

The Interface Microstructures and Mechanical Properties of Laser Additive Repaired Inconel 625 Alloy

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Abstract: The microstructure and micro-mechanics around the repaired interface, and the tensile properties of laser additive repaired (LARed) Inconel 625 alloy were investigated. The results showed that the microstructure around the repaired interface was divided into three zones: the substrate zone (SZ), the heat-a ected zone (HAZ), and the repaired zone (RZ). The microstructure of the SZ had a typical equiaxed crystal structure, displaying simultaneously precipitated block-shaped MC-type carbides (NbC, TiC), with bimodal sizes of approximately 10 m and 0.5 m and an irregularly shaped flocculent Laves phase. Recrystallization occurred in the HAZ, and led to significant grain growth; a portion of the second phase dissolved in the original grain boundaries. In the RZ, there was a columnar crystal structure, and the size increased with increasing deposition thickness. Moreover, the microstructure between the layer interface and layer interior was guite di erent, presenting an overlapping transition zone (OTZ), in which the dendritic structure coarsened and more Laves phase were precipitated, compared to in the layer interior. The hardness and tensile properties of the LARed samples were equivalent to those of the wrought substrate, which indicates that laser additive repairing (LAR) is a reliable repair solution for damaged and mis-machined components comprising Inconel 625 alloy.

Keywords: laser additive repairing; Inconel 625 alloy; interface microstructures; micromechanics

1. Introduction

Inconel 625 is a nickel–chromium solid-solution strengthened alloy, which is largely strengthened by Nb and Mo [1,2]. It is widely used to fabricate high-temperature components in aeronautical, aerospace, marine, chemical, and nuclear industries, due to its extraordinary combination of high yield and tensile strength, excellent creep strength, and outstanding corrosion resistance at elevated temperature [3–5]. However, these components are easily damaged owing to their aggressive service conditions, and can also be mis-machined during processing [6]. If these damaged and mis-machined components can be repaired rapidly, considerable savings in materials, processing time, and costs can be achieved.

Laser additive manufacturing (LAM) [7] has attracted much attention in the past ten years. By combining laser cladding with rapid prototyping techniques, LAM is an advanced fabrication technique for producing fully dense near-net-shape metallic components on metallic substrates [8]. Based on LAM, laser additive repairing (LAR) technology has been developed [9–11]. By using the damaged or mis-machined components as substrates, the geometry and mechanical properties of the damaged or mis-machined components can be repaired using LAR without deteriorating

the performance of the body parts. Compared with traditional repair technologies [12–14], such as

electrobrush plating, thermal spraying, and argon arc welding, LAR has the advantages of a high electrobrush plating, thermal spraying, and argon arc welding, LAR has the advantages of a high degree of automation, a small heat a ected zone, metallurgical bonding between the repaired zones and degree of automation, a small heat affected zone, metallurgical bonding between the repaired zones the body part, and a reasonable repair cost [15]. A number of metallic components made of di erent and the body part, and a reasonable repair cost [15]. A number of metallic components made of type of materials, including stainless steel, cobalt-based alloys, titanium alloys, and nickel-based alloys, different type of materials, including stainless steel, cobalt-based alloys, titanium alloys, and

have been repaired using LAR technology [16–18].

nickel-based alloys, have been repaired using LAR technology [16–18].

In recent years, the processing parameters, microstructures, and mechanical properties of Inconel In recent years, the processing parameters, microstructures, and mechanical properties of

625 fabricated using LAM technology have attracted much attention [19–22]. Dinda et al. [23] studied Inconel 625 fabricated using LAM technology have attracted much attention [19–22]. Dinda et al. [23]

the microstructural evolution and structural thermal stability of a LAM Inconel 625 alloy. The results studied the microstructural evolution and structural thermal stability of a LAM Inconel 625 alloy.

indicated that the as-deposited microstructure mostly consisted of columnar dendrites that were stable. The results indicated that the as-deposited microstructure mostly consisted of columnar dendrites.

up to 1000 C. Rombouts et al. [24] found that Inconel 625 deposited using directed energy deposition that were stable up to 1000 °C. Rombouts et al. [24] found that Inconel 625 deposited using directed

(DED) also showed a microstructure of dendrites parallel to the build direction. Rivera et al. [25] energy deposition (DED) also showed a microstructure of dendrites parallel to the build direction.

observed fine grain structures at the layer interfaces of Inconel 625 produced using solidstate additive Rivera et al. [25] observed fine grain structures at the layer interfaces of Inconel 625 produced using

Inconel 625 produced using manufacturing. Compared to samples fabricated using LAM, not only the microstructures of the solid-state additive manufacturing. Compared to samples fabricated using LAM, not only the

repaired part, but also the microstructures of the interface between the substrate and the repaired microstructures of the repaired part, but also the microstructures of the interface between the

part, are essential to the mechanical properties of the component repaired using LAR. The research substrate and the repaired part, are essential to the mechanical properties of the component repaired

component repaired work of LAR for nickel-based alloys mainly focuses on the repair defects, processing parameters, using LAR. The research work of LAR for nickel-based alloys mainly focuses on the repair defects,

microstructures, and mechanical properties of repaired samples. Onuike et al. [10] used DED technology processing parameters, microstructures, and mechanical properties of repaired samples. Onuike et

to repair the internal cracks in Inconel 718 alloy. Sui et al. [9] studied the tensile deformation behavior of al. [10] used DED technology to repair the internal cracks in Inconel 718 alloy. Sui et al. [9] studied

LARed Inconel 718 alloy with a non-uniform microstructure. To the best of our knowledge, no studies the tensile deformation behavior of LARed Inconel 718 alloy with a non-uniform microstructure. To

have investigated the relationship between the microstructure and micro-mechanical properties of the best of our knowledge, no studies have investigated the relationship between the microstructure

LARed Inconel 625 alloy around the repaired interface.

and micro-mechanical properties of LARed Inconel 625 alloy around the repaired interface. In order to explore the potential of LAR as a reliable repair solution for damaged and mis-machined In order to explore the potential of LAR as a reliable repair solution for damaged and

Inconel 625 components, Inconel 625 alloy substrates, with premade trapezoidal groove shaped defects, mis-machined Inconel 625 components, Inconel 625 alloy substrates, with premade trapezoidal

were repaired using LAR in this study. The microstructures around the repaired interface and the groove shaped defects, were repaired using LAR in this study. The microstructures around the

corresponding mechanical properties were investigated.

repaired interface and the corresponding mechanical properties were investigated.

2. Materials and Methods

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2.1. Materials

2.1. Materials

The raw materials were prealloyed Inconel 625 powders prepared using a plasma rotating The raw materials were prealloyed Inconel 625 powders prepared using a plasma rotating electrode process. These powders had spherical shapes with sizes of 75~125 m, as shown in Figure 1a.

electrode process. These powders had spherical shapes with sizes of $75\sim125~\mu m$, as shown in Figure The microstructure of the powders showed a fine dendritic morphology on the surface, which

1a. The microstructure of the powders showed a fine dendritic morphology on the surface, which was caused by the rapid solidification during atomization (Figure 1b). Before the LAR experiment,

was caused by the rapid solidification during atomization (Figure 1b). Before the LAR experiment, the powders were dried in a vacuum oven at 120 10 C for 2 h. The LAR process was performed on

the powders were dried in a vacuum oven at 120 ± 10 °C for 2 h. The LAR process was performed on heat treated wrought Inconel 625 substrate, for which the chemical composition is listed in Table 1.

heat treated wrought Inconel 625 substrate, for which the chemical composition is listed in Table 1.

The chemical composition of Inconel 625 powder is also listed in Table 1. The chemical composition of Inconel 625 powder is also listed in Table 1.

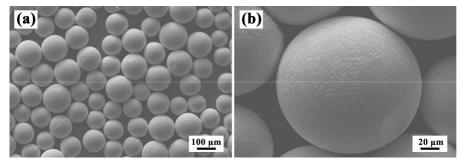


Figure 1. Morphologies of Inconel 625 powders at (a) low and (b) high magnifications.

Figure 1. Morphologies of Inconel 625 powders at (a) low and (b) high magnifications.

Table 1. The chemical compositions (wt %) of Inconel 625 alloy powder and substrate.

Material	Ni	Cr	Mo Nb	Fe	Ti	Al	C	Co	Mn	Si	P
Powder	Bal.	21.92	9.09 3.62	3.71	0.20	0.17	0.036	0.009	0.015	0.06	0.003
Substrate	Bal.	21.70	8.90 3.27	4.40	0.18	0.12	0.030	0.010	0.170	0.15	0.008

Materials 2020, Table 13, xFOR1. The PEER chemical REVIEW compositions (wt %) of Inconel 625 3 of 16 alloy powder and substrate. Materials 2020 PEER REVIEW 2020, FOR 13, x 3 of 16 Mo Nb Fe Τi ΑI C Co Mn Si Material Çr Experimental **Experimental Pr**öcedures Powder Bal. 21.92 9.093.62 3.71 0.20 0.17 0.036 0.009 0.015 0.06 0 The LAR experiments were performed on a LAM system (LAM, LSF-Nanjing, 12000). 8.90 3.27 4.40 0.18 0.12 0.030 Substrate 0.008 The LAR experiments were performed on a LAM system (LAM, LSF-Naming, which consists of a fiber laser with a wavelength of 1070 nm, a five-axis numerical control workin which consists of a fiber laser with a wavelength of 1070 nm, a five-axis numerical control working table, a powder feeder system with a coaxial nozzle, and an inert atmosphere glove box (oxygen 2.2. Experimental Procedures table, powder feeder system with a coaxial nozzle, and an inert atmosphere glove box (oxygen content ≤ 10 ppm). Argon gas was used to protect the molten pool from oxidation and deliver the content ≤ 10 ppm). Argon gas was used to protect the molten pool from oxidation and deliver the alloyThepowdersLAR.experiments were performed on a LAM system (LAM, LSF-12000, Nanjing, China), alloy powders. which The consists LAR process of a fiber was last erperformed with a wavelonthength substrate of 1 070withnm,a preafive-machined-axisnumerical groove control defect, as working shown The LAR process was performed on the substrate with a pre-machined groove defect, as shown table, in Figure apowder 2a. Then feeder the defects ystem was with repaired coaxial layer nozzle, b

ylayerandusingan inerttheLAMatmospheresystem, gloveasshownbox in(oxygenFigure in Figure 2a. Then the defect was repaired layer by layer using the LAM system, as shown in content2b.Figure103 $a Argon schematic {\bf gaswas} of the {\bf used} scanning to {\bf protect} strategy the {\bf molten} of the LAR {\bf pool} processor {\bf user} {\bf u$ ssfrmoxidation. The scanning and deliver directions the 2b. Figure 3 shows a schematic of the scanning οĬ the LAR The scanning strategy process. directions alloyinthepowderssamelayer. followed a zigzag pattern, and were rotated by 90 degree in the following layer. in the same layer followed a zigzag pattern, and were rotated by 90 the following processTheLARparametersprocesswasareperformedlistedinTableonthe2.substrate with a pre-machined groove defect, as shown in

The process parameters are listed in Table 2.

FigureA

2tensilea. Thentesting the defect barwascut repaired from the layer repaired by layers ampleusing by the spark LAMerosysion tem,. The asshvown lumein fraction Figure 2 of b. A tensile testing bar was cut from the repaired sample by spark erosion. The volume fraction of Figure the repair 3 shows zone ainsothematic cross-of section the scanning of the tensile strat gy testing of the bar LAR was process 50%, as The shown scaning Figure directions 2c,d. in the

the repair zone in the cross-section of the tensile testing bar was 50%, as shown in Figure 2c,d. same layer followed a zigzag pattern, and were rotated by 90 degree in the following layer. The process

parameters are listed in Table 2.

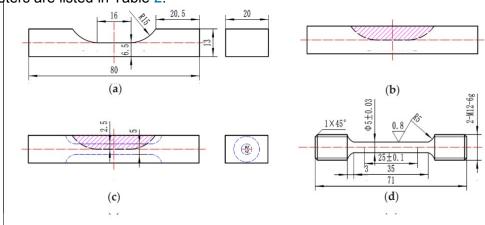


Figure 2. Sketch of (a) substrate with pre-machined groove defect, (b) LARed sample, (c) the position Figure 2. Sketch of (a) substrate with pre-machined groove defect, (b) LARed sample, (c) the position Figure 2. Sketch of (a) substrate with pre-machined groove defect, (b) LARed sample, (c) the position of the tensile testing bar in the LARed sample, and (d) shape and size of the tensile testing bar.

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testing bar.

of the tensile testing bar in the LARed sample, and (d) shape and size of the tensile testing bar.

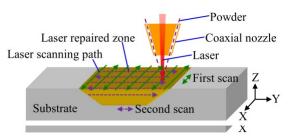


Figure 3.. Schematic of the scanning strategy of the LAR process...

Figure 3. Schematic of the scanning strategy of the LAR process. **Table 2.** Process parameters of LARed Inconel 625 alloy.

Table 2. Process parameters of LARed Inconel 625 alloy.

Power	Speeding	Laser Spot	Increment of Z	Feeder -	Overlaps
Laser Laser (kW)	Scanning Speed (mm/min) Scanning	Laser Spot Diameter (mm)	Increment of Axis (mm)	Powder Feeder Rate (g/min)	Overlaps (%) Overlap
Power	Speed	Laser Spot	Increment of	Powder Feeder	
1.4	(mm/min) ₄₀₀	Diameter ₃ (mm)	Z Axis _{0.5} (mm)	Rate ₆ (g/min)	₄₅ (%)
Power				G	
(kW)					
	(mm/min)	Diameter (mm)	Z Axis (mm)	Rate (g/min)	(%)
(kW)					
.4	400	3	0.5	-6	45
4	400	3	0.5	6	45

A tensile testing bar was cut from the repaired sample by spark erosion. The volume fraction of

the repaiMicrostructureszoneinthe crossand-stectionxturesof aroundthetensilethetestingrepairedbarwasinterface50%,as wereshownexaminedFigure 2byc,d.optical Microstructures and textures around the repaired interface were metallogMicrostructuresaphy(OM, examined by optical OlympusandtexturesOLS4000, aroundTokyo, the

Japan),repairedscainningterfaceelectronwere microscopyexamined by(SEM,opticalFEI metallography (OM, Olympus OLS4000, Tokyo, Japan), scanning electron microscopy

mHetallogrliosNanolabphy(OM,600i,OlympusHillsboro,OLS4000,OR,USA),Tokyo,andJap an), electrons canning backscattered electron microscopy diffraction (SEM,

(EBSD, FEIEDAX, Helios Helios Nanolab 600i, Hillsboro, OR, USA), and electron backscattered diffraction (EBSD, EDAX, Mahwah, NJ, USA). Elemental analysis was carried out using energy-dispersive X-ray spectrometry Mahwah, NJ, USA). Elemental analysis was carried out using energy-dispersive X-ray spectrometry (EDS, EDAX, Mahwah, NJ, USA). Before the microstructure observation, samples were ground on (EDS, EDAX, Mahwah, NJ, USA). Before the microstructure observation, samples were ground on 500-2000 grit silicon carbide papers and mechanically polished. Polished samples were then electro 500-2000 grit silicon carbide papers and mechanically polished. Polished samples were then electro etched under an 8 V direct current (DC) for 15 s in a reagent of 10% aqueous chromic acid solution to etched under an 8 V direct current (DC) for 15 s in a reagent of 10% aqueous chromic acid solution to Nanolab 600i, Hillsboro, OR, USA), and electron backscattered di raction (EBSD, EDAX, Mahwah, NJ, USA). Elemental analysis was carried out using energy-dispersive X-ray spectrometry (EDS, EDAX, Mahwah, NJ, USA). Before the microstructure observation, samples were ground

