Fabrication and Weldability Aspects of Ni- and Ni–Fe Based Superalloys—A Review

Joel Andersson

Abstract Superalloys are commonly used in structural components of aero-engines. Superalloys in general, Ni- and Ni–Fe-based superalloys, belong to an important group of materials used in aerospace applications. Fabrication and associated weldability aspects of structural components for the hot section of aero-engine gas turbines continue to be of high importance to the manufacturing industry within this discipline. Cracking and specifically hot cracking as well as strain age cracking is a serious concern during the welding and additive manufacturing (AM) of these structural components. The cracking phenomena can occur during welding, AM or subsequent heat treatment of precipitation-hardening superalloys. The cracking behaviour can be influenced by several factors, i.e., chemical composition in terms of hardening elements and impurities, the microstructure of base material, and weld zone, together with corresponding welding, AM and post-treatment process parameters. This paper provides a review of Ni- and Ni–Fe-based superalloys concerning fabrication and weldability aspects within the context of structural components of aero-engines. Also, the paper offers insight and analyses to research publication data of welding and AM of superalloys in the context of annual publication developed over the years as well as specific contributions from countries, affiliations, and specific researchers.

Keywords Hot cracking · Strain age cracking · Superalloys · Welding · Additive manufacturing

Introduction

Superalloys, in particular, the precipitation hardening Ni- and Ni–Fe-based superalloys, belong to the most critical class of materials in realizing the aero-engines seen today and on long-term future horizon. The trend in the past decades, regarding

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large hot structural aero-engine components, has been through fabrication. Fabrication of hot structural components such as a turbine exhaust casing requires extensive knowledge of welding of the aforementioned class of materials. Fabrication is, apart from welding, also dependent on know-how of metallurgical aspects of different material forms, i.e., sheet, forging, and casting as well as their implications on welding, where additive manufacturing (AM) is a recent tool that potentially can further enhance the fabrication concept of hot structural components. The fabrication concept, as such, benefits from the fact that one can utilize the best out of each type of material form, i.e., castings can be utilized where complex geometrical shapes are needed, and sheet/wrought material form can be used when high strength and less complex geometries are to be used. It also means that it is possible to utilize different types of alloys within the same component, hence, expensive alloys can be minimized and used where it is really needed. This rationale provides a path of tailoring complex structural components which in turn can reduce the overall weight and cost, depending on the circumstances. However, the journey to fully comprehend, master, and understand the fabrication concept requires a comprehensive understanding of material aspects in relation to material form and processes such as welding and AM. There are several obstacles such as cracking aspects in welding and AM which need to be addressed properly to avoid costly mistakes.

Research of Superalloys, Welding, and Additive Manufacturing and Its Global Presence

Research within AM technology has sky-rocketed since 2010. In Fig. 1, the amount of research (publications) in connection with “welding”, “additive manufacturing”, and “superalloys” are presented. Publications on “welding” and “superalloys” date back to ~1950s whereas “additive manufacturing” appeared for the first time in ~1985. Both “welding” and “additive manufacturing” have increased significantly in 2000 and 2010, respectively, whereas research on “superalloys” have levelled up from a quite low level from its start in the 1950s to a more moderate level since 1990s until today.

In Fig. 2, it can be seen that when combining the search strings of “welding” and “additive manufacturing” with “superalloys”, the amount of research within the field of superalloys in combination with welding or AM is about ~60 and ~40 times less, respectively, than the overall amount of research carried out within the research fields of welding or AM.

Primary production as well as research of superalloys have traditionally had a strong presence in G8 countries (France, Germany, Italy, Japan, United Kingdom, United States, Canada, and Russia). Looking into the number of publications of “welding AND superalloys” and “additive manufacturing AND superalloys”, Figs. 3and4, the top-ten countries regarding number of publications comprises the following countries (full list in Appendices 1 and 2):

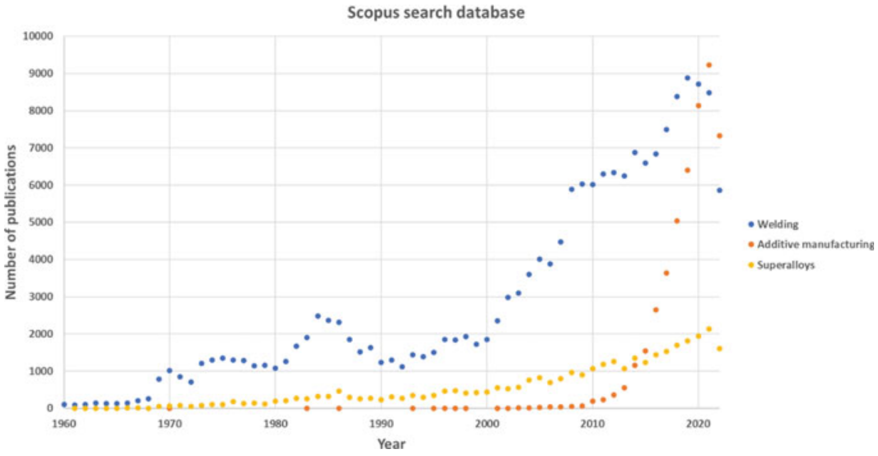


Fig. 1 Number of publications versus years for “welding”, “additive manufacturing”, and “superalloys” [1–3]

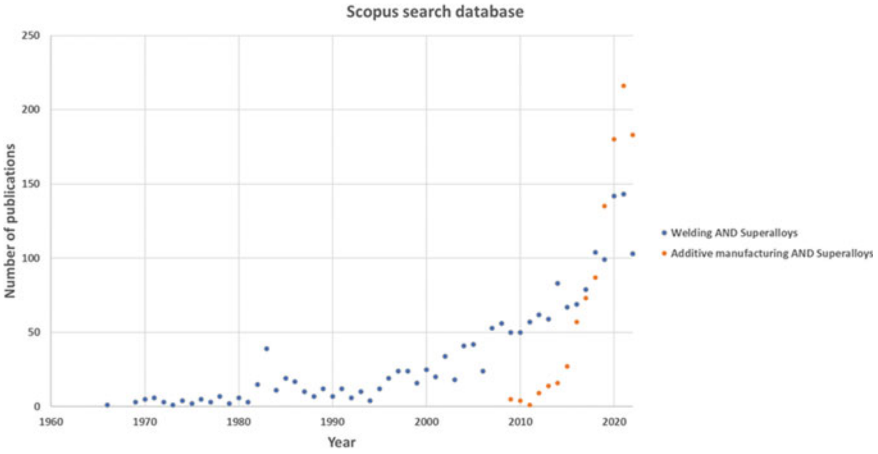


Fig. 2 Number of publications versus years for “welding AND superalloys” and “additive manufacturing AND superalloys” [4, 5]

- “welding AND superalloys”

  1. China
  2. United States
  3. India
  4. Canada
  5. Japan
  6. United Kingdom
  7. Iran

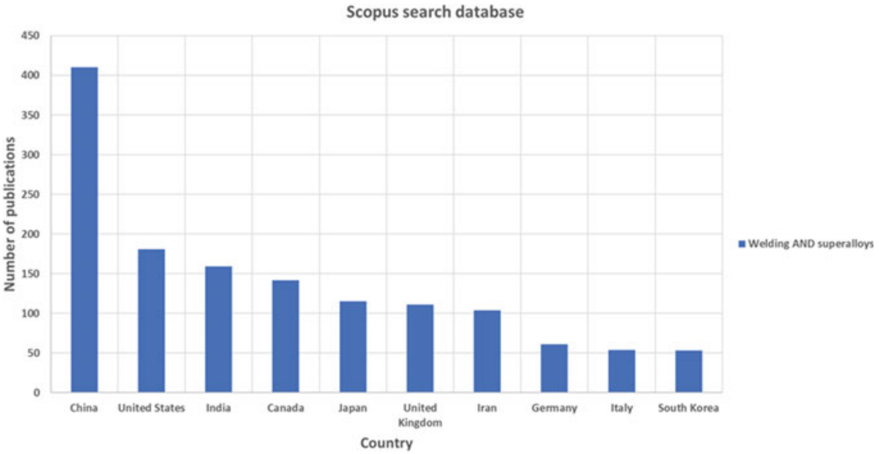


Fig. 3 Number of publications versus country for "welding AND superalloys" [6]

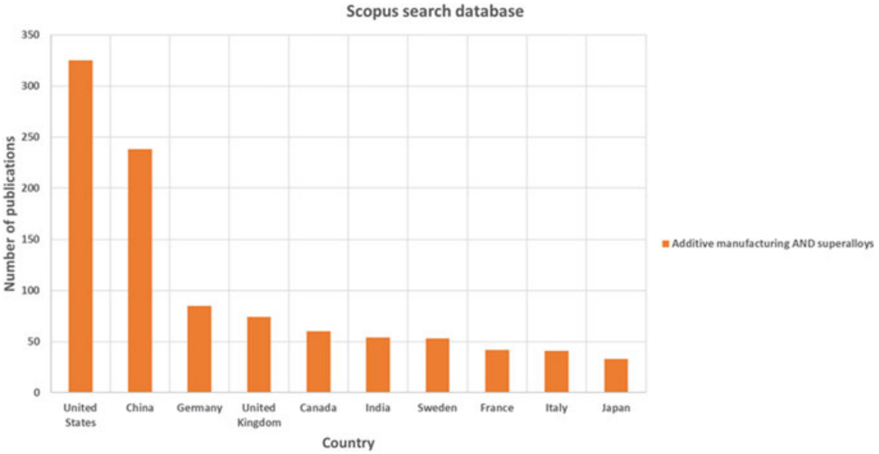


Fig. 4 Number of publications versus country for "additive manufacturing AND superalloys"

8. Germany
9. Italy
10. South Korea

- "additive manufacturing AND superalloys"

  1. United States
  2. China
  3. Germany
  4. United Kingdom
  5. Canada

6. India
7. Sweden
8. France
9. Italy
10. Japan

Most of these countries holds a “leading” position within both fields of research (“welding AND superalloys” and “additive manufacturing AND superalloys”), except Iran and South Korea which do not enter the top-ten list of “additive manufacturing AND superalloys” as well as Sweden and France who do not enter the top-ten list of “welding AND superalloys”. China is by far producing most of publications within the research field of “welding AND superalloys” where the remaining publications are evenly distributed among the other countries. However, United States followed by China is producing most of the publications in the field of “additive manufacturing AND superalloys” where the remaining countries are far behind regarding publications.

Looking further into research affiliations, Figs. 5and6, for the fields of interest the top-ten affiliations are as follows (full list in Appendices 3 and 4):

- “welding AND superalloys”
    1. University of Manitoba, Canada
    2. Northwestern Polytechnical University, China
    3. Chinese Academy of Sciences, China
    4. Harbin Institute of Technology, China
    5. Vellore Institute of Technology, India
    6. Osaka University, Japan
    7. Ministry of Education China, China

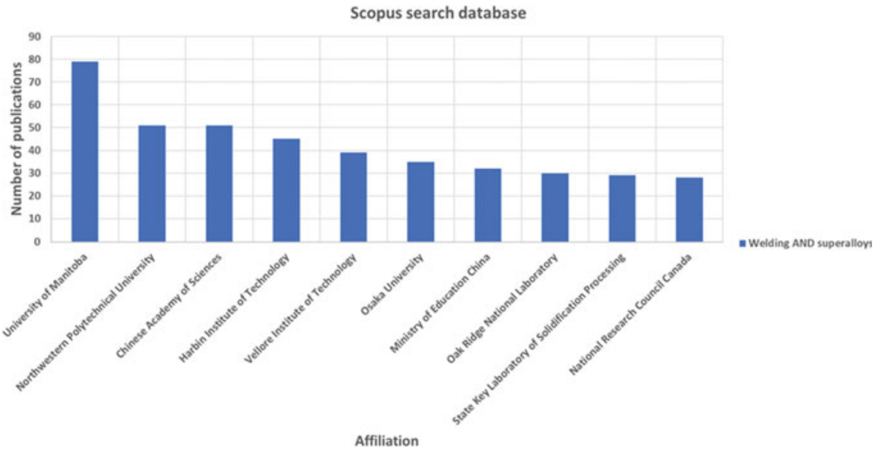


Fig. 5 Number of publications versus affiliation for “welding AND superalloys” [8]

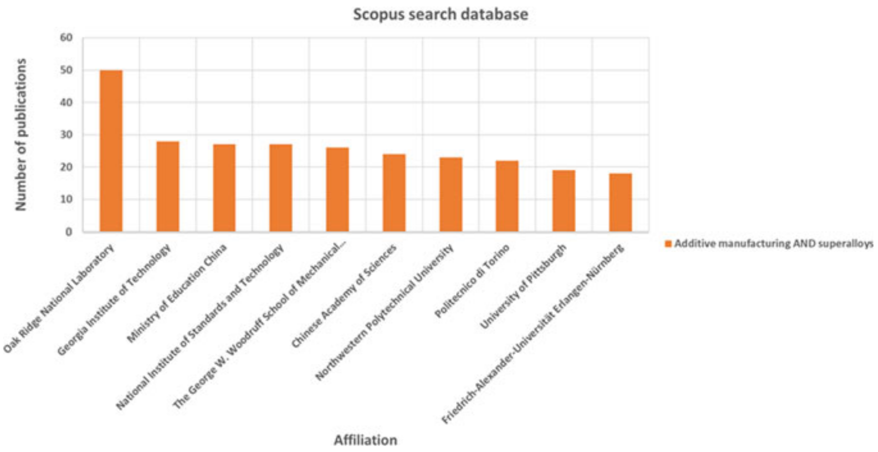


Fig. 6 Number of publications versus affiliation for "additive manufacturing AND superalloys" [9]

8. Oak Ridge National Laboratory, USA
9. State Key Laboratory of Solidification Processing, China
10. National Research Council Canada, Canada

- "additive manufacturing AND superalloys"

1. Oak Ridge National Laboratory, USA
2. Georgia Institute of Technology, USA
3. Ministry of Education China, China
4. National Institute of Standards and Technology, USA
5. The George W. Woodruff School of Mechanical Engineering, USA
6. Chinese Academy of Sciences, China
7. Northwestern Polytechnical University, China
8. Politecnico di Torino, Italy
9. University of Pittsburgh, USA
10. Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

There is a mix of institutes and universities among the two fields of research, however, Oak Ridge National Laboratory, Chinese Academy of Sciences, Northwestern Polytechnical University, and Ministry of Education China holds a top-ten position in both fields where University of Manitoba and Oak Ridge National Laboratory outrun the others in the research fields of "welding AND superalloys" and "additive manufacturing AND superalloys", respectively.

On an individual author basis, the number of publications of "welding AND superalloys" and "additive manufacturing AND superalloys", Figs. 7and8, disclose the following top-ten list of authors (full list in Appendices 5 and 6):

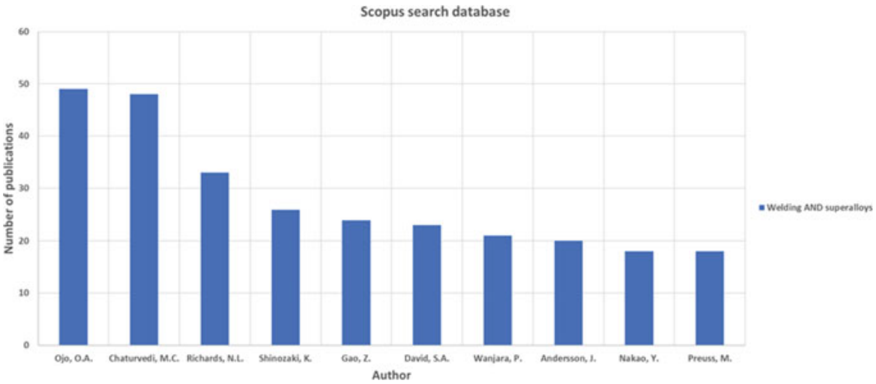


Fig. 7 Number of publications versus author for “welding AND superalloys” [10]

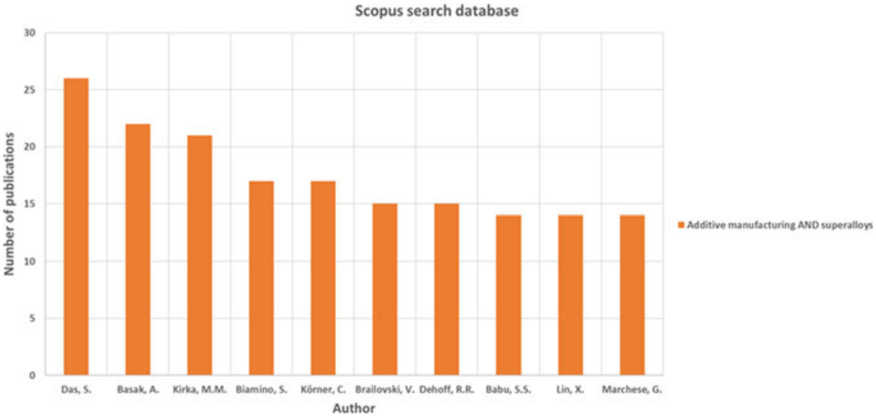


Fig. 8 Number of publications versus author for “additive manufacturing AND superalloys” [11]

- “welding AND superalloys”
    1. Ojo, O.A.
    2. Chaturvedi, M.C.
    3. Richards, N.L.
    4. Shinozaki, K.
    5. Gao, Z.
    6. David, S.A.
    7. Wanjara, P.
    8. Andersson, J.
    9. Nakao, Y.
    10. Preuss, M.

- "additive manufacturing AND superalloys"
  1. Das, S.
  2. Basak, A.
  3. Kirka, M.M.
  4. Biamino, S.
  5. Körner, C.
  6. Brailovski, V.
  7. Dehoff, R.R.
  8. Babu, S.S.
  9. Lin, X.
  10. Marchese, G.

Opposite to what has been seen regarding countries and research affiliations, there is no individual author that "qualifies" in the top-ten list of both fields of research.

The above search in the number of publications versus year, country, affiliation, and author do give some insight to the spread and presence of research in the fields of interest, however, a more in-depth analyses considering patents and research funds would add further insights.

Welding of Superalloys

There is a fair number of superalloys being used in a wide range of industrial applications where the most used ones in aerospace can be classified as either Ni and Ni–Fe-based solid solution hardening (i.e., Inconel 625, Hastelloy X, Nimonic 75, Incoloy 800, Haynes 556, Multimet N-155) or precipitation hardening (i.e., Waspaloy, Haynes 282, Inconel 939, Inconel 718, Alloy A-286, Incoloy 925) type of superalloys. The aerospace sector alone accounts for about 70% of the total market share with respect to superalloy usage [12]. However, a comprehensive classification of superalloys takes a stand on the base elements (Ni, Ni–Fe, and Co), primary hardening mechanism (solid solution hardening, precipitation hardening, and oxide dispersion strengthening), and material form (i.e., cast, wrought, and powder). The solid solution hardening superalloys most often find their usage in applications where resistance towards thermal loads and environmental resistance are of importance whereas the precipitation hardening superalloys are frequently used when higher demands for strength are required.

In welding with both arc and high-energy beam processes, welding results in high temperatures and large temperature gradients at the location of the heat source, which leads to thermal stresses [13–15] and microstructural inhomogeneities [16] being formed at the region of the weld and these can in turn lead to weld cracking [17, 18]. The magnitude of stress and inhomogeneities vary between the different processes and there are many pros and cons to the selection of a specific process. Gas tungsten arc welding process (GTAW) is frequently used [19–21] since it provides means for clean and high-quality welds as well as being in-expensive in comparison to high-energy beam processes, however, problems related to high heat input, lower penetration, and more limited ability regarding automation tend to favor laser beam welding (LBW) [22, 23]. There has been significant development on GTAW process enabling deeper penetration and increased robustness, which in some way makes it rival other high-energy beam processes like LBW. LBW, despite being significantly more capital intensive [24] in comparison to GTAW, still possesses advantages regarding automation and control, particularly for directed energy deposition (DED) applications. However, recent techniques such as pulsed mode of gas metal arc welding (GMAW), cold metal transfer (CMT), and various modes of GTAW as Force GTAW, K-TIG, and high frequency (HF) GTAW show very promising results in producing high-quality welds not at least including weld thicknesses larger than 3 mm, which historically has been a limit thickness for GTAW [25–29].

Still, issues regarding weld cracking persist to various degrees depending on the specific alloy of interest and irrespective of welding process. In general, the driving force for weld cracking originates from both internal and external sources. The internal sources have already been implicitly mentioned above, i.e., solidification shrinkage stresses, which vary significantly depending on welding process and process parameters. Welding process control has developed tremendously in the last decades, which has resulted in better control and the ability to use very low heat input for preventing weld cracking.

Weld Cracking Mechanisms of Superalloys

Weldability can be defined as "a measure of the ease with which a metal or an alloy can be welded or joined without degradation to the weldment microstructure or properties during or after welding and for the duration of its intended service" [30]. In this context, susceptibility towards cracking during welding and post-weld heat treatment (PWHT) is of major importance. There are different types of weld cracking mechanisms that come to play during welding and AM of superalloys, where hot cracking and solid-state type of cracking, primarily strain age cracking (SAC), are of high importance especially for Ni- and Ni–Fe-based precipitation hardening superalloys utilized in hot structural component for aero-engines [31, 32]. Many types of crack criteria exist to explain why and how cracking occurs, where the first criteria dates back to ~70 years [33–36]. The relationships between metallurgical and mechanical factors are complex, making it hard to include them in a crack criterion, while most criteria do not account for the physical phenomena linked to cracking, but instead are more related to macro-, and micro-conditions than can result in cracking [36]. In general, most cracking criteria can be divided into mechanical and non-mechanical [36] where the non-mechanical ones commonly are based on aspects such as thermal history, chemical composition, and brittle temperature range (BTR) [33, 34]. The mechanical-based criteria, on the other hand, are normally based on critical strain rate, critical strain, or critical stress [33–36]. It has been found that the mechanical criterion is of special use in predicting cracking based on numerical simulations of various kinds, whereas the non-mechanical criterion has been successful in predicting compositional dependencies of cracking [36].

Hot Cracking

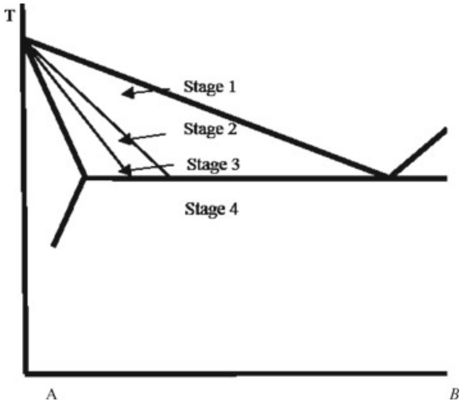
The weld cracking that takes place during welding is referred to as hot cracking and is further divided into solidification cracking and heat affected zone (HAZ) liquation cracking, respectively.

Solidification Cracking

Solidification cracking is found in the fusion zone (FZ), whereas HAZ liquation cracks occur in the HAZ. There are several theories that have been developed over the years to explain these types of cracking mechanisms [37–39]. One concept referred to as “Borland’s generalized theory”, Fig. 9, separates the solidification range into four different stages [39]:

- Stage 1: Primary dendrites form as the temperature drops below the liquidus temperature.
- Stage 2: The dendrites interlock by forming a solid network. In this stage, only the liquid can move between the dendrites.
- Stage 3: The grain development occurs. Here, the liquid is not capable of free movement as it is hindered by the continuous network.
- Stage 4: All the liquid solidifies.

Fig. 9 Solidification stages according to Borland´s “generalized theory”; adapted from [39]



Borland postulated that cracks could form in stage 2 if a continuous dendrite network is formed, however, healing through backfilling is also possible at this stage. Borland defined a "critical solidification range" (CSR) associated with stage 3. In stage 3, substantial cracking can take place since the liquid backfilling is no longer possible. Borland's generalized concept has been further developed by Matsuda et al. [40]. Nevertheless, most existing theories concur on the fact that susceptibility towards solidification cracking is dependent on the combination of metallurgical factors together with local strain at the final stage of solidification. The solidification range is one important factor regarding solidification cracking where a wider range enhances cracking susceptibility [41, 42]. However, liquid distribution and grain boundary wetting are also of high importance, where a low surface tension tends to enable the liquid to better wet the grain boundaries and increase the risk of cracking.

Ni- and Ni–Fe-based superalloys will always be at some risk to solidification cracking since they solidify fully austenitic, however, welding procedure and parameters combined with the chemical composition of the specific alloy determine the susceptibility of an alloy. High heat input is, for instance, something which in general aggravates cracking since it decreases the temperature gradient which in turn increases the solid–liquid region where cracking can take place. There are several aspects to look out for regarding the effects of chemical composition of an alloy, where certain elements, such as, B, C, Si, Mo, and Nb are more important than others when it comes to the influence of solidification temperature range as well as the terminal eutectic type that form at the end of solidification [42–44]. So, solidification cracking is strongly related to the solidification process within the FZ; the amount of solute redistribution and solidification path, solidification temperature range and amount as well as distribution of solute rich interdendritic liquid at the end of solidification [45].

Heat Affected Zone Liquation Cracking

The region located just outside the FZ refers to the partially melted zone of the HAZ. When the applied strain can no longer sustain the locally induced strain, a crack appears. The susceptibility towards this type of cracking normally worsens with increasing heat input, however, the parent metal grain size and alloying content are the most important factors in determining the susceptibility towards HAZ liquation cracking. The nature of grain boundary liquation is of central importance, where trace elements such as B, P, and S are important aside from major elements like Nb. The actual liquation mechanism is triggered by two different types: penetration mechanism and segregation mechanism. The aforementioned trace elements are of crucial importance in the segregation mechanism where B segregates via non-equilibrium or equilibrium mechanisms. Equilibrium segregation decreases with increasing temperature due to increased diffusivity whereas non-equilibrium segregation increases with increasing temperature and takes place during cooling from high to low temperature in terms of diffusion of vacancy-solute complexes to the grain boundaries [46–48].

In a study on cast Haynes 282 where the influence on pseudo hot isostatic pressing temperature on susceptibility towards HAZ liquation cracking was investigated using Varestraint weldability testing [49] it was concluded, by performing nanoSIMS analysis, that free B was not present at 1120 and 1160 °C for a dwell time of four hours, meaning that non-equilibrium segregation was not effective at these temperatures. However, at 1190 °C for a dwell time of 4 h the decomposition of C-B precipitates allowed the B to diffuse and segregate at the boundaries which were believed to be the cause of the aggravated extent of cracking, Fig. 10 and 11.

Apart from segregation driven liquation, the following phenomena (see bullet list below) regarding penetration liquation mechanism have been reported in the literature [50–52], where the penetration mechanism primarily is claimed to be governed by eutectic melting, and constitutional liquation [42, 53]:

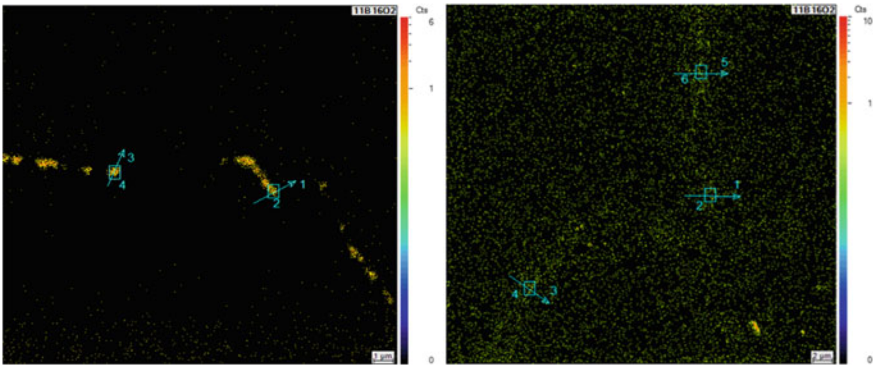
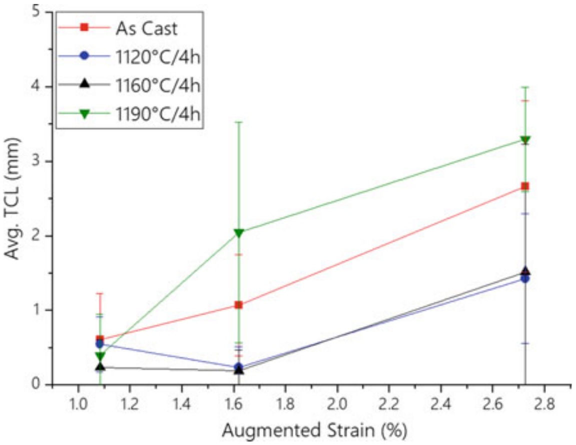


Fig. 10 NanoSIMS elemental map showing the particle segregation of B (left image) in the grain boundary in the 1120 °C /4 h condition and enrichment of B along the grain boundaries in the 1190 °C /4 condition, respectively adapted from Singh and Andersson [49]

Fig. 11 Average total crack length in the HAZ of cast Haynes 282 [49]



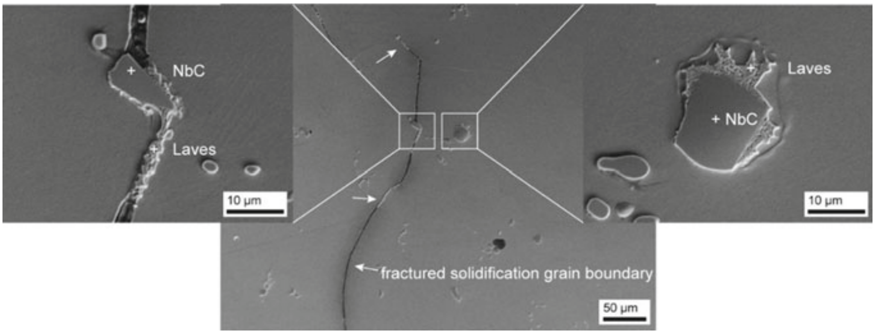


Fig. 12 Grain boundary cracking within a Gleeble weld-simulated HAZ microstructure with constitutional liquation of Nb(Ti) MC-type carbides located on and in close vicinity to the cracked grain boundary. The γ-Laves eutectic surrounding the particles indicates the formation of liquid where the presence of further gamma-Laves eutectic is indicated by right facing arrows [56]

- Constitutional liquation of secondary phases.
- Melting of the matrix.
- Liquation of precipitation hardening phases in high-volume fraction γ' alloys.
- Melting of residual eutectic in cast material.

Constitutional liquation was originally proposed by Pepe and Savage for "maraging steel" weldments [51], where the main aspect of this mechanism refers to a secondary particle being exposed to fast heating rate during welding. This implicates insufficient time for the particle to completely dissolve through solid state diffusion and as a result it encounters liquation since a compositional gradient is generated at the local particle–matrix interface, leading to partial dissolution of the precipitate and a solute-enriched area. A liquid develops consequently as soon as the local eutectic composition is reached and it is most common in Nb-bearing superalloys [49, 54, 55]. An example of a constitutional liquation of NbC in ATI 718Plus can be seen in Fig. 12 [56].

The liquation mechanism in cast ATI 718Plus during weld thermal cycling can be seen as a combination of several contributing factors, as discussed in the previous sections, and is summarized in Fig. 13 [55, 57].

The HAZ thermal cycle in Fig. 13 is divided into three stages, based on temperature ranges between the eutectic temperature (Te), solidus temperature (Ts), and peak temperature (Tp), which are highlighted in the pseudo-binary phase diagram. Stage 1 (up to Te) is characterized by the dissolution of Nb-rich phases, with a higher diffusion rate along the grain boundaries as compared with the grain interior. In this stage, liquation occurs from the solute segregation of minor elements, which lowers the effective solidus of the alloy. In Stage 2 (between Te and Ts), liquation is possible from the melting of the Laves phase or by constitutional liquation of MC carbides, depending on the chemistry after the homogenization heat treatments. In Stage 3 (between Ts and Tp), bulk melting occurs, with the extent of melting based on the amount of Nb in solid solution. The overall contribution will depend on the

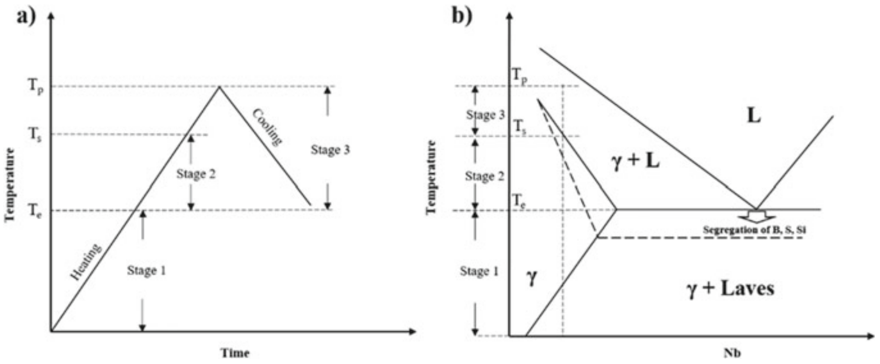


Fig. 13 **a** HAZ thermal cycle divided into three stages based on the temperatures and **b** corresponding pseudo-binary phase diagram for cast ATI 718Plus [55]. Adapted from Radhakrishnan and Thompson [57]

contribution from solute segregation, Laves melting, constitutional liquation of MC carbides and supersolidus melting of the matrix [49, 54, 55].

Strain Age Cracking

Ductility dip cracking (DDC) is a solid-state type of cracking mechanism commonly observed in solid solution hardening Ni-based superalloys and it occurs during cooling in the temperature range of Ts (solidus) and ~0.5Ts, which is concomitant with a significant drop in ductility [45]. When significant contraction stresses take place simultaneously with the drop in ductility, DDC could be observed and have been significantly researched for alloys such as 617 and 740 [45]. However, another solid-state type of cracking phenomena being more predominant in comparison to DDC when dealing with aero-engine structural components is referred to as strain age cracking (SAC). SAC is a type of cracking that occurs in the solid state, without any prerequisites of liquid phase, when hardening takes place in the alloy. As it is closely related to the kinetics of hardening in superalloys, this type of cracking phenomena is primarily of concern for γ' hardening type of alloys and was one of the original drivers for the development of Alloy 718 [58], an alloy that is immune against SAC, however, still suffers from hot cracking. Strain age cracking, as a cracking phenomenon, dates back to the early 1960s. In general, SAC occurs during the post-weld heat treatment (PWHT) and is consequently sometimes referred to as "PWHT cracking" or "Reheat cracking" because of high weld stresses at the same time that hardening occurs in γ' precipitation hardening Ni-based superalloys [59, 60]. The actual cracking mechanism is related to low ductility in the weld HAZ and the material's inability to accommodate stress relaxation. So, stress localization in the HAZ occurs because of reduced strength in comparison to the base material. It is therefore reasonable to assume that a softer material decreases the risk of encountering problems with SAC, whereas a harder material tends to be less resistant [61–67]. Over-aging the material is another approach to mitigate the risk of SAC if a normal solution heat treatment is not feasible, since it reduces the material's strength in favor of stress relaxation in the base material [63].

Chemical Composition and Microstructure

One of the first correlations on susceptibility towards SAC regarding the influence of alloying elements was suggested by Prager and Shira [61], who proposed a significant influence of Al and Ti concentrations on precipitation behavior of the γ' phase. The more of these alloying elements, the higher the volume fraction and precipitation kinetics of the γ′ phase. The more of these alloying elements, the higher the volume fraction and precipitation kinetics of the γ′ phase, which in turn adversely affects the risk of SAC. In Fig. 14, which is based on what Prager and Shira postulated [61], it can be seen that a combined level of Al + Ti content above 6at-% leads to severe problems with regard to SAC, which is also evident by comparing the high susceptibility of René 41 [68] with that of Alloy 718. The sluggish strengthening reaction of (γ" in Alloy 718 compared) enables stress relaxation to occur in advance of any hardening reactions, which puts them in a highly immune state regarding SAC [69].

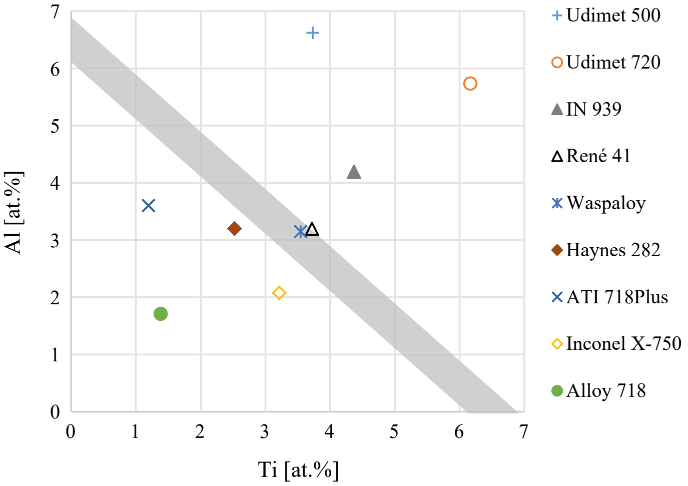


Fig. 14 Adapted Prager-Shira diagram showing [61] Al and Ti concentrations (at.%) of commercially available superalloys. Reduced weldability above the grey line [60]

Other alloying elements, such as C and B, have been claimed to be beneficial in enhancing the resistance towards SAC, due to grain size control [70–72] as well as grain boundary cohesion [71, 73], respectively.

From a microstructural perspective, finer grain size as well as homogenous microstructure have been found to be of importance in preventing SAC as compared to coarse grain size and segregated microstructure, since the distribution of strain can be accommodated over a larger grain boundary area [62, 66, 67, 74]. The aforementioned strain can, apart from residual stresses and external restraint, originate from the mismatch between the austenitic matrix and the γ' phase and lead to the development of contraction stresses, that in turn, induce tensile stresses on the grain boundaries and consequently raise the susceptibility towards SAC [61, 75–77]. However, current research work presumes a significant correlation between lattice misfit and susceptibility towards SAC even though no available quantifiable data provide the actual time–temperature range where SAC takes place [66, 67, 78–81]. So, in summary it can be concluded that the main factors that influence susceptibility towards SAC are related to [60]:

- Strain
  - External weld restraint as well as solidification shrinkage strain
  - Precipitation induced stress
- Stress localization at grain boundaries
  - Grain size
  - Carbides
- Precipitation kinetics
  - Chemical composition
    - γ' phase volume fraction
  - Deformation hardening
- Stress relaxation
  - Young's modulus
  - Time-temperature regime.

Weldability Testing

Weldability as such is quite a broad concept covering everything from actual welding to service performance and should therefore be treated with care to avoid misunderstanding of its meaning. When it comes to material's inherent weldability and actual fabrication of hot structural components and specifically susceptibility towards cracking during welding and PWHT one needs to be careful in assessing the overall cracking susceptibility to avoid costly mistakes. So, based on experience [31, 49,

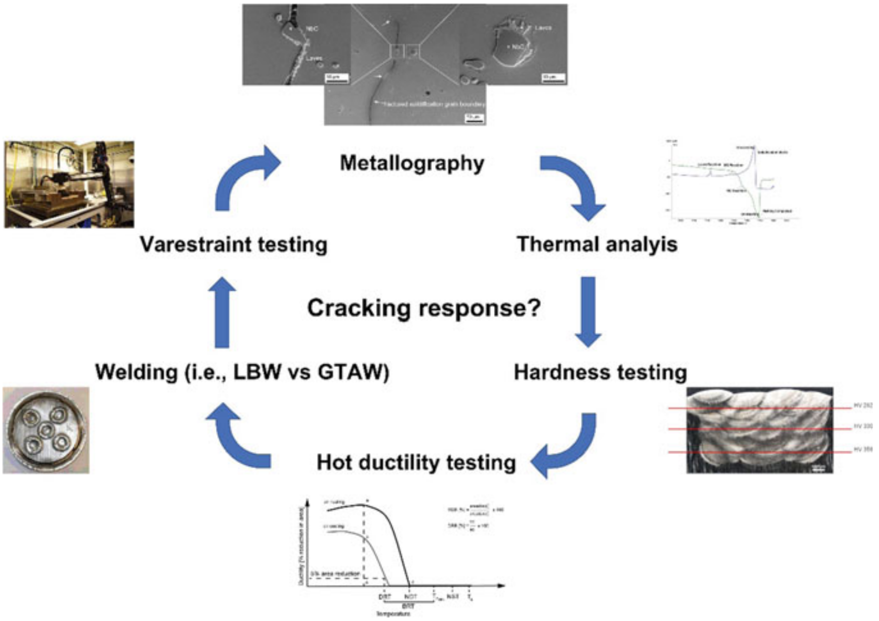


Fig. 15 Proposed procedure in assessing susceptibility toward cracking during welding and PWHT of superalloys. Adapted from Andersson [77]

82–86] in the evaluation of cracking susceptibility and in utilizing different types of assessment methods, an approach [77] is proposed as disclosed in Fig. 15. The proposed procedure in assessing susceptibility toward cracking is utilizing a variety of tools where each one of them provides insightful knowledge on the specific material's behavior.

Utilizing characterization tools such as optical microscopy or scanning electron microscopy (SEM) is something that nowadays is easily accessible and that provides good insight to what phases and constituents are present in the actual material. In Fig. 16, a detailed high-resolution image of the Laves eutectic can be seen in cast Alloy 718 [87].

Information gained from microstructural characterization can be used to enhance understanding of cracking mechanisms [88]. Various kinds of thermal analyses, such as differential scanning calorimetry (DSC) in Fig. 17, can be used to investigate possible phase reactions during heating and cooling in welding, even though these methods are significantly slower in heating and cooling rate in comparison.

Information from thermal analyses and microstructure characterization can be coupled to increase understanding and develop pseudo-binary phase diagrams, Fig. 18. Pseudo-binary phase diagrams can be used to explain possible liquation mechanisms such as constitutional liquation, Fig. 18.

Hardness testing is a valuable tool to quickly gain insight into susceptibility toward SAC, in terms of precipitation kinetics especially when combined with repair welding

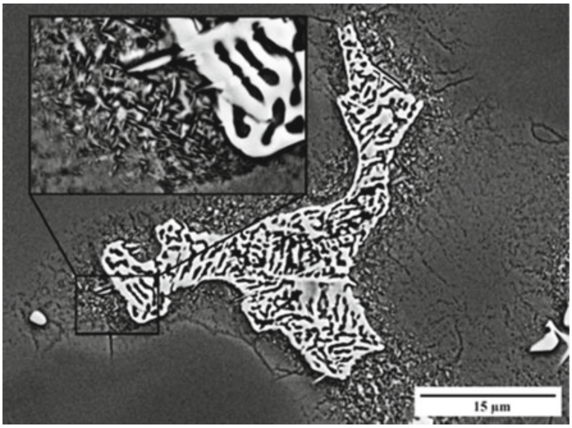


Fig. 16 Backscattered SEM image of Laves phase with eutectic morphology in cast Alloy 718 [87]

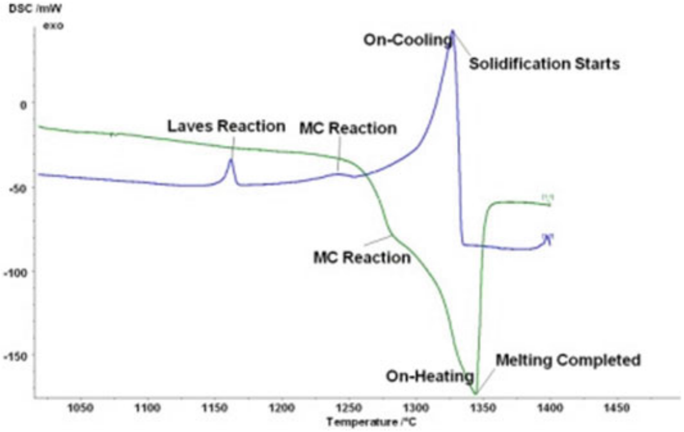


Fig. 17 A differential scanning calorimetric thermograph of Alloy 718 disclosing different phase reactions upon heating (green curve) and cooling (blue curve) [50]

or heat treatments of various kinds as illustrated in the time–temperature-hardness (TTH) diagrams in Fig. 19.

Hot ductility testing through Gleeble simulation can be used to tailor specific thermal–mