Numerical Analysis of Solidification Behavior during Laser Welding Nickel-based Single-crystal Superalloy Part III: Auspicious Control of Dendrite Tip Undercooling

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Abstract. Location-dependent dendrite tip undercooling is numerically elucidated to predict crystallography-assisted resistance to centerline grain boundary formation and morphology transition of stray grain formation ahead of dendrite tip in the ternary Nickel-Chromium-Aluminum molten pool during course of nonequilibrium solidification for explanation arduous solidification behavior control of microstructure melioration. Heat input is not so salient as welding configuration for auspicious solidification behavior and beneficial microstructure development. Advantageous symmetry of welding configuration efficiently lessens dendrite tip undercooling for prevalent dendrite morphology stability of planar interface with alleviation of columnar/equiaxed transition (CET) phenomenon. The bimodal distribution of undercooling ahead of dendrite tip is symmetrically dominant for (001)/[100] growth crystallography with capability of increasing morphology of interface kinetics for epitaxial growth and guarantees single-crystal potential. Alternatively, the distribution of undercooling ahead of dendrite tip is asymmetrically prevalent for (001)/[110] growth crystallography with inefficiency of nonhomologous solidification behavior for discontinuous intersection of solidification interface. Undercooling ahead of dendrite tip inside [010] growth region is not so wide as inside [100] growth region, where thermometallurgically initiates unstable solidification interface and inferior solidification behavior, with unfavorable crystallography in the case of asymmetrical (001)/[110] welding configuration. The smaller heat input is applied, the narrower undercooling ahead of dendrite tip is acquired to significantly mitigate microstructure anomalies with favorable solidification conditions, meliorate metallurgical properties and potentially improve weldability with viability of epitaxial columnar morphology and vice versa. Optimum heat input, especially low laser power and high welding speed together, is a viable and robust way to limit plethora of undercooling and easily decrease solidification behavior anomalies. When low laser power or rapid welding speed is chosen, low heat input not only lessens [100] dendrite growth region, where is spontaneously vulnerable to columnar/equiaxed transition, as ramification of prominent dendrite tip undercooling, but also metallurgically ameliorates [001] dendrite growth region, where morphologically aids epitaxial growth and activates stable planar interface, with achievable diminution of dendrite tip undercooling. Symmetrical (001)/[100] welding configuration, in which undercooling ahead of dendrite tip is preferably narrower than asymmetrical (001)/[110] welding configuration, is one of the most important ingredient for auspicious control of dendrite tip undercooling, once other welding conditions are similar. The main reason, why welding conditions (both low heat input and (001)/[100] welding configuration) is quite superior to welding conditions (both high heat input and (001)/[110] welding configuration), is attributable to favorable crystallography-dependent thermometallurgical factors to suppress inhomogeneous microstructure as long as solidification conditions within marginal stability range. Satisfying crack-free microstructure
development is strongly interdependent on kinetics-related solidification behavior through scrupulous control of dendrite tip undercooling to balance between microstructure amelioration and weld depth requirement. The mechanism of columnar/equiaxed transition elimination, by which kinetic driving forces of abnormal microstructure development within high-undercooling region on either left or right side of weld pool is diminished through challenging method of crystallography-dependent dendrite tip undercooling control, is therefore proposed. Finally, there is reasonable consensus between numerical analysis results and experiment results. The numerical analysis provides credible insight into where is liable to microstructure anomalies and why dendrite tip undercooling suppresses stray grain formation for successful laser surface modification of Ni-based single-crystal superalloy.

