Microstructures of high-strength steel welding consumables from directed thermal cycles by shaped laser pulses

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Abstract

Filler wire metallurgy was modified through temporally shaped laser pulses, controlling cooling cycles in a recently developed method. Trends were identified through efficient mapping while maintaining representative thermal cycles of welding processes. A primary pulse melted preplaced filler wires while a secondary, linearly ramped-down pulse elevated the nugget to re-austenization temperatures. Ramped-down pulses resulted in linear cooling rates comparable with and exceeding furnace-based methods, between 50 and 300 °C/s. The linear decay of laser output power guided the temperature through a regime to obtain desired microstructures. For three very high-strength steel filler wire chemistries, quenching resulted in smaller plates with cross-hatched microstructures, accompanied by grain boundary ferrite. Finer bainite microstructures started forming for fast linear temperature decay, about 250 °C/s. Slower decay or a weaker third cycle formed coarser microstructures with coalescent sheaves and less cross-hatching.

Keywords Filler wire · Consumable · Welding · Thermal cycle · Microstructure · Cooling rate

1 Introduction

Systematic study of weld wire consumable microstructures subjected to unique thermal cycles during welding is desirable for improved understanding of underlying mechanisms. The weld metal and heat-affected zone (HAZ) show large changes in microstructural composition after welding, even over small distances, due to region-specific thermal histories. Chemical variations between specific microstructural regions present challenges for mechanism identification.

High-strength steel filler wires are investigated here, aiming to achieve high toughness with improved understanding and advanced chemical concepts. Particular focus is given to quenched and tempered (Q+T) steels with yield strengths above 960 MPa where there are few appropriate filler materials. These grades of steel are applied in thicknesses greater than 8 mm, challenging thicknesses for single-pass laser keyhole welding. Advanced methods for

welding 50-mm-thick high-strength low-alloy (HSLA) steel include double-sided gas metal arc welding (GMAW), studied by Chen et al. [1]; however, this is only applicable where access to both sides of the sheet are possible. When this is not possible, multi-layer techniques can be used, such as the multi-layer technique developed and optimized by Li et al. [2] for 30-mm-thick steel plates. However, each weld pass experiences multiple and varied thermal cycles with dissimilar cooling rates. Overlapping of pulsed laser exposure was studied in detail by Chatterjee et al. [3], with detailed analysis of microstructures in laser beam-welded dissimilar metals [4, 5].

Kurc-Lisiecka and Lisiecka [6] studied rapid cooling rates, generated by low thermal inputs, with $t_{8/5}$ times ranging between 0.6 and 1.3 s. These cooling rates yielded microstructures of allotriomorphic ferrite (α), polygonal ferrite (α_f), fine-grained upper and lower bainite (α_b , α_{lb}), and martensitic islands (α'). Acicular ferrite (α_a) is associated with increased toughness, and was described by Loder et al. [7] to compete with bainite formation in the presence of non-metallic inclusions (NMI). Fattahi et al. [8] found NMIs with a minimum diameter of 0.2 μm to be favorable, while Sarma et al. [9] found that 10–36% of inclusions at this size started α_a -nucleation. Acceptable mechanical properties of welded R4 grade steel were

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reported by Jorge et al. [10], with tensile strengths of the weld metals obtaining up to 860 MPa. The influence of NMIs on the mechanical properties and workability of down-stream processes was evaluated by Gupta et al. [11]. The microstructure of a GMAW, for a heat input of 1.8 kJ/mm and a post weld heat treatment of 600 °C for 2 h, consisted of tempered α' and α ; the Mn and Cr content was higher than the here studied consumables, while the C and Si content was lower. The thermal cycles that result from multi-pass techniques affect the microstructure through two temperature-dependent mechanisms, recrystallization or grain growth. The final shape, size, and type of grains were found by Liu et al. [12] to be influenced by multiple thermal cycles.

Pipe-line steels grades (of at least grade X80) face similar challenges with microstructures and toughness behavior of weld metals in cold climate operations, below -60 °C. GMAW of X80 at a traveling speed of 5 m/min was demonstrated by Midawi et al. [13] using two similar consumables chemistries to the here studied pipeline wire consumable. Their wire contained lower amounts of Mn and Ni. The weld diluted 30% with a primarily interlocking α_a microstructure with NMIs detected. Grain boundary α was observed with a fraction of α_I . When cooling rates of 20–30 °C/s occur, desirable acicular microstructures can be achieved, avoiding α_I and α , with similar results found by Tang and Waldo [14]. Keehan et al. [15] found that cooling times of $t_{8/5} = 3 - 13$ s changed a mainly α_{lb} and α' mix with interspersed coalesced bainite to a relatively fine α_b and α_{lb} mixture. Tang and Waldo [14] enhanced α_a formation with increased Mo concentrations, with dual parallel lath α_a , while Madariaga et al. [16] showed increased volume fractions of α_a using two-stage cooling with lower cooling rates.

Competitive formation of α , α_I , and α_W is repressed by Ti-based inclusions, which was determined by Blais et al. [17]. Lee et al. [18] found that Ti-oxide, Ti oxysulfide, and Ti-Ca-oxysulfide inclusions can influence austenite (γ) grain size, and inclusion density. Jung et al. [19] studied migration of boron to grain boundaries in relation to increasing NMI nucleation potential. Zhang et al. [20] found a lower degree of mismatching between the nucleants and the crystal structure, resulting in higher nucleation potential of Ti inclusions containing O and N. Kang et al. [21] observed a Mn depleted zone (a result from the short diffusion range of Mn) with increased amounts of Ti inclusions, which enhanced α_a nucleation.

Microstructures can be tailored from the melt directly or through thermal post-heat treatments, altering an existing microstructure. The primary is exemplified by a furnace-melted homogeneous sample subjected to heat treatment, having the transient metallurgy during cooling being observed in situ (recording at 15 fps) by a laser scanning

confocal microscope, demonstrated by Wan et al. [22], or by a ceramic-covered steel substrate dipping technique shown by Loder and Michelic [23]. Tempering post-processing heat treatments have been studied by Nouredine and Allaoui [24], showing improved mechanical properties in X70 HSLA weldaments. A post-welding heat treatment approach was studied with Gleeble systems, which are advanced thermal cycling equipment, utilized by Moeinifar et al. [25] to emulate multi-layer depositions thermally. Similarly, Fu et al. [26] investigated the changes of the microstructures for specific thermal treatments. The ability to isolate the thermal behavior is of significant importance to many fields, particularly in additive manufacturing that also is highly dependent on high quality parts. In additive manufacturing, Yan et al. [27] studied and identified the thermal signatures that lead to characteristic microstructures and deformations.

Applications using filler wire material cannot be directly modelled in the above manner. Microstructural alterations can be achieved with extended cooling cycles, special wire chemistries, or through multiple thermal cycling, which are hereby demonstrated using the “Snapshot” method. Filler wire characterization is typically done via multiple, wide GMAW tracks, for extraction that is then mechanically tested, e.g., via tensile and Charpy V-notch tests. The link from thermal cycles to microstructures is not provided by this method, and further, the sample is composed of heterogeneously melted wire under multiple heating cycles. Lalam et al. [28, 29] created a neural network of weld metal properties in literature to initiate linking of mechanical properties (understood on a qualitative basis) of ferritic steel welds to the conditions that they experience, described as dependencies of chemistry, thermal input, and post weld heat treatment.

Robertson et al. [30] recently developed a proficient technique for investigating filler wire microstructures, designated as the “Snapshot” method, by drilling a pocket into a metal plate, inserting cut wire lengths, and fusing a sample nugget by laser beam exposure. The thermal cycle is expected to be representative of seam welding. This approach easily provides alternatives via temporal shaping of the laser pulse to achieve customized thermal cycles, even multiple cycles.

Thermocouples, pyrometers, or thermal imaging can measure the thermal history experienced at a specific position of the welded metal, with limitations as explored by Sundqvist et al. [31]. Here, for the Snapshot method, it was preferred to apply a technique known as Dualscope, based on high-speed imaging (HSI) where the camera image is split into two domains, each recording the process in a different spectral window, which enables the unknown emissivity to be cancelled out when deriving the temperature field. Similar methods are being developed, like those used by Devesse et al. [32], with progression of more accurate emissivity identification. Emission-based measurements are

limited to surface temperature measurements, while Abderazak et al. [33] employed computation fluid dynamics to predict volumetric temperature fields. During welding, complex melt pool convections can alter the temperature field, as was observed by Sundqvist et al. [31], depending on the driving forces like Marangoni convection accelerated by surface tension gradients or flow initiated by laser-induced ablation pressure. Chemical inhomogeneity of the weld metal arises from base metal diluting into the wire material. Investigations on the effect of pulse shape variants, and hence the thermal history, on the microstructure were examined for laser spot welding, employing combinations of ramping laser power, as demonstrated by Bertrand and Poulon-Quintin [34] in the use of dissimilar metals in dental applications.

Here, wire consumables for the high-strength structural steel S960QL of yield strength >960 MPa and of pipeline grade X80 are studied. These steels are typically used with welding techniques like laser arc hybrid welding (LAHW) and narrow gap multi-layer welding (NGMLW) due to their lower cooling rates than GMAW. The recently developed efficient Snapshot technique is demonstrated here for the first time for systematic study of microstructure trends depending on different thermal cycles. To the knowledge of the authors, no method exists to mimic welding processes from granular components for metallographic studies at heating and cooling rates comparable with laser beam welding. Thermal cycles that are representative of many welding techniques (i.e., laser beam welding and narrow gap multi-layer welding) in a stationary manner were achieved with the use of long exposure to laser beam radiation. The modulation of the laser power was assumed to replicate the moving heat source in traditional welding, allowing for a more gradual cooling rate.

2 Methodology

The highly efficient Snapshot method is a technique that was originally demonstrated for observation of microstructural evolution originating from characteristic laser pulse-driven thermal cycles, see Fig. 1. Shaping the laser pulse, exhibited by Robertson et al. [30], alters the thermal cycle in a manner that is representative of welding methods that use filler wire. The wire and base metal can be processed together to observe material mixing, and microstructures for a unique thermal cycle, or the individual materials can be processed individually to determine their individual impacts for the processing cycle. The Snapshot method offers the opportunity to study weld metal microstructures in the solid phase, starting from austenization temperature. The application can, in principle, be applied for any welding technique and even other steel-processing techniques, e.g., additive

Fig. 1 (a) Schematic of the “Snapshot” method (with: a—laser beam, b—laser beam inclination angle, c—focal plane position, d—cavity with cut wire pieces, e—base metal sheet, f—Dualscope camera). (b) Laser beam power as a function of time, schematically, for the pulse sequences: square pulse (duration t_1) for melting and an elective second reheating pulse linearly ramped down (duration t_2 , four pulse variants indicated)

manufacturing or heat treatment. The Snapshot method is particularly suitable for laser welding techniques because it achieves high cooling rates. Extended temporal pulsing was used previously to tailor the microstructure of the weld metal from the molten state, where it has been adapted further here to mimic multi-cyclic processes.

Here studied are two commercially available solid HSLA steel filler wires, provided by the wire manufacturing company Lincoln Electric. The wires are designated as LNM MoNiCr (EN ISO 16834-A: G Mn4Ni2CrMo), an under-matched wire for Q+T steel S960QL, and as LNM MoNiVa (EN ISO 16834-A: G M Mn3Ni1CrM), an over-matched wire for pipeline steel X80. In addition, a novel, developmental metal-cored wire was investigated, LNM MoNiCr-9X. This filler wire demonstrated a very high impact strength for its higher alloying content. All filler wires are designed to provide high toughness, with the investigation of improving mechanical properties by altering microstructural composition via thermal cycle tailoring. The chemical composition and mechanical properties of the base metals and associated filler wires are found in Tables 1 and 2, respectively.

Holes were drilled into 12-mm-thick sheets of S960QL steel with a diameter of 5.5 mm and a depth of 7 mm, as shown in Fig. 1(a). All of the wires had a diameter of 1.2 mm and were shortened to 8 mm lengths. Each hole contained 16 acetone cleaned wire pieces that were vertically inserted. The wires were arranged to tightly pack the cavity and reduce the voids between the wires. Excess wire above the cavity rim was ground flush to the base plate to provide a flat processing surface for the laser beam. A continuous wave (cw) IPG YLR-15000 Yb: fiber laser (1070 ± 10 nm wavelength) with a nominal output power of 15,000 W produced the laser beam. Optionally, the laser beam can be operated in pulsed mode with pulse lengths >200 μ s.

Table 1 Chemical composition (wt.%) of the here studied base metals and wires (balance: Fe)

	Material	C ^{*J}	Si ^{*J}	Mn ^{*J}	P	S	Cu ^{*J}	Mo ^{*J}	Ni ^{*J}	Cr ^{*J}	B ^{*J}
Base metal	S960QL ^{*T}	0.20	0.50	1.60	0.020	0.010	0.300	0.700	2.000	0.800	0.005
	X80 ^{*A}	0.03	0.21	1.78	0.013	0.003	0.008	0.183	0.013	0.158	0.001
Wire	LNM MoNiCr ^{*T}	0.09	0.80	1.80	—	—	—	0.550	2.200	0.300	—
	LNM MoNiVa ^{*T}	0.08	0.44	1.70	—	—	0.250	0.300	1.350	0.230	—
	LNM MoNiCr-9X ^{*A}	0.11	0.60	1.45	0.011	0.010	—	(Mo+Ni+Cr = 2.54)			—

^{*J}Intentional alloying elements, ^{*T}Typical values, ^{*A}Actual values

A 400- μ m-diameter processing fiber guided the beam into a Precitec YW52 optics by which it is focused (beam parameter product, BPP, 14.6 mm-mrad). The collimating and focusing lenses had focal lengths of 150 mm and 250 mm, respectively. Selected optical parameters of both the laser source and the optics are given in Table 3.

The laser beam was defocused by setting the focal plane 5 mm above the plate surface for the melting, square pulse (P_S) and 45 mm for the subsequent reheating pulse (P_{RhI} - P_{RhIV}). The beam diameters, measured at the plate surface, were approximately 0.8 mm and 4.0 mm, respectively. The chosen beam diameters ensured melting of the loose wires in the first step and avoiding remelting in the subsequent steps. Argon was utilized as the protective gas, to reduce surface oxidation, with a flow rate of 18 l/min. The step-by-step outline of the process is given in Table 4.

The pulse P_S is a square pulse of 2 kW for 8 s, see Fig. 1(b), which causes self-quenching conditions similar to those laser beam welding, yielding a solid nugget sample. These pulse parameters were chosen to promote melting of the wire material while avoiding fusion with the base metal. The Snapshot method can be altered in duration to allow for fusion and mixing the filler wire with the base metal. After reaching ambient conditions, a reheating pulse (P_{Rh}) was applied to sufficiently increase the nugget temperature, while remaining solid, to either recrystallize new γ -grains (if exceeding austenizing temperature A_3) or to temper the microstructure. Linear decrease of the pulse power is anticipated to linearly decrease the surface temperature. The above conditions are a part of a larger, systematic study of 88 combinations of pulse shapes, materials, and dilution rates.

Four pulsing cases designated by P_{Rh} (Fig. 1(b)) were studied with the parameters given in Table 5. The pulse shapes chosen here were assumed to have a similar thermal cycle to that of a moving heat source as seen in other welding methods. The use of a single or multiple pulses with various shapes offers many tailoring options for obtaining a particular thermal cycle strategy. The presented case utilizes a square pulse to generate an undiluted weld nugget that is convenient for further thermal processing. The square nature of the pulse yields a quenching cooling cycle that is representative to laser beam welding. The secondary pulse with decayed output power (ramped-pulse) simulates a reduced heat flux as in slower welding processes like arc welding or multi-layer processes. The gradient of the power decrease would then reflect on the speed at which the heat source would travel away from the measured point. The ramped-pulse also presents the opportunity to obtain austenization temperatures followed by linear cooling to a lower temperature, to enable controlled temperature conditions, like the thermal cycles that are used in furnaces to observe the formation of some microstructures.

For the demonstrated case, the initial square pulse fuses the only filler wire as in traditional wire-based processes with the option to fuse the filler material to the base metal (though it is not necessary). When only the wire material is processed, a case where the lack of fusion between the nugget and the substrate is the aim, it can be assumed that there is no change to the chemical composition of the wire material. This provides a controlled composition of material to be thermally processed. Additionally, if the material is not fused to the substrate, but is in contact with it, it is assumed

Table 2 Mechanical properties of the base metals and wires (all-weld metal)

	Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation A (%)	Impact strength (J)	
					−40 °C	−60 °C
Base metal	S960QL ^{*T}	960	980–1150	12	40	—
	X80 ^{*A}	550	690	18	240	235
Wire	LNM MoNiCr ^{*T}	> 890	950	> 15	70	> 50
	LNM MoNiVa ^{*T}	710	790	20	70	—
	LNM MoNiCr-9X ^{*A}	849	891	18	81	63

^{*T}Typical values, ^{*A}Actual values

Table 3 Selected parameters of the laser source and focusing optics

Characteristic	Value	Unit
Operation mode	Continuous wave (cw)	
Wavelength	1070 ± 10	nm
Nominal output power (cw)	15,000	W
Switch ON/OFF time	100	μsec
Laser source BPP	10.5	mm-mrad
Output fiber core diameter	400	μm
Collimating lens focal length	150	mm
Focusing lens focal length	250	mm
BPP after beam switch	14.6	mm-mrad
Beam diameter first pulse	0.8	mm
Beam diameter second pulse	4.0	mm

to have representative heat conductive environment as a weld. In the presented case, the first pulse provides controlled chemical conditions by melting wire pieces to a nugget, and the second pulse provides controlled heat treatment. The second pulse (and additional pulses, mimicking multiple thermal cycles) does not melt the nugget but it exceeds the austenization temperature, assuming to restart and carry out controlled microstructure development, by a controlled cooling cycle, e.g., a linear decay.

A second reheating pulse was also investigated, P_{Rh2} , with the same parameters as P_{RhIV} , after ambient

Table 4 Step-wise procedure of the Snapshot method

Step	Action
1	Prepare the base material hole to required dimensions
2	Cut filler wire to lengths greater than hole depth
3	Clean base plate and cut wires with acetone
4	Vertically insert wires until cavity is packed tightly
5	Use a grinder to remove excess wire material, such that the processing surface is flat
6	Attach thermocouples as desired (i.e., at surface, weld root, between wires, etc.) or set up thermal measuring devices
7	Place prepared sample underneath laser optics
8	Start thermal recording (continuous or per pulse)
9	Irradiate the wire until completely molten in a shielding gas-rich environment
10	Stop laser irradiation and defocus the laser beam
11	Design a temporal pulse shape
12	Re-irradiate the solid nugget without melting to induce additional thermal cycles
13	Evaluate thermal recording
14	Repeat steps 11 and 12 as necessary to replicate weld process
15	Select microstructural domain near thermal measurement which will be representative to welding (i.e., surface domain to compare with optical thermal measurements)

Table 5 Pulse parameters

Name	Initial power (W)	Final power (W)	Ramp time (s)
P_S	2000	2000	8
P_{RhI}	400	200	5
P_{RhII}	400	200	10
P_{RhIII}	300	200	5
P_{RhIV}	300	200	10
P_{Rh2}	300	200	10

conditions are obtained. For P_{Rh2} , the beam is transposed 2 mm off-axis from the original center, to spatially generate manifold thermal cycle combinations across a single nugget. This arrangement will alter the microstructure further through region-specific thermal treatment. Micrographs from nugget cross sections were obtained using optical microscopy methods in two locations, the center of the nugget and the top surface, for analysis of observed microstructure morphologies. A cold wire addition, laser-welded joint was made using a NGMLW technique. The sample was composed of 30-mm-thick S960QL (the same batch as used in the Snapshot method) with machined edges having a gap of 4 mm that was first butt-joint welded by autonomous laser beam welding at the 2-mm nose to prevent root humping (or root sagging). The same laser source was used, with comparable optics of the same focusing lengths (Table 3). Then, 1.2-mm-diameter LNM MoNiCr weld wire with a feed rate of 3.8 m/min was fed into the gap, using 6 kW continuous wave laser output power, traveling at a speed of 1.2 m/min to produce layer heights of approximately 1 mm. The laser beam was defocused to a spot diameter of 4.5 mm to ensure laser beam interaction with the sheet edges. The weld metal was then sampled and prepared using metallographic procedures for microstructural evaluation to then be compared with the Snapshot method.

The Dualscope method with HSI was utilized to record the thermal cycles. This device splits the image from the camera (RedLake Mono N4-S2, operated at 1000 fps, exposure time 30 μs, resolution 260 μ/px) into a left hand and right hand image. Each side has a unique bandpass filter (width 40 nm), the left a 680 nm and the right a 769 nm. Based on Planck's law and from a calibration curve via a sample in a furnace, the temperature is calculated. For the presented case, the temperature is calculated per pixel and time step, from the ratio of the grayscale values between the filtered right hand and left hand images. The Dualscope method has advantages compared with other measurement methods, like that it is contactless or that it reduces the uncertainty of the emissivity. The Dualscope, however, has limitations in the temperature range (for the most reliable range, 700–1200 °C was chosen, via exposure time) and is dependent on certain conditions, like saturation.

Fig. 2 Micrographs of GMAW. (a) LNM MoNiVa, (b) LNM MoNiCr; (c), (d) laser-melted LNM MoNiCr-9X, two magnifications

3 Results and discussion

The most significant microstructure trends of this first systematic Snapshot study are presented and discussed here, with respect to the aforementioned goals for enhancing the weld metal properties of high-strength steels. The results are provided in three sections: the microstructural analysis, the thermal analysis, and the comparison of Snapshot and NGMLW microstructures.

3.1 Microstructural analysis

Three wire types were used in this study: LNM MoNiCr, LNM MoNiVa, and LNM MoNiCr-9X. In Fig. 2(a, b), multi-layer GMAW microstructures (heat input 1.2 kJ/mm) are shown for LNM MoNiCr and LNM MoNiVa wire consumables as a reference to the microstructures produced by the Snapshot method. The cross-hatching microstructures indicate significant amount of α_a , which is desirable for high toughness. Figure 2(c, d) shows a typical microstructure from the Snapshot method (at two magnifications, here for LNM MoNiCr-9X, by P_{RhI}), tending to packages of parallel plates, oriented perpendicular to each other.

Figure 3 depicts natural quenching microstructures, P_S , compared with reheating P_{RhI} and P_{RhIV} , for LNM MoNiCr, Fig. 3(a–c), and for LNM MoNiCr-9X, Fig. 3(d–f). Representative areas i–iii are highlighted.