on 500-2000 grit silicon carbide papers and mechanically polished. Polished samples were then electro etched under an 8 V direct current (DC) for 15 s in a reagent of 10% aqueous chromic acid solution to reveal the microstructure. All EBSD samples were polished using an argon beam under a voltage of 5 kV and a current of 110 A for 20 min before the EBSD test. The EBSD test used a voltage of 20 kV and a step size of 1 m. Xray di raction (XRD, TDF-3000, Dandong, China) scanning was carried out at a constant scanning speed of 10 /min with Cu K radiation, and recorded in 2 ranging from 30 to 100. To identify tiny phases in the microstructures, a transmission electron microscope (TEM, FEI Titan G2 60-300, Hillsboro, OR, USA) equipped with EDS was applied. The TEM samples, with a 3 mm diameter disc shape, were prepared by mechanical grinding to ~50 m and then twin-jet polished in a solution of 250 mL HCLO₄+750 mL methanol at a temperature of 30 C and a voltage of 25 V. Vickers hardness of the samples was tested under a load of 200 g and a duration time of 15 s along the deposition direction. The elastic modulus and microhardness of di erent zones were evaluated by nano-indentation (Hysitron TI-950, Minneapolis, MN, USA) under a load of 5 mN. The room temperature tensile properties of the LARed samples and substrates were tested using a floor model universal testing system (CMT5105, Jinan, China), at a displacement rate of 2 mm/min. For each tensile test condition, three samples were used to calculate the average values and standard deviations of strengths, elongations, and area reductions. The ultimate tensile strength, 0.2% o set yield strength and elongation, was obtained from the resulting stress-strain curves, and the area reduction was determined by measuring the crosssectional area before and after failure. The fracture morphology was observed using SEM.

3. Results and Discussion

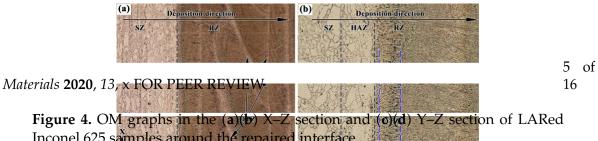
3.1. Microstructure Around the Repaired Interface

3.1.1. Grain Structures

Figure 4a–d show the microstructures in the X–Z section and Y–Z section of the LARed samples around the repaired interface, respectively. The interface between the substrate and the repaired zone presents good metallurgical bonding. No obvious defects, such as cracks and pores can be observed. A transition of microstructure can be observed along the deposition direction, dividing the area into three zones: the substrate zone (SZ), the heat-a ected zone (HAZ), and the repaired zone (RZ) (see Figure 4b,d). Inside the RZ, a narrow overlapping transition zone (OTZ) can be observed, between two adjacent deposited layers or tracks (see Figure 4b,d). The width of the OTZ is approximately 0.15 mm. The SZ consists of a mixture of finely and large equiaxed grains. The grains in the HAZ are hard to reveal under the same erosion conditions, suggesting a composition variation in grain boundaries. Detailed grain structure observation was carried out using EBSD, as in the following. RZ presents a columnar dendritic structure that grows epitaxially along the deposition direction. In addition, the dendritic structure in the OTZ between two adjacent deposited tracks is coarser than other areas in the RZ.

Detailed investigations on the microstructures around the repaired interface of the LARed Inconel 625 were carried out using EBSD. Figure 5a–d show the EBSD images in the X–Z section and Y–Z section of the LARed samples around the repaired interface, respectively. The three zones of SZ, HAZ, and RZ can be easily distinguished in the EBSD images, showing grains with different sizes and distributions. The SZ has typical equiaxed grains, with a bimodal grain size distribution. Annealing twins can be observed in the recrystallized grains. Grains in the HAZ grew significantly larger compared to those in the SZ. In the RZ, large sized columnar grains grew epitaxially from the mother grains in the HAZ. The height of the columnar grains can be as large as the layer height. The widths and heights of the columnar grains increase as the deposition height increases. The OTZ cannot be observed in the EBSD maps.

approximately 0.15 mm. The SZ consists of a mixture of finely and large equiaxed grains. The grains in the HAZ are hard to reveal under the same erosion conditions, suggesting a composition variation in grain boundaries. Detailed grain structure observation was carried out using EBSD, as in the following.



Inconel 625 samples around the repaired interface.

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the Zsection deposition of LARedheight Incoincreases el 625 sampl. The s cannotaroundbeobservedtheepairedin theinterfaceEBSD. maps.

Deposition direction

OTZ

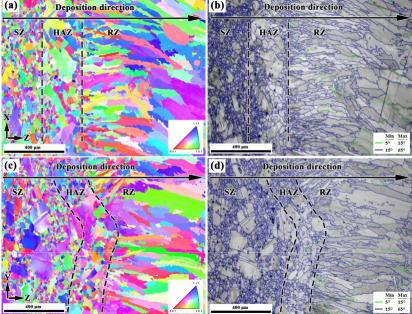


Figure 5. EBSD results of the LARed Inconel 625 samples around the repaired interface in the (a)(b)

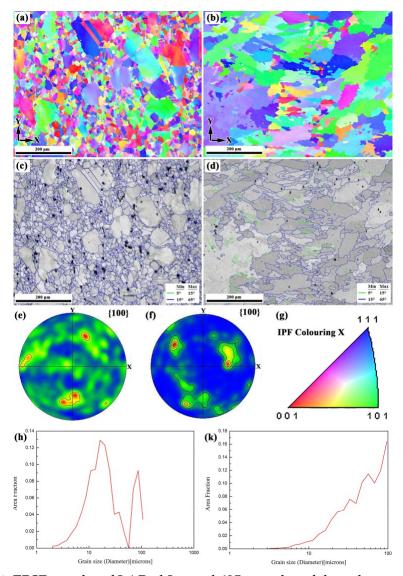


Figure 6. EBSD results of LARed Inconel 625 samples of the substrate zone (SZ) (a)(c)(e)(h) and the **Figure 6.** EBSD results of LARed Inconel 625 samples of the substrate zone (SZ) (a,c,e,h) and the

repaired zone (RZ) (b)(d)(f)(k) in the X–Y section: (a)(b) IPF orientation maps, (c)(d) band contrast

repaired zone (RZ) $(\mathbf{b}, \mathbf{d}, \mathbf{f}, \mathbf{k})$ in the X–Y section: (\mathbf{a}, \mathbf{b}) IPF orientation maps, (\mathbf{c}, \mathbf{d}) band contrast maps,

maps, (e)(f) {100} pole figures, (g) IPF and (h)(k) grain size distribution. (e,f) {100} pole figures, (g) IPF and (h,k) grain size distribution.

3.1³.2¹. ²Phases ^{es} and ^{and} Precipitations

Figure 7 shows the X-ray diffraction patterns of the RZ and SZ in the repaired sample. It can be Figure 7 shows the X-ray di raction patterns of the RZ and SZ in the repaired sample. It can be

demonstrated that the RZ and SZ in the LARed samples both mainly consist of the y (Ni–Cr) phase demonstrated that the RZ and SZ in the LARed samples both mainly consist of the (Ni–Cr) phase

without peaks from other precipitates [26], such as 0 γ' (Ni3Al(Ti)), γ'' (Ni3Nb), δ (Ni3Nb), Laves (Ni,

without peaks from other precipitates [26], such as (Ni₃Al(Ti)), "(Ni₃Nb), (Ni₃Nb), Laves (Ni, Fe,

Fe, Cr)2(Nb, Ti, Mo), and carbide phases, due to their low volume fractions or absences. Cr)₂(Nb, Ti, Mo), and carbide phases, due to their low volume fractions or absences. Furthermore,

Furthermore, the diffraction peak intensity of the (200) crystal plane of the γ phase in the RZ is the di raction peak intensity of the (200) crystal plane of the phase in the RZ is higher than that of higher than that of the (111) crystal plane, which also indicates that the microstructure in the RZ has

the (111) crystal plane, which also indicates that the microstructure in the RZ has a strong texture.

a strong texture.

Detailed SEM investigations were applied to the areas around the repaired interface. Figure 8 Detailed SEM investigations were applied to the areas around the repaired interface.

shows SEM images of the SZ. A large number of precipitates can be seen in the grain boundaries and shows SEM images of the SZ. A large number of precipitates can be seen in the grain boundaries and

grain interior (Figure 8a,b). The precipitates have two typical average sizes of 10 m and 0.5

grain interior (Figure 8a, b). The precipitates have two typical average sizes of 10 µm and 0.5 ŭm.

The large precipitates mainly have irregular shapes. The small precipitates have both flocculent shapes The large precipitates mainly have irregular shapes. The small precipitates have both flocculent and polygonal shapes (see Figure 8c). The chemical compositions of the matrix (as indicated by point shapes and polygonal shapes (see Figure 8c). The chemical compositions of the matrix (as indicated

precipitates mainly comprised Nb and Ti, while the matrix was rich in Ni and Cr but depleted in Nb comprised Nb and Ti, while the matrix was rich in Ni and Cr but depleted in Nb and Ti. The results

Materials **2020**, 13, x FOR PEER REVIEW

and Ti. The results indicate that Nb and Ti in the matrix were segregated to form large precipitates. indicate that Nb and Ti in the matrix were segregated to form large precipitates. These large precipitates

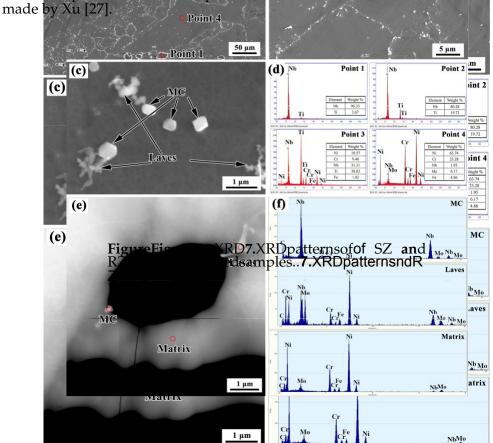
These large precipitates were assumed to be MC-type carbides (M is Nb or Ti), while the matrix was were precipitates assumed to be MC-type carbides (M is Nb or Ti), while the matrix matrix typecarbidesNband(MTi,iswhileNbortheTi),matrixwhilewastherichmatrixinNiwasand assumedCrbutdepletedtobeain Nb(Ni-Cr)

Tito.Thebe resultsay assumedand indicate(Ni-Cr) thatsolidNb solutionandTiin. the TEM matrix observations were segregated and to the form equipped large precipitates EDSX.ray solid solution. TEM observations and the equipped EDS X-ray microanalysis were carried out to clarify

microanalysisTheselargewereprecipitatescarriedwereoutassumedtoclarifyto betheMCsmall-type preccarbidespitates(Mis(shownNborTi),inwhileFigurethe 8ematrix-f). Thewas EDS the small precipitates (shown in Figure 8e,f). The EDS analysis results revealed that the polygonal

analysis assumed results to revealed requipped and the floculent equipped and the floculent equipped and the floculent phase was a Laves phase, which is consistent with the microaral was a Laves phase, which is consistent with the equipped and the floculent phase was a Laves phase, which is consistent with the microaral was a Laves phase, which is consistent with the observations made by Xu [27]. observations made by Xu [28].

analysis results revealed that the polygonal shaped precipitate was NbC, and the flocculent phase was Policyes plase, which is consistent with the observations



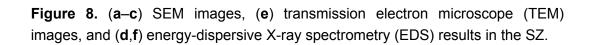


Figure 8. (a–c) SEM images, (e) transmission electron microscope (TEM) images, and (d,f)

Figure 9a presents the microstructure of repaired samples around the repaired interface. The Figure 9a presents the microstructure of repaired samples around the repaired interface. microstructure is quite different in the SZ and the RZ along the deposition direction. Similarly to the The microstructure is quite di erent in the SZ and the RZ along the deposition direction. Similarly SZ, a large amount of white precipitates are also seen in the HAZ and RZ. From the previous to the SZ, a large amount of white precipitates are also seen in the HAZ and RZ. From the previous analysis, we can see that the precipitates of the SZ mainly consist of large (approximately 10 μ m) analysis, we can see that the precipitates of the SZ mainly consist of large (approximately 10 m) irregular shaped MC-type carbides (M is Nb and Ti), small (approximately 0.5 μ m) polygonal irregular shaped MC-type carbides, and flocculent shaped Laves phase. In the HAZ, there are still many large MC-type carbides, and flocculent shaped Laves phase. In the HAZ, there are still many large irregular irregular shaped MC-type carbides, but some small sized precipitates dissolved in the original grain shaped MC-type carbides, but some small sized precipitates dissolved in the original grain boundaries,

boundaries, as shown in Figure 9b.

as shown in Figure 9b.

For the RZ, the microstructure indicates epitaxial growth of the columnar dendritic structure, For the RZ, the microstructure indicates epitaxial growth of the columnar dendritic structure, and a large amount of white precipitates occur along the dendritic boundaries, as shown in Figure and a large amount of white precipitates occur along the dendritic boundaries, as shown in Figure 9a. 9a. In addition, compared to the microstructure in the layer interior, the amount of precipitates is In addition, compared to the microstructure in the layer interior, the amount of precipitates is greater, greater, and the size is largest in the OTZ around the repaired interface, as shown in Figure 9cd. The and the size is largest in the OTZ around the repaired interface, as shown in Figure 9c,d. The precipitates precipitates mainly have flocculent shapes. Figure 9f shows the EDS analysis results of the flocculent

mainly have flocculent shapes. Figure 9f shows the EDS analysis results of the flocculent shaped phase shaped phase and the matrix phase. The results of the EDS analysis reveal that the main hardening

and the matrix phase. The results of the EDS analysis reveal that the main hardening elements Nb elements Nb and Mo are rich in the flocculent shaped phase, which is the characteristic Laves phase

and Mo are rich in the flocculent shaped phase, which is the characteristic Laves phase of Inconel 625 of Inconel 625 alloys [28,29]. This indicates a somewhat heavy segregation in the OTZ. Figure 10 alloys [28,29]. This indicates a somewhat heavy segregation in the OTZ. Figure 10 further shows the further shows the high resolution transmission electron microscopy (HRTEM) image and the EDS

high resolution transmission electron microscopy (HRTEM) image and the EDS results of nanosized results of nanosized precipitates in the RZ. The EDS analysis indicates that it is NbC. Therefore, the

precipitates in the RZ. The EDS analysis indicates that it is NbC. Therefore, the precipitates of the RZ mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of the flocculent shaped Laves phase and a small amount of mainly consist of

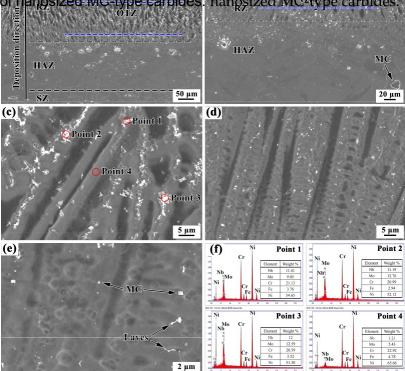


Figure 9. Microstructures of LARed samples in different zones: (a) SZ+heat-affected zone (HAZ)+RZ,

Figure 9. Microstructures of LARed samples in di erent zones: (a) SZ+heat-a ected zone (HAZ)+RZ,

(b) HAZ+RZ, (c) overlapping transition zone (OTZ), (d, e) RZ, and (f) EDS taken from laves phase (b) HAZ+RZ, (c) overlapping transition zone (OTZ), (d,e) RZ, and (f) EDS taken from laves phase and and matrix phase of OTZ around the repaired interface.

matrix phase of OTZ around the repaired interface.

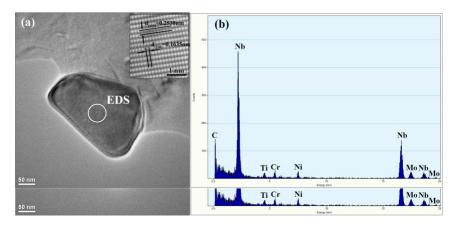


Figure 10. HRTEM images (a) of LARed samples in the RZ, and (b) the EDS

results of a NbC precipitate.

Figure 10. HRTEM images (a) of LARed samples in the RZ, and (b) the EDS results_{precipitate}ofNbC

10. HRTEM images (a) of LARed samples in the RZ, and (b) the EDS results of a

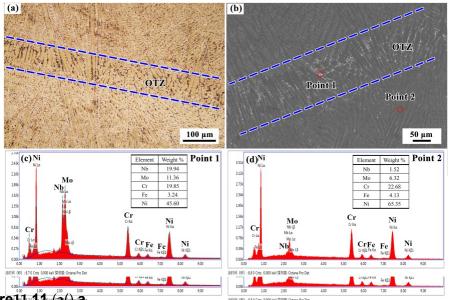
precipitate.
3.1.3. Microstructure in the Overlapping Transition Zone
3.1.3. Microstructure in the Overlapping Transition Zone

3.1.3. FiguMicrostructure11showsinthethemicrostructureOverlappingTransitionoftheOTZo nebetween two adjacent deposited tracks in the Figure 11 shows the microstructure of the OTZ between two adjacent deposited tracks in the RZ.

OTZ between two adjacent deposited tracks in the RZ. RZ. Similarly to the OTZ around the repaired interface, the microstructure of the OTZ in the RZ also Similarly to the OTZ around the repaired interface, the microstructure of the OTZ in the RZ also presents Figure 11 shows the microstructure of the OTZ between two adjacent deposited tracks in the presents a coarse columnar dendritic structure in Figure 11a. The width of the OTZ is also a coarse columnar dendritic structure in Figure 11a. The width of the OTZ is also approximately 0.15 RZ. Similarly to the OTZ around the repaired interface, the microstructure of the OTZ in the RZ also approximately 0.15 mm. Particularly, a large amount of white precipitates occur along the dendritic mm. Particularly, a large amount of white precipitates occur along the dendritic boundaries in the presents a coarse columnar dendritic structure in Figure 11a. The width of the OTZ is also boundaries in the OTZ, as shown in the Figure 11b. The EDS results of the precipitates demonstrate OTZ, as shown in the Figure 11b. The EDS results of the precipitates demonstrate that they are Laves approximately 0.15 mm. Particularly, a large amount of white precipitates occur along the dendritic that they are Laves phase, as shown in Figure 11c,d.

that they are Laves phase, as shown in Figure 11c,d. phase, as shown in Figure 11c,d.

boundaries in the OTZ, as shown in the Figure 11b. The EDS results of the precipitates demonstrate that they are Laves phase, as shown in Figure 11c,d.



FigureFigure11.11.(a(),a

(bb))MicrostructuresMicrostructuresofofOTZOTZandandthethe($\mathbf{c}(\mathbf{c})$)EDSEDSresultsresults ofofLavesLavesandand(d(d)) matrixmatrixphasesphases...

Figure 11. (a), (b) Microstructures of OTZ and the (c) EDS results of Laves and (d) matrix phases.

The

Fürthermore,

microstructuralcharacteristicsbetweenthetheOTZOTZandandlayerlayerinterinteriorareq uiteare diquiteerent, different, which which can be can explained be explain by the classical by the oretical classical theoretical model of growth dendrited uring growth the solidification during the microstructural characteristics between the OTZ and layer interior are quite different process solidification to get her interior are quite different process solidification in the microstructural characteristics between the OTZ and layer interior are quite different process solidification in the microstructure of the model of the model of goether in the model of goether in the model of canexplainedbeexplainbythedclassicalbythe theoreticalclassical theoreticalmodof dendritemodel Ni-based alloy can be described as follows 4D_LG r[31]:=(1)#ADTΓ, $r = \pi$ is the liquid $4D\Gamma$ inter-di usion coe cient, k is the equilibrium where G is the Gibbs-Thomson coe cient, DT is the non-equilibrium ange. Furthermore, according to Gibbs-Thomson coefficient $\chi_{\text{is the the}}^{(1)}$ inter-diffusion coefficient, k is Kurz and Fisher analysis [32], the primary dendritic spacing can be expressed by a function of the equilibrium diffusion coefficient, ΔT is the non-equilibrium solidification range. Furthermore, where Γ is the Gibbs-Thomson coefficient, DL is the liquid interdiffusion coefficient, *k* is the dendritic tip radius r as [33]: equilibrium diffusion coefficient, ΔT is the non-equilibrium solidification range.

according to the Kurz and Fisher analysis [32], the primary dendritic spacing λ can be expressed by a

Materials 2020, 13, 4416 10 of

function of the dendritic tip radius r as [33]:

$$\sqrt{\frac{r}{r}}$$

$$\underline{\lambda} = \mathbf{r} \quad \mathbf{G}$$
(2)

Therefore, the primary dendritic spacing λ is identified as a function of temperature gradient G Therefore, the primary dendritic spacing is identified as a function of temperature gradient G and the growth rate R as

follows:

and the growth rate R as follows:

The product $G \cdot R$ (cooling speed) governs the size of the solidification structure [34]. Thus, the The product G R (cooling speed) governs the size of the solidification structure [34]. Thus,

difference in the temperature gradient G and the growth rate R during the LAR process should be the di erence in the temperature gradient G and the growth rate R during the LAR process should be

the primary reason for the different morphologies in the OTZ. During the LAR process, the material

the primary reason for the di erent morphologies in the OTZ. During the LAR process, the

is deposited track-by-track and layer-by-layer. When a new track is deposited, the top portion of the

is deposited track-by-track and layer-by-layer. When a new track is deposited, the top portion of

material in the previous track is remelted, and then forms a molten pool, as shown in Figure 12. The

the material in the previous track is remelted, and then forms a molten pool, as shown in

temperature of the previous track is higher than that of the previous layer, therefore, the The temperature of the previous track is higher than that of the previous layer, therefore, the temperature

temperature gradient at the overlapping line, G, is less than at the other fusion line, G. gradient at the overlapping line, G_1 , is less than at the 1 other fusion line, G_2 . Consequently, the G2R

Consequently, the $G \cdot R$ (cooling rate) is lower at the overlapping line and higher at the other fusion

(cooling rate) is lower at the overlapping line and higher at the other fusion line. This leads to a

line. This leads to a significant increase in the primary dendritic spacing λ along the overlapping line significant increase in the primary dendritic spacing along the overlapping line of the molten pool, of the molten pool, which forms an OTZ between tracks. which forms an OTZ between tracks.

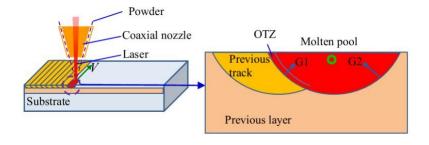


Figure 12. Schematic illustration of the temperature gradient, G, and growth rate, R, distribution in **Figure 12.** Schematic illustration of the temperature gradient, G, and growth rate, R, distribution in the themoltenmoltenpoolpoolduringduringthetheLARLARprocess.process.

ThesizeofoftheLavesphasesisisatttributedtotoththe concentrationofof the alloyingoving elementsents.. During theLARprocess, solidification solidification in in the Inconel 625 alloyst arts with the the primary li quid→!y reaction, causing the **accumulation** of Nb,Mo,Mo,C,C,andandTi theintheinterdendriticendriticand and grain grain boundary boundary liquids liquids. Thus,. Tthus, eLavthes Lavesphase phaseandMCand-typeMCcarbidestypecarbidescanprecipitatcanecipitateintheseinregionsthese.regionsThen,the.Then,subsequ entthesubsequentliquid! liquid(+NbC) - (yeutectic+NbC)reactionutecticconsumesreactionconmostumesofthemostca theavailable,carbonuntilavailable,anotheruntileutecticanothreactionreutecticl! rb**o**fn reaction+Laves →occurs,γ+ finishingLavesoccurs, the solidification finishing the process solidification [27]. The Lavesprocessphase[27] .is The anun Lavoidable esphase terminalisan unavoidsolidificabletionterminalphasein solidificationInconel625alloysphase.However,inInconesolidification625alloys. cansolidificationstronglyinfluenceconditionsthe conditionsHowever, canextentstronglyofniobiuminfluencesegregationtheextentandof niobiumtheamountsegregationofLaves phaseandthe[35amount].Thus,ofa Lavesslowcoolingphase[35]rate. Thus,(GR) ina slowtheOTZcoolingcausesrate $a(Glarge \cdot R)$ in segregation the OTZ causes of the a alloyinglargesegregationelements,ofwthichealleadsoyingtoelements,theformationwhichoflea

dslargeto theamountformationofLavesofa phaselarge.amount of Laves phase.

3³.2⁻². Composition Distribution

 $The^{\text{The}}EDS^{\text{EDS}}line^{\text{line}}scanning}^{\text{scanning}}results^{\text{results}}show^{\text{show}}that^{\text{that}}the^{\text{the}}mamajoralloying}^{\text{alloying}}ele$ $ments,^{\text{elements}}such^{\text{such}}asNi^{\text{as}}and^{\text{Ni}} \quad Cr,^{\text{and}}are^{\text{Cr}}, \quad distributed^{\text{aredistributed}}uniformly^{\text{uniformly}}from^{\text{from}}the$ $the SZ \quad to^{\text{SZ}} \quad the^{\text{to}} \quad the^{\text{RZ}},^{\text{RZ}}as \quad as shown^{\text{shown}}in \quad i^{\text{Figure}}Figure^{\text{Figure}}13^{13}. The^{\text{The}}fluctuations^{\text{fluctuations}}of^{\text{form}}some$ $elements are^{\text{are}}mainly due^{\text{due}}to^{\text{to}}the^{\text{the}}detections of^{\text{of}}precprecipitations. However, the^{\text{the}}Nb^{\text{Nb}}and^{\text{a}}$ $^{\text{nd}}Mo^{\text{Mo}}elements are^{\text{are}}$ $distributed more uniformly in^{\text{in}}the^{\text{the}}RZ^{\text{RZ}}compared to^{\text{to}}in^{\text{in}}the^{\text{the}}SZ^{\text{SZ}}. This^{\text{This}}is^{\text{is}}mainly due^{\text{due}}to^{\text{to}}the^{\text{the}}segregation of^{\text{of}}Nb^{\text{Nb}}and Mo elementse ts in the SZ to to form alarge amount of of MC MC type-type carbide carbide and Laves Laves phases phases, while while the the degree degree of segregation regation of the alloying alloying elements in the in the RZ RZ is weak, is and k, and the the precipitated precipitated phase phase is low in addition. In the ion, degree the degree segregation of segregation of segregation of the layer interior, this is due to Nb and Mo elements segregating and forming a large amount of Laves phase.$

compared $^{\text{Materials}2020}$ to 13 in $^{.4416}$ the layer interior, this is due to Nb and Mo elements segregating and forming a^{11} large 016 amount of Laves phase.

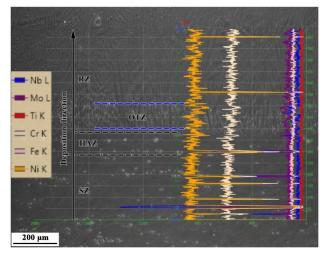


Figure 13. EDS line scanning results of the LARed Inconel 625 alloy sample along the deposition

Figure 13. EDS line scanning results of the LARed Inconel 625 alloy sample along the deposition direction.

direction.

- 3.3. Mechanical Properties
- 3.3. Mechanical Properties
- 3.3.1. Hardness
- 3.3.1. Hardness

Figure 14 shows the Vickers hardness along the deposition direction, around the repaired interface.

The

hardnessFigure14valuesshowshavethe

no Vickers notable hardinesse rence along between deposition the SZ and direction, RZ. The around average the hardness repaired is interpretate oximately. The hardness 24020 HV values.

have no notable difference between the SZ and RZ. The average

hardnessThe microisapproximately-mechanical 240properties±20HVof. the LARed Inconel 625 alloy samples were evaluated using a nanoindentationThemicro-

mechanical for the reduced properties modulus of the (ELARedr) and microhardness Inconel 625 alloy (H) saround mples thw e rerepaired evaluated interface using. The ananoind entation ion for load the-

depthreducedcurvesmodulusfthematrix(E) and phasemic robardness die rentzones(H)

of around the LARed the

repairedsamples

 $interface {\it are shown}. The in Figure nano indentation {\it 15}. The {\it responses} load-depth {\it of the shown} is a constant of the {\it responses} and {\it of the shown}. The {\it interface are shown} is a constant of {\it of the shown} is a constant$

thecurvesLARedof theInconelmatrix625 phasealloy arein predominantlydifferentzones plastic,ofthe LARedalthoughsamplessomeelasticare

shownrecoveryinuponFigurerelease15a .ofThethe loadresponsescanalsoof

betheobservedLARed. Inconelboth figures,625alloysmallare

plateauredominantlycanbeseenplastic, at the although maximum some load, elastic which recovery is indicative upon release of crep of in the the load Inconel can also 625 be alloy observed.. In both The figures, resultant small load-depth plateau curves can be werse en used at the to max obtain um nthe Hload, nd which Erby employing is indicative the of procedure creep in the of Inconel Oliver and 625 Pharralloy. [36]. The E_r was then used, together with Poisson's ratio (), to calculate the elastic modulus The resultant (E) from the load following-depth curve sequation: were used to obtain the H and Er by employing the procedure of Oliver and Pharr [36]. The Er was then used, together with Poisson's ratio (v), to calculate the

where E is the elastic modulus of the indenter (1140 GPa) is 7 its Poisson's ratio (0.07) is Furthermore, the Poisson's ratio used for the Inconel 625 alloy was set to 0.303 [38]. The obtained whindentation E is the modulus elastic

 $(modulus Er) and microhardness of the indenter (H(1140) data GPa) of the and LARed \emph{vi} is its Incone IPoisson's 625 ratio alloy (0 sample .07) [37] in. Furth dierent rmore, zone stheare Poisson's shown in Figure ratio used 15b. for The the Er values Inconel for 625 dialloyerent was zone set reveal to 0.303 imperceptible [38]. The obt changes in ed.$

The indentatimic ro hardness modulus of (the Er) matrix and microhardness phase in the RZ(H) is data approximately fthe LARed 5.1

GPa,Inconelwhich625isalloyslightlysamplehigherin differentthanthat ofzonesthe SZare(approximatelyshowninFigure4.8 GPa)15b.. Theis Eisr duevaluestotheforweakeningdifferet zonesofthe sregregationvealimperceptibleoftheNb changesandMo.alloyingThemicrohardnesselementsintheof RZthe. Inmaddition,trixphasetheinmicrohardnesstheRZisapproximatelyofthematrix5phase.1GPa,in thewhichHAZis slightlygenerallyhigherdemonstratesthanthat

lofwerthevalueSZ(appproximately44.8.6 GPa)... This is attributed due to the toweakening the dissolution of the of type of carbide the Nbandand Laves Moalloying phases and elements the growth in the of RZ the. In grains addition, in the the HAZ microhardness. In particular, of the matic rohardness ix phase in of the the distributed due to the tower and the distributed due to the the MC-type of carbide the Nbandand Laves Moalloying phases and elements the growth in the the tributed due to the tower and the distributed due to the tower and the tributed due to the tributed due to the tower and the tributed due to the tower and the tributed due to the tri

demonstrates the OTZ is approximately lower value 4.7

(approximately GPa, which is slightly 4.6 GPa) lower. This than is

attributedthatoflayerto

inttheriordissolutionintheRZof(approximattheMC-

typely carbide 5.1 GPa) and. The Laves formation phases

 $and {\it of abundant} the growth {\it Laves} of the {\it phases} grains$

inthetheOTZHAZisdue.In

toparticular,thelarge

the segregation microhardness of alloying of the elem a trix ents

 $Nb phase and in Mothe. The OTZ Laves is approximately {\tt phase} is brittle 4.7$

GPa,harmfulwhichphase,is

andslightlyconsumeslowr

at han large that amount of layer of Nb interior and Mo, in and the decreases RZ (approximately the approximately the

mount

5**of**.1

NbGPa)and.

TheMo

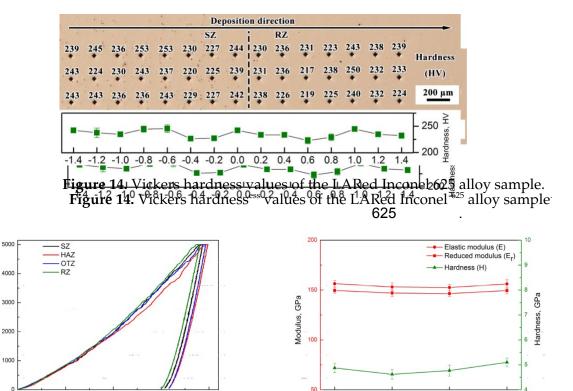
 $formation in the {\it matrix}, of a bundant {\it which} leads Laves to the phases {\it decrease} in the {\it of} OTZ the {\it microscopic to the phases} decrease in the {\it of} OTZ the {\it microscopic to the phases} decrease in the {\it of} OTZ the {\it microscopic to the phases} decrease in the {\it of} OTZ the {\it microscopic to the phases} decrease in the {\it of} OTZ the {\it microscopic to the phases} decrease in the {\it of} OTZ the {\it of}$

 $ohardness is due to the large of the segregation matrix phase of alloying the {\tt OTZ} elements.$

Nb and Mo. The Laves phase is a brittle harmful phase, and consumes a large amount of Nb and Mo,

and *Materials* decreases **2020**, *13*, xthe FOR amount PEERREVIEW of Nb and Mo in the matrix, which leads to the decrease of 12 theof 16 microhardness of the matrix phase in the OTZ.

Materials and decreases ²⁰²⁰, ¹³, ⁴⁴¹⁶ the amount of Nb and Mo in the matrix, which leads to the decrease of ¹² of the ¹⁶ microhardness of the matrix phase in the OTZ.



SZ

SZ

HAZ

(b)

OTZ

OTZ

RZ

RZ

Figure 15. (a) Nanoindentation load–depth curves and (b) indentation modulus and hardness data of **Figure 15.** (a) Nanoindentation load–depth curves and (b) indentation modulus and hardness data of (a) (b) thethematrixmatrixphasephaseinindifferentdier entzoneszonesofofthetheLARedLARedsamples.

Figure 15. (a) Nanoindentation load–depth curves and (b) indentation modulus and hardness data of $3^3.3^3.2^2$. TensilethematrixTestsphase in different zones of the LARed samples.

200

The robintemperature tensile properties of the the LARedsample and the attreated wrought Tests

substrate are listed in Table 3. The tensilestrength and ductility of LARedsamples are similar to the rooms ile properties edis sample and the those of the wrought substrate which indicates that LARIS are liable approach for damage dand missubste are listed in Table 3. The of tensile strength and ductility of LARed samples are

tr- similar to

昗

Load

50

100

Indentation Depth, nm

mis-machinedcomponentsmadeof the Inconel 625 all loy.
those of the wrought substrate, which indic tes that LAR reliable approach for damaged is compare the tensile behaviors of the samples in the various conditions, tensile testing of

Table 3. Room temperature tensile properties of wrought and LARed Inconel 625 alloy samples.

compare the tensile behaviors f the samples in the various conditions, tensile testing the samples are almost the same, which indicates that they have similar the large that they have similar they have similar the large that they have similar they have similar

samplecurves stressarealmostlevel thatspecimenstheyhaveinallsimilarcases ten 587 3 44.7 0.5 45.0 0.7 properties. The LARed sample demonstrative of the stress strain curves in the stress ample and yields at a different stress level.	andoftheyieldsdifferentatadifferentsamples .theAftersameyielding,whichtheindicatestensile isileshow LARed sample 908 5 tes a slightly steeper elastic response than the clastic elongation, period before 43.7 0.3 vel. After yielding, the tensile specimens in all
cases show	$almost {\bf Table} parallel {\bf 3.} Roomstress temperature-$
straincurvestenileinpropertiestheplasticofe	longationwroughtandperiodLARedbeforeIncon
elfracture625alloy. samples.	
	the samples in the various conditions, tensile
	d the results are shown in Figure 16. The tensile
Ultimate _{Tensile} Are of wrought and LARed Inconel 625 alloy sam	a Table 3. Room temperature tensile properties uples.
Yie	eld Streng Elongation
In the second	ie, which indicates that they have similar tensile
The Number ARed Strength sampleste demonstrates Ultimate slightly Tensile	epero-elastic(Mpa)response6than(%)ction the
ch (Mna)	Violation of Floreston W(0/)
yi aldsost pada erent stress levela After yield	Yield Strength Elongation. Ψ(%) ing, the tensile specimens in all cases show liel
Number Strength stressLARed-strainsamplecurvs In the the	od beforeo5870.2(Mpa)±3fracture.

stressLARed-strainsamplec plastic908elongation±5	urvs Yn	the 44. 6 7 ±(%)0.5	7 0.12(17) pa) ±5 11 dota10.	45.0 ± 0.7		
Wrought	σb (Mpa)			Ψ (%)		
Wrought substrate	914±4	572±6	45.3 ± 0.4	43.7 ± 0.3		
LARed sample	908±5	587±3	44.7 ± 0.5	45.0 ± 0.7		
Wrought substrate	914±4	572±6	45.3 ± 0.4	43.7 ± 0.3		

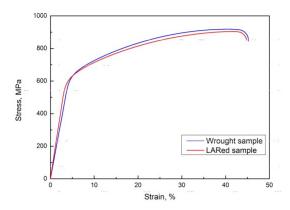


Figure 16. Typical tensile test curves of LARed sample and wrought substrate.

Figure 16. Typical tensile test curves of LARed sample and wrought substrate **Figure 16.** Typical tensile test curves of LARed sample and wrought substrate

Figure 17 shows the fractographs of the wrought sample. The fracture surface of the wrought Figure 17 shows the fractographs of the wrought sample. The fracture surface of the wrought

Figure 17 shows the fractographs of the wrought sample. The fracture surface of the wrought sample exhibits fine dimples, which indicate a ductile mode of failure associated with good tensile sample exhibits fine dimples, which indicate a ductile mode of failure associated with good tensile

sample exhibits fine dimples, which indicate a ductile mode of failure associated with good tensile properties. In addition, a large number of secondary cracks can be found. The fractograph of the properties. In addition, a large number of secondary cracks can be found. The fractograph of the

properties. In addition, a large number of secondary cracks can be found. The fractograph of the wrought sample shows a distinct morphology, with MC-type carbides inside the larger dimples. At the wrought sample shows a distinct morphology, with MC-type carbides inside the larger dimples. At

wrought sample shows a distinct morphology, with MC-type carbides inside the larger dimples. At same time, the second phase MC-type carbides are torn, as shown in Figure 17b. It is evident that the same time, the second phase MC-type carbides are torn, as shown in Figure 17b. It is evident that

the same time, the second phase MC-type carbides are torn, as shown in Figure 17b. It is evident that the MC-type carbides are primarily responsible for making the fracture process easier by providing the MC-type carbides are primarily responsible for making the fracture process easier by providing

the MC-type carbides are primarily responsible for making the fracture process easier by providing favorable sites for excessive microvoid initiation, and the growth of macroscopic cracks

favorable sites for excessive microvoid initiation, and the growth of macroscopic cracks. favorable sites for excessive microvoid initiation, and the growth of macroscopic cracks.

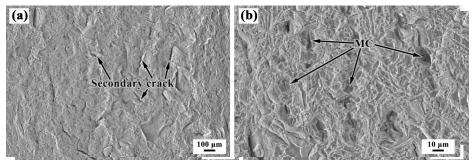


Figure 17. Fractographs of the wrought substrate sample at (a) low and (b) high magnifications.

Figure 1717. Fractographs. of of the thewrought substrates ubstrates ample at at (a() alow) low and and (b() bhigh) high magnifications magnifications.

Figure 18 shows the fractographs of the LARed sample. A mixed fracture occurred in the Figure 18 shows, how, the the fractographs fractographs of the other practice. The samples which included the SZ and RZ, and the fractographs are quite different, as shown in Figure which samples, mithed which included the SZ and RZ, and the fractographs are quite different, as shown in Figure which samples, included which included size of quite effect different, as shown in Figure 18 shows the high-magnification SEM image of the SZ, which is similar to the wrought Figure 18 bhows the high-magnification SEM image of the SZ, which is similar to the wrought Figure 18 shows the high-magnification SEM image of the SZ, which is similar magnification. SEMimage SEMimage SEMimage SEMO finage the SZ contains a dimpled surface indicative of ductile failure, and where fracture of the SZ contains a dimpled surface indicative of ductile failure, and where sample where the fracture theory contains a dimpled surface indicative of ductile failure, as where fracture theory contains a dimpled surface indicative of ductile failure, as surface dimpled indicative surface of indicaductileve failure of ductile and failure in surface dimpled indicative surface of indicaductileve failure of ductile and failure in surface dimpled indicative surface dimples and tear edges in the RZ fracture have a particles inside the large dimples. The dimples and tear edges in the RZ fracture have a particles inside the large dimples inside final particles in the failure of ductile and the surface dimples and the read and the surface of indicative surface indicative dimples and the surface indicative distributed in the sample, the surface of indicated the surface of indicated indicative of ductile and the surface indicative distributed in the sample, the surface of indicated indicative indicati

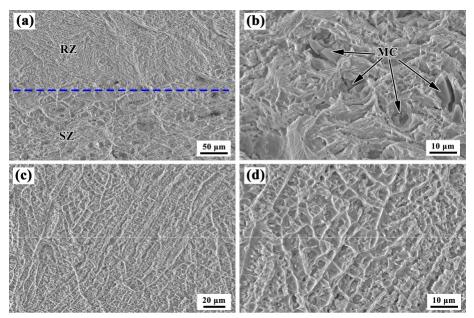


Figure 18. Fractograph of the LARed sample: (a) SZ+RZ, (b) SZ, and (c,d) RZ.

Figure 18. Fractograph of the LARed sample: (a) SZ+RZ, (b) SZ, and (c,d) RZ.

RZ.

4. Conclusions

carbidesLavesandare

In this paper,, Inconelc 1 625 alloy substratest with premade trapezoidal groove shaped defects were repaired using LAR. The microstructuresstr ts around the repairedir interfacet rf and the corresponding mechanical properties were investigated.. The conclusions are outlined below::

- The microstructurearound the the repaired repaired interface interface of of aLARed Inconel Inconel 625 $can^{\text{bedivided}}bedivided^{\text{into}}$ 625^{alloy}alloy^{can} three into three zones: zonthes: SZ, the HAZ, SZ, HAZ, and and and and and are RZSZ. The has SZatypicalhas $typical^{equiaxed} equiaxed^{crystal} \textbf{struc} crys \textbf{t}^{ure} alstructure^{witha} bimodal with$ grain_{bimodal}size grain distribution, sizedistribution, while in the while HAZ, in recrystallization the HAZ, recrystallization occurs and leads occurs to significant and leads grain to $grain^{\text{theRZ}}, growth^{\text{there.}} \cdot \text{areIn} \qquad \text{}^{\text{very}} theRZ, \text{}^{\text{large}} there^{\text{columnar}} are very^{\text{grains}}, large$ growth significant. In and columnar the size grains, of the and columns the size increases of the with columns an increases with the number an increase of deposited layers.
- precipitatesin thein SZthemainlySZmaiconsistly consistoflarge (approximatelyoflarge(approxi10m)atelyand small10μm)(approximatelyandsmall O(approximately.5m)block-shaped0.5µm)MCblock-type-shapedcarbiesMC(MtypeisNbcarbiand esTi)(MandisirregularlyNbandTi)shapednd irregularlyflocculent Lavesshapedphaseflocculent.IntheLavesHAZ,phasethere. areInthestillHAZ,manytherelargeareblockstill-shapedmany largeMCtypeblockcarbides,-shaped butMCsom-type precipitatescarbides, but dissolve ome precipitatesintheoriginaldissolvegrainboundaries in the original. For thegrainRZ,boundariessomeLaves.ForandthefewRZ,MCsome-typ

precipitatedfewMC-

typealongcarbidestheepitaxialareprecipitatedgrowthdendriticalongboundartheepitaxial es. growth dendritic

Theboundamicrostructureies. between two adjacent deposited tracks presented an overlapping transition

zoneThemicrostructure(OTZ), which the between dendritic two structure adjacent coarsene d,depositedandtracksmorepresentedLavesphasen ovprerlappingcipitated the(OTZ), layer which interior the. The den width ritic of comparedtransition tozonein structuretheOTZ wascoarsened, approximately and more 0.15

Lavesmm. The phase lower precip GR intated he

OTZcomparedledtotoaninincreasethelayerin interiordendrite. Thearmwidthspacing of theandOTZthe formwasationpproximatelyoftheLaves0.15phasemm.. The lower TheG·R inVickerstheOTZ_{hardness}ledtoan_{and}increaseindentationdendrite_{modulus}arm spacing_{fromthe}and_{sz}the_{to} formation_{theRZalong}ofthe_{the}Laves_{deposition}phase.

 $dir Thection \textit{Vickers} were \textit{^{hardness}} not notably \textit{^{and}} diindentationer ent the \textit{^{modulus}} LARed$ samples, from the and SZ $were {}^{to the} approximately {}^{RZalong the} 240 {}^{deposition} 20 HV. \\$ The direction microhardness were not notably of the matrix different phase in the inthe LARed RZ (approximately samples, and were 5.1GPa) approximately was slightly 240 higher ±20 $of^{\textit{microhardness}} the SZ (approximately^{\textit{ofthematrix}} 4.8 GPa), \textit{phase} while \textit{in the the}$ that^{The} slightly alower RZmicroha^{(app}rdness^{oximately}generally^{5.1GPa)}achieved^{was} value higher (approximately than that of the 4. SZ 6GPa) (approximately in the HAZ. particular, GPa), while the the microhardness microhardness of the generally matrix achieved phase in $the^{alower}OTZ$ ⁴GPa.^{.6GPa)}whichⁱⁿ thewas HAZ slightly. In value was (approximately 4.7 lower^{particular},than thatthe of microhardness layer interior ofin. the RZ^{matrix}(approximately^{phaseinthe}5.1^{OTZ}GPa)^{was}.The^{approximately}fluctuationof $microhardness {}^{GPa,whichwas} of \\$ the slightly matrix lower phase than around that the of $repaired {}^{layer interior} interface {}^{the}was {}^{RZ} mainly (approximately caused by a constant of the constant of the$ segregation GPa). The fluctuation of the Nb and of the Momicrohardness allowing elements of the .

matrix phase around the repaired interface was mainly caused by the segregation of the Nb

The yield strength and elastic modulus of the LARed samples were higher than those of

Mo alloying elements. wrought sample. The tensile strength and ductility of the LARed samples were similar to those of

The yield strength and elastic modulus of the LARed samples were higher than those of the the wrought sample. Both the SZ and RZ presented a dimple fracture surface, and a large number wrought sample. The tensile strength and ductility of the LARed samples were similar to those of secondary cracks could be found in the SZ. The dimples and tear edges had a clear orientation of the wrought sample. Both the SZ and RZ presented a dimple fracture surface, and a large number of secondary cracks could be found in the SZ. The dimples and tear edges had a clear in the RZ. The comprehensive tensile properties of the LARed Inconel 625 alloy are equivalent to those of the wrought alloy.

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