded 4340 steel specimens

The overview for the laser clad specimen designs (Type I, II and III), their fabricated details and anticipated fatigue failure modes will be discussed in this section. The fatigue performance of the unclad 4340 steel substrate specimen will be used as the baseline or reference S-N curve test data for comparison to the three laser cladded fatigue specimen designs called Type I, II and III respectively. The AISI 4340 steel substrate material was oil quenched from 860 °C and tempered at 610 °C for 160 min. The 4340 steel substrate yield strength and ultimate tensile strength specimen are 916 MPa and 1021 MPa respectively. The chemical composition of the 4340 steel is given in Table 1.

The substrate specimen and the schematic illustration of its fatigue failure mode at the mid-section of the specimen gage area are shown in Fig. 1.

2.1.1. Type I specimen design and fabrication

Fatigue specimens for investigating fatigue failure at the clad toe region are referred to as Type I specimen. Type I specimens were tested in the as-clad conditions where the clad region resides