Plate-like structures are seen in all micrographs, marked by area i, with conglomerates of plates into single packages in area ii. The plates occur either in a parallel arrangement, iii in Fig. 3(a), or in 60° orientations, iii in Fig. 3(d). For P_{RhI} the plates become finer than for P_S . In the case of P_{RhIV} (Fig. 3(c, f) iii), the plates grew into each other (conglomeration) to join into a larger block, though in some regions it is still possible to see the secondary plates grow from a primary plate. The perpendicular cross-hatching of

Fig. 3 Micrographs of wires LNM MoNiCr (a–c) and LNM MoNiCr-9X (d–f); pulses: (a, d) P_S , (b, e) P_{RhI} , and (c, f) P_{RhIV} (typical areas i–iii, squares magnified)

the secondary plates and primary plates is exemplified in iii of Fig. 3(e), an indicator of α_a . Micro-alloying elements in the filler material allow for interlocked dendritic structures to form, even for grain refinement in prolonged cooling conditions. Both wires were designed for high toughness and as such tend to form a combination of α' , bainite, and in sufficient cooling times, α_a . High toughness can be expected from the interlocking structures found in both the natural quenching and the reheated samples. The enveloped dark phase appears to be NMIs. Larger segregations of dark phases appear to be martensitic in nature and are likely α' islands left from the transformation process, or α_{lb} . The higher alloyed wire LNM MoNiCr-9X behaved similar to LNM MoNiCr, with a slight tendency to more interlocking, finer plates, and smaller packages.

Micrographs of the processed pipeline wire are shown in Fig. 4. For quenching, thick, short plates (typically 2–4 μm wide, 5–15 μm long) were formed, in iii in Fig. 4(a), mostly interlocking, accompanied by α_{gb} , ii (up to 10 μm thick) and by NMIs. P_{RhIV} (Fig. 4(b)) leads to fine plates (less than 1 μm thin, 15–20 μm long), to a lesser extent interlocking (often as a singlet or doublet plate), i, and partially parallel, iii, with less α_{gb} , ii (rather 3–5 μm thin).

A weaker second reheating pulse (Fig. 4(c)) shows mainly parallel plates, ii, about 1 μm thin but coagulating to larger structures, i, in distinct blocks, while hardly any more grain boundaries can be seen, indicating tempering without re-austenization. All samples show that a combination of parallel and cross-hatched plates is formed, though to different extent. For all three wire materials, for the reheating cycles, the trend favors parallel (on cost of interlocking) plates that join to form conglomerates with extended heating.

Scanning electron microscopy (SEM) was used to further highlight some of the microstructural differences between pulse P_{RhI} and pulse P_{RhII} (Fig. 5) for the LNM MoNiVa filler wire. For the shorter pulse, P_{RhI} Fig. 5(a), the bainitic plates are very parallel and narrow. Plate widths are approximately 1 μm while several microns long. In the longer pulse, P_{RhII} Fig. 5(b), the plates begin to coalesce into larger structures, with widths between 3 and 5 μm .

Fig. 5 SEM micrographs at two different magnifications for the wire LNM MoNiVa for pulse cycle (a, c) P_{RhI} and (b, d) P_{RhII}

The large coalesced structures are nearly absent in higher magnification of Fig. 5(c) while a number of the coalesced structures are observed in Fig. 5(d). As was seen with optical microscopy, the longer pulse cycle lead to a coarser structure, with wider needles, coalesced grains, and more acicular structures.

3.2 Thermal analysis

The surface of a processed nugget is seen in Fig. 6(a). The temperature measurement during natural quenching typically led to surface temperature fields as seen in Fig. 6(b, c). Figure 6(d) shows a typical cooling cycle of the nugget surface after P_S , slowing down. Figure 6(e) shows the thermal cycle during P_{RhI} , showing an increase of the temperature (above A_3 , meaning recrystallization is realized), followed by an equilibrium/plateau and linear cooling.

Not measured but extrapolated is the subsequent quenching, towards martensite transition temperature, M_s . The measured linear cooling at (within limits) constant cooling rate is evidence of temperature control proportional to linear laser power ramp down, to generate a corresponding microstructure, systematically by the Snapshot method.

Fig. 4 Micrographs of wire LNM MoNiVa; pulses: (a) P_S , (b) P_{RhIV} , and (c) P_{Rh2} (typical areas i–iii, rectangles magnified)

Fig. 6 (a) Nugget surface appearance, (b), (c) measured temperature field at time 1.63 s and 1.81 s after switching-off P_S , (d) measured temperature decay (maximum and local average temperature) after P_S , quenching, (e) and after P_{RhI} , showing a linear decay

More complex pulses could lead to a cooling cycle that is guided past the M_S temperature, demonstrating complete control of the tailoring of the microstructure, even extension of a time spent at a given temperature.

3.3 Comparison of snapshot and NGMLW microstructures

The four chosen pulse cycles (the combination of the square pulse and the ramping pulse) were used to generate different conditions that are present in a NGMLW. The resulting microstructures from the Snapshot method are

then compared with the microstructures that were generated in a NGMLW using materials from the same batch, both the base material and filler wires.

The here generated microstructures show different morphology aspects than α_a -based microstructures in literature. The latter result from a vast amount of arc welding and Gleeble studies, mainly for lower strength wires and mostly for cooling rates in the range of 1–30 °C/s (for $t_{8/5}$), exceptionally up to 50 °C/s. Here the metal experienced 50–300 °C/s, representative for fast laser-based techniques like laser arc hybrid welding, causing typically 60–700 °C/s.

Fig. 7 Snapshot micrographs of (a) P_{RhI} , (b) P_{RhIII} , and (c) P_{RhIV} utilizing LNM MoNiCr filler wire, and comparable microstructural constituents in the weld cap of a NGMLW (d–f) (different locations

near the fusion line, increasing in lateral distance from (d) to (f) using LNM MoNiCr filler wire; bounding boxes indicate morphological similarities

Comparison of the microstructures found in the Snapshot method with a NGMLW shows similarities in the morphologies of the formed microstructures (Fig. 7). The composition of the NGMLW and the Snapshot is made up of bainites, ferrites, and martensite. The cross-hatching of microstructures has a tendency to increase toughness, while coalesced and tempered microstructures often yield lower impact toughness. The first, unpublished, mechanical testing of the NGMLW confirms this trend. The highlighted regions in Fig. 7 show where the morphologies of selected microstructures are similar, though the size of the grains and packets is different. Characterization of the morphologies is discussed further by Kaplan et al. [35], in a co-current work of the Snapshot method. This can be contributed to different cooling rates of the sampled Snapshot method to the weld cap for this particular NGMLW sample. Using other pulse shapes to obtain different cooling rates would then be able to replicate different sections of a large weld for microstructural evaluations.

4 Conclusions

A new, highly efficient method for testing filler wire material under controlled thermal cycling was proposed in this paper. Temporal pulse shaping yielded linear cooling rates of the weld metal, further providing varied microstructural compositions. The major findings are summarized as follows:

1. A recently developed testing method was demonstrated to enable an efficient, systematic study of the impact of tailored thermal cycles on the microstructure of welding consumables, to be replicated in the welding process.
2. Linear ramp down of laser power enabled the decrease of surface temperature in a linear manner, at constant high cooling rate in the range 50–300 °C/s, hence much faster than furnace-based methods and even including the molten state.
3. For the new highly alloyed consumable and the two commercial steel wires at their respective application strength limit, the main trends were similar; fast quenching of typically 200 °C/s has caused short, thicker plates of widely random orientation, which can be favorable for high toughness.
4. Fast cooling at constant rate in the range 200–300 °C/s caused more parallel, thinner plates, indicating bainite, while four times slower cooling generated coarser packets in which plates coagulated, even more pronounced for a weaker third pulse.
5. Systematic representative mapping and improved understanding through the Snapshot method can facilitate optimization of the filler wire chemistry, welding processes, and hence the generated weld metal properties.
6. Comparable microstructural components were observed between the Snapshot method and a NGMLW having the same material composition.

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