1. Introduction

Laser processing repair of gas turbines and vanes is an important cost-efficient application, extends life of Ni-based superalloy components, such as CMSX-4 and CMSX-10, and reduces cost. Epitaxial growth weld is deficiency of cracking with apropos symmetry of microstructure development. However, vexing nucleation and growth of stray grain formation are morphologically profuse as result of unpromising transport phenomenon of solidification behavior during microstructure development. Recent breakthroughs of welding metallurgy advance understanding of solidification behavior of Ni-based superalloys and subsequently provide guideline for crack-free microstructure development during laser processing manufacture as follows. Lippold et al.[1-5] optimized the effect of alloying Nb, Fe, Mo, C and Hf on solidification behavior, solidification cracking and ductility-dip cracking susceptibility of Ni-30Cr superalloy by spontaneous healing with high-Cr nickel-based filler wire during gas tungsten arc (GTA) welding through thermodynamic computation and experiment methods. Moreover, the weld overlay microstructure development and heat-affected zone liquation cracking susceptibility of HY-100, HSL A-100 and HSL A-65 and F22 Alloys during gas tungsten arc welding with nickel-based filler wire 625 were analyzed. Dupont et al. [6-9] analyzed the effect of Ni-Cr-Fe filler wires FM82H and FM52 on welding metallurgy and weldability of nickel-based superalloys A690 and A600, such as microstructure development and ductility-dip cracking, during welding by computation and microstructure characterization. Moreover, welding parameters, stray grain formation and solidification cracking susceptibility of Ni-based single-crystal superalloy CMSX-4 are correlated by electron beam welding and gas tungsten arc welding. Kou et al. [10-12] evaluated microstructure development and solidification cracking susceptibility of austenitic, ferritic and duplex stainless steels during gas tungsten arc welding. Moreover, the effect of heat input on microstructure development of Ni-WC cladding on 1018 steel substrate during gas metal arc welding (GMAW) was analyzed by thermodynamic calculations and experiments. Taheri et al. [13,14] discussed the solidification behavior, solidification cracking and liquation cracking susceptibility of nickel-based superalloy GTD-111 during laser welding. Li et al. and Wang et al. [15,16] simulated the microstructure development of nickel-based superalloys 270 and Inconel 718 during laser welding through Monte Carlo method and multi-scale model. Ramirez et al. and Ghasemi et al. [17,18] evaluated microstructure development, fusion zone solidification cracking and heat-affected zone liquation cracking susceptibility of Ni-Cr-Co superalloy IN740 and Hastelloy superalloy during gas tungsten arc welding. Yu et al. and Zhang et al. [19,20] analyzed the effect of Inconel 625 filler wire on solidification behavior and microstructure development of nickel-based superalloys IN713LC and Incoloy 825 during gas tungsten arc welding and electron beam welding. Wei et al. and Chen et al. [21,22] analyzed the microstructure development of nickel-based superalloy GH4169 during electron beam welding with filler wire. Li et al. [23] analyzed the microstructure development of nickel-based superalloy GH3039 cladding layer by direct energy deposition. Binesh et al. [24] analyzed the solidification behavior of nickel-based superalloy IN738LC during bonding. Wang et al. [25] analyzed the microstructure development of Ni-based single-crystal superalloy during brazing with Ni-Cr-W-B filler. The ambition of this work is to decrease microstructure heterogeneities, improve reparability and repeatability of laser repair industry fabrication through pertinent thermometallurgical factors control.
2. Mathematical model

2.1. Heat Transfer Model
By use of step-by-step optimization routine, classical Rosenthal solution is applied to axisymmetrically predict steady-state solid/liquid interface development to facilitate fast and reliable convergence during molten-pool interface advancement. Heat input is limited by two variables, such as laser power and welding speed, over a series of welding conditions to increase predictive capacity of the model without consideration of welding configuration. Molten-pool dimensions are subsequently discretized in the X, Y and Z three directional cross sections for solidification conditions determination by reproducible numerical analysis derivative. Either laser power or welding speed is well intercorrelated with molten-pool dimensions. The temperature-independent thermophysical properties of commercial engineering materials, such as nickel-based single-crystal superalloy CMSX-4, are available in the open literature.

2.2. Dendrite Selection Model
With assumption of minimum undercooling or minimum velocity mechanism, dendrite intersection and transition boundaries rely on molten-pool geometry and welding configuration for prediction of thermodynamical solidification behavior and kinetic microstructure development. Axisymmetrical and nonaxisymmetrical growth crystallography of both (001)/[100] and (001)/[110] welding configurations on either half side of molten pool are included. Location-dependent dendrite growth is limited by preferential <100> crystallographic orientation across solid/liquid interface in order to compare discrepancy of solidification behavior and microstructure development. Flexible welding configurations are closely correlated with growth crystallography to modify microstructure development of interior weld.

2.3. Multicomponent Dendrite Growth Model
Quadratic Kurz-Giovanola-Trivedi (KGT) model is chosen to iteratively predict interface phenomena, such as solute redistribution and alloying partition between solid and liquid, in order to satisfy thermodynamics and kinetics requirement in the different parts with implicit numerical analysis solution and sufficient accuracy under constraint of growth crystallography. Once the thermometallurgical coupling model is sufficiently convergent and solvable by discretization of solid/liquid interface, minimum dendrite tip undercooling is obtainable. High diffusion of chromium and aluminum in nickel dominates morphology and size of dendrite growth and prompts solidification interface development of γ gamma phase in the case of multicomponent superalloy solidification.

\[
\frac{4\pi^2\Gamma}{R^2} + 2 \sum_{i=1}^{2} \frac{P_{e,i}m_iC_{o,i}(1-k_i)\xi(P_{e,i})}{(1-(1-k_i)\eta(P_{e,i}))} + G_{si} = 0
\]  

where \(\Gamma\) is the Gibbs-Thomson coefficient, \(R\) is the dendrite tip radius, \(P_{e,i}\) is the Peclet number for \(i\), \(m_i\) is the liquidus slope, \(C_{o,i}\) is the initial concentration for \(i\), \(k_i\) is the partition coefficient for \(i\), \(\xi(P_{e,i})\) is a function of the Peclet number, \(\eta(P_{e,i})\) is the Ivantsov solution (\(i=Cr\) or \(Al\)) and \(G_{si}\) is the average temperature gradient nearby the dendrite tip.

2.4. Dendrite Tip Undercooling Model
To simplify the procedure, minimum dendrite tip undercooling is introduced. Three different types of undercooling, especially thermal undercooling, constitutional undercooling and curvature undercooling, consist of total dendrite tip undercooling around periphery of solid/liquid interface in ternary nickel-chromium-aluminum superalloy. Because thermal undercooling is not as wide as constitutional undercooling and curvature undercooling, and is negligible. Only constitutional undercooling and curvature undercooling are considered. Minimum dendrite tip undercooling is flexibly adjustable as small as possible for columnar morphology of stable planar interface development. The relationship between molten-pool geometry and dendrite tip undercooling is established.

\[
\frac{4\pi^2\Gamma}{R^2} + 2 \sum_{i=1}^{2} \frac{P_{e,i}m_iC_{o,i}(1-k_i)\xi(P_{e,i})}{(1-(1-k_i)\eta(P_{e,i}))} + G_{si} = 0
\]
A general methodology procedure of mathematical model is readily proposed for microstructure reconstruction of inhomogeneity and discontinuity in the weld interior of longitudinal and transverse cross sections by variety of welding conditions through this straightforward way for in-depth understanding of undercooling-aided microstructure degradation.

3. Results and Discussion

![Graphs and diagrams showing results and discussion](figures)

(a) Symmetrical fusion boundary development, (d) solidification interface angle in the transverse cross section, (e) dendrite region intersection and (b) symmetrical undercooling ahead of dendrite tip in (001)/[100] growth crystallography. (f) Dendrite region intersection and (c) asymmetrical undercooling ahead of dendrite tip in (001)/[110] growth crystallography.

Figure 1. The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration.

The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration is shown in figure 1. When (001)/[100] dendrite growth crystallography is prevalent, welding configuration is determining concern for planar interface growth and stray grain formation resistance essential, and differentiates crystallography-dependent interface kinetics of nonequilibrium solidification behavior during microstructure development. In other words, diffusion-controlled dendrite growth is discontinuously limited by welding configuration. Competitive growth regions of [010],[100], [010] and [001] dendrites are separately dominant with discern transition boundary outlines and discontinuous crystallographic orientations for symmetrical microstructure development. High undercooling of dendrite tip is confined in growth region of [100] dendrite. The proximity of [100] dendrite to top side centerline of weld pool prominently facilitates propensity for microstructure anomalies, i.e. morphology instability of columnar/equiaxed transition, and centerline cracking. The bimodal distribution of undercooling
ahead of dendrite tip is beneficially axisymmetrical everywhere around periphery of solidification interface to advance crystallographically degradation-resistant microstructure development by diffusion transport phenomenon during nickel-chromium-aluminum molten-pool solidification. Homologous [001] epitaxial growth of columnar morphology is obtainable with favorable interface kinetic driving forces, especially minimal dendrite tip undercooling, under feasible single-crystal solidification conditions, as solidification proceeds upwards. Although high-undercooling growth region of [100] dendrite preferentially contributes to stray grain formation with equiaxed morphology and impedes epitaxial dendrite growth, the size of [100] dendrite growth region is particularly smaller than other parts for improvement of weld performance and amelioration of solidification cracking resistance and metallurgically reduces microstructure degradation. This troublesome problem is inevitable and increases difficulty of single-crystal morphology development. The increasing dendrite tip undercooling incurs insidious size and morphology of stray grain formation as consequence of solute enrichment, and activates significant instability of planar growth interface. Besides promoting epitaxial growth, this salient symmetry of welding configuration efficiently warrants opportunity for desirable solidification behavior to eliminate weld defect and microstructure heterogeneities in the absence of centerline grain boundary formation in order to control weld quality. Comparatively, when (001)[110] dendrite growth crystallography is dominant, the location-dependent distribution of dendrite tip undercooling is nonaxisymmetrical. High-undercooling growth region of [100] dendrite, where is located on the right side of molten pool, increases hindrance to stable planar interface growth to thoroughly deteriorate weld integrity, within which microstructure anomalies is kinetically driven by unfavorable metallurgical properties, i.e. wider undercooling and copious solute buildup ahead of dendrite tip, with aid of unsatisfying growth crystallography. This asymmetrical distribution of dendrite tip undercooling is consistent with other factors, such as stray grain formation, primary dendrite trunk spacing, solidification temperature range, supersaturation and solute redistribution within γ phase etc. Compared with foregoing result, three components of dendrite growth region [010], [001] and [100], which epitaxially grow near fusion boundary, are coexistent after indispensable dendrite region intersection. Centerline grain boundary formation is disadvantageous with growth region impingement of [010] and [100] dendrites on the top surface. In addition to different location and shape of dendrite growth regions between two welding configurations, the size of dendrite growth region is also dissimilar, although the same heat input is imposed. Wider undercooling ahead of dendrite tip is prominently limited inside of [100] dendrite growth region to increase tendency for asymmetrical microstructure development. In other words, [100] dendrite growth region is inferior to other regions and [001] dendrite growth region is superior to other regions. Dendrite tip undercooling in the growth region of [010] dendrite is narrower than in the growth region of [100] dendrite. The latter is liable to undercooling-induced microstructure anomalies, such as columnar/equiaxed transition and stray grain formation. The consistency of growth kinetics of dendrite tip, such as alloying redistribution and supersaturation, is good prerequisite and guidance for microstructure optimization. Because growth crystallography contributes to microstructure development, the welding metallurgy mechanism of nonsymmetrical solidification behavior, by which undercooling-induced microstructure degradation kinetically occurs, is thus proposed. Significant dendrite tip undercooling is one of the contributing metallurgical factors morphology instability and for weldability degradation, and necessitates the optimization of welding conditions. It is crystallographically negligible dendrite tip undercooling at epitaxial growth region of [001] dendrite to metallurgically possess resistance to undesirable planar instability of solid/liquid interface, and thus provide another appropriate way to simultaneously avoid columnar/equiaxed transition and stray grain formation. The wider minimum dendrite tip undercooling is imposed, the more susceptibility to solidification cracking is thereby induced. Auspicious microstructure development is symmetrically attributed to undercooling-resistant (001)[100] welding configuration. Dissimilarly, insidious microstructure development is nonsymmetrically attributed to undercooling-susceptible (001)[110] welding configuration.
Figure 2. The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration with increase of welding speed.

The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration with increase of welding speed is shown in figure 2. When (001)/[100] dendrite growth crystallography is prevalent, high welding speed is able to simultaneously decrease three-dimensional geometries of both molten pool and separate dendrite regions as result of limiting heat input. To better understand the relationship between solid/liquid interface location and dendrite tip undercooling, flexible symmetry and asymmetry growth crystallography are used with initiation of dendrite growth intersection in different parts. It is necessary to balance between challenging single-crystal epitaxial growth and satisfactory weld pool geometry. There are two opposing directions between deep weld depth and negligible columnar/equiaxed transition. They are not simultaneously satisfied. Complexity of solidification behavior optimization is obvious. Transverse section is divided into four subregions. Transition boundaries around [100] dendrite subregion are geometrically activated as long as discontinuity of dendrite growth. Not only is single-crystal epitaxial growth of undercooling-resistant [001] dendrite safely retrieved, but also smaller growth region of undercooling-susceptible [100] dendrite is obtained to kinetically alleviate interface instability by means of increasing welding speed. Otherwise, the single-crystal microstructure development is dominantly exacerbated with serious thermomeetallurgical driving forces. It is important that increase of single-crystal epitaxial growth is preferable for robust weld without cracking. Contribution of axisymmetrical dendrite growth crystallography to
solidification behavior conveniently improves degradation-resistant microstructure development, suppresses diffusion-controlled stray grain formation and potentially withstands solidification cracking by reason of conspicuous metallurgical and morphological factors that are elucidated by flexibility of welding conditions. Viable solidification conditions, i.e. high temperature gradient and fast dendrite growth velocity, sufficiently facilitate mitigation of undercooling ahead of dendrite tip around solidification interface, which are integral part of proper control of thermo-assisted metallurgical driving forces. Although fast dendrite growth velocity results in unstable solidification interface and is detrimental to single-crystal epitaxial growth, pertinent increase of welding speed leads to steep temperature gradient to compensate for problem of high dendrite growth velocity and sustain single-crystal nature. The higher welding speed is evaluated, the narrower undercooling ahead of dendrite tip is crystallographically imposed by depletion of solute buildup under nonequilibrium solidification conditions to subsequently lessen columnar/equiaxed transition and also decrease tendency towards centerline cracking susceptibility. Inevitably, nonequilibrium alloying partition considerably occurs as result of preferential solidification conditions for the microstructure and morphology control to impair interface instability, and microstructure of single-crystal epitaxial growth is thoroughly driven by appropriateness of favorable solidification interface kinetics behind meliorable metallurgical properties. When activating undercooling-susceptible growth region of [100] dendrite with variation of size and shape, significant solute buildup and redistribution ahead of dendrite tip result in severe dendrite tip undercooling, columnar/equiaxed transition and stray grain formation together. Comparatively, when (001)/[110] dendrite growth crystallography is dominant, besides reduction of undercooling-susceptible region size of asymmetrical dendrite growth, undercooling ahead of dendrite tip is beneficially mitigated by increase of welding speed in the interior of molten pool to enable metallurgical resistance to morphology instability of columnar/equiaxed transition. Fast welding speed is an advantageous way with capability of grain boundary formation decrease nearby centerline and weld quality improvement during final stage of solidification. The contraction of undesirable high-undercooling growth region of [100] dendrite is nonaxisymmetrically predominant on the right half part, when the expansion of low-undercooling growth region of [001] dendrite is pertinent in the vicinity of molten-pool bottom to lead to single-crystal potential of epitaxial growth. The consistency thermometallurgical behavior of solidification interface in the different regions contributes to nucleation and growth of columnar morphology dendrite. The same heat input is importantly designed on left half and right half sides, nevertheless, the severe nonaxisymmetry of undercooling ahead of dendrite tip is separately distributed. This controlling factor considerably increases the severity of wider dendrite tip undercooling at particular location. Anomalous dendrite tip undercooling occurs in the growth region of [100] dendrite. The location of susceptibility to microstructure degradation and solidification cracking is selective and obstructs epitaxial growth. When high laser power and fast welding speed are combined, the small heat input is fairly beneficial to narrow undercooling development around dendrite tip interface and thus constrains metallurgical integrity and unsymmetrical microstructure development. The usefulness of this application is tenable. Alternatively, when high laser power and slow welding speed are combined, the large heat input widens undercooling ahead of dendrite tip, worsens solidification interface instability and produces microstructure heterogeneity and irregular morphology. Therefore, two types of serious solidification cracking susceptibility, such as axisymmetrical cracking around centerline and nonaxisymmetrical cracking, are essentially alleviated by allowable limit of heat input. Lower heat input is another dominant contributing factor for good weld quality.
Figure 3. The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration with decrease of laser power.

The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration with decrease of laser power is shown in figure 3. When (001)/[100] dendrite growth crystallography is prevalent, the size of undercooling-susceptible [100] dendrite growth region is lessened on the upper surface to efficiently meliorate microstructure development. Different weld depths and widths are precisely achievable. Undercooling is decreased by reduction of laser power with solute redistribution ahead of dendrite tip, which is metallurgically consistent with contribution of increasing welding speed to dendrite tip undercooling to aid solidification interface stability. Location-dependent undercooling ahead of dendrite tip is prone to phenomena of morphology transition, microstructure anomalies and subsequent solidification cracking. Minimum dendrite tip undercooling mechanism is straightforward application for evaluation and design of different stages of microstructure development. Symmetry and discontinuity of transition boundaries are similar with preceding results when only changing heat input, such as either welding speed or laser power. Undercooling ahead of dendrite tip is significantly mitigated with reduction of inferior columnar/equiaxed transition, nucleation and growth of insidious stray grain formation, and prevention of microstructure degradation and centerline cracking, while solidification approaches molten pool centerline. It is indicative of undercooling distinction ahead of dendrite tip between solidification interface location at bottom and top side of molten pool. The lower laser power...
is evaluated, the narrower undercooling and smaller solute enrichment ahead of dendrite tip are axisymmetrically imposed on the top surface to avoid columnar/equiaxed transition and irregular interface morphology, and increase resistibility to interface instability during terminal stage of solidification and vice versa. Appropriate low laser power is the favorable one for prevention of the nucleation and growth of stray grain formation through decreasing dendrite tip undercooling, facilitates nonequilibrium solidification behavior to improve resistance to centerline cracking, and thereby provides alternative thermometallurgical way for amelioration of centerline cracking susceptibility. Comparatively, when (001)/[110] dendrite growth crystallography is dominant, the interdependency of solidification behavior, microstructure development and solidification cracking susceptibility on growth crystallography is nonaxisymmetrical and provides necessary information about interface stability evaluation. High-undercooling growth region of [100] dendrite plays an overwhelming role in inferior growth kinetics of dendrite tip to impart single-crystal epitaxy, because microstructure degradation strongly depends on dendrite morphology, solid/liquid interface location and solute profile. Decrease of undercooling-susceptible growth region of [100] dendrite satisfactorily occurs, where is less prone to interface instability and morphology transition, thereby increasing crack-resistant microstructure melioration by solute dispersion and diffusion. Moreover, beneficial growth region of low-undercooling [001] dendrite is preferred to metallurgically satisfy single-crystal epitaxial growth, and the variation differentiates the acceptable and unacceptable microstructure development. When equivalent heat input is applied to either side of molten-pool, the undercooling ahead of dendrite tip on the left side is less wide than right side as a result of conspicuous growth crystallography difference. Ameliorable solidification conditions around solidification interface, within which steep temperature gradient and slow dendrite growth velocity coexist, increase resistibility to dendrite tip undercooling and fairly contribute to continuity of interface development with decreasing laser power. Satisfactory low heat input, within which small laser power and slow welding speed are combined, contributes to nonequilibrium partition of gamma γ phase during weld pool solidification, and is important contributing factor for weldability improvement. It is necessary for further optimize the welding conditions to improve weld quality through microstructure modification. Despite low laser power is alternatively beneficial to crack-free microstructure amelioration and enables undercooling-induced weld metallurgical properties improvement, too low laser power is difficult for spontaneous epitaxial growth of substrate and requirement of weld depth. The effect of nonaxisymmetrical dendrite growth crystallography on microstructure degradation cannot be counterbalanced by low laser power.

The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration with diverse molten-pool geometries is shown in figure 4. When (001)/[100] dendrite growth crystallography is prevalent, growth region of columnar [001] dendrite is epitaxially extended, whereas growth region of equiaxed [100] dendrite is diminished. The difference between weld interior regions is attributable to shallow molten-pool depth through useful laser surface modification. The promising result is quite consistent with foregoing numerical analysis. Increasing solid/liquid interface stability and undercooling-resistant microstructure development are controlled by molten-pool shape with symmetrical crystallographic orientation. The existence of dominant epitaxial growth is foremost phenomenon. Dendrite tip undercooling is further narrowed on the center part to kinetically stabilize planar interface morphology and dendritically develop intriguing single-crystal epitaxial growth for controllable high-quality weld. Small heat input method, within which low laser power and fast welding speed are combined, is the most favorable driving forces for stable interface development to thermometallurgically impede irregularities of microstructure development, such as columnar/equiaxed transition and stray grain formation. Three-dimensional shallow molten-pool shape energetically contributes to auspicious interface kinetics of single-crystal epitaxial growth with axisymmetry of growth crystallography for mitigation of dendrite tip undercooling in order to induce crack-resistant microstructure development. It is imperative to minimize formidable solidification interface instability, such as columnar/equiaxed transition, and prevent centreline microstructure degradation as well as cracking potential through optimum low heat input under nonequilibrium solidification conditions. Comparatively, when (001)/[110] dendrite
growth crystallography is dominant, grain boundary formation nearby centerline is significantly diminished by high welding speed that axially meliorates microstructure homogeneity.

Figure 4. The promising interrelationship between epitaxy of dendrite region intersection, development of dendrite tip undercooling and dissimilar welding configuration with diverse molten-pool geometries.

Beneficial growth region of [001] dendrite is advanced by limitation of heat input to compensate for detrimental growth region of [100] dendrite through proper microstructure modification. The irregularities of undercooling ahead of dendrite tip are mitigated in the shallow molten-pool geometry. Meanwhile, stray grain formation is lessened by narrower dendrite tip undercooling of molten pool, although nonsynchronous solidification engenders enormous location-dependent undercooling ahead of dendrite tip. Shallow molten-pool geometry advantages over deep weld-pool shape, internally renders favourable solidification conditions and thermometallurgical factors to epitaxially ameliorate microstructure development in multpart subregions through progressive welding conditions optimization, and thus improves phase stability and microstructure stability in the absence of solidification cracking. Reasonable relationship between welding conditions, molten-pool shape, solidification conditions, dendrite tip undercooling and selectivity of microstructure degradation is established by appropriate methods to elucidate reasons of two typical solidification cracking susceptibilities in the proximity of vulnerable dendrite growth region. Finally, the calculation results of crystallography-dependent and degradation-susceptible solidification interface kinetics are compliant with experiment results, and proffer tenable explanation the effect of auspicious and
insidious solidification behavior on microstructure development to metallurgically reduce solidification cracking phenomena [26,27]. Furthermore, the deleterious intermetallic phases of eutectic and peritectic reactions are thermodynamically suppressed in the terminal interdendrite liquid to stabilize primary solidification path. Nonequilibrium partitionless solidification of γ phase is kinetically favored with minimal dendrite tip undercooling. Briefly, low heat input is of significant importance by which elimination of columnar/equiaxed transition, refinement of dendrite growth, suppression of nonequilibrium solidification temperature range, mitigation of solute redistribution and partition, relief of supersaturation and diminution of dendrite tip undercooling are simultaneously satisfied and consistency is met for superior single-crystal epitaxial growth.

4. Conclusions

Welding conditions are thoroughly designed for microstructure development melioration with axisymmetrical and nonaxisymmetrical dendrite growth crystallography by three-way procedure of dendrite kinetics optimization to pertinently understand solidification interface development and morphology transition phenomena of well-developed microstructure. On the basis of preceding results, a series of conclusions are separately provided as follows.

- For (001)/[100] growth crystallography, undercooling ahead of dendrite tip is axisymmetrically distributed for auspicious microstructure development to improve resistibility to centerline cracking.
- For (001)/[110] growth crystallography, undercooling ahead of dendrite tip is nonaxisymmetrically distributed for insidious microstructure development to degenerate resistibility to solidification cracking.
- Microstructure degradation is only limited in growth region of [100] dendrite, where is either located nearby centerline in (001)/[100] welding configuration or located on the right side of molten pool in (001)/[110] welding configuration. Conspicuously, single-crystal epitaxial growth is limited in growth region of [001] dendrite in the bottom of molten pool.
- When direct comparing dendrite tip undercooling between (001)/[100] dendrite growth crystallography and (001)/[110] dendrite growth crystallography, the former is not as wide as the latter for beneficial symmetry development of interface kinetics.
- Indispensable low heat input, within which small laser power and fast welding speed are combined, suppresses undercooling ahead of dendrite tip to increase ameliorable microstructure development under nonequilibrium solidification conditions, however, high heat input, within which large laser power and slow welding speed are combined, increases high-undercooling dendrite growth region to thermometallurgically degenerate microstructure development.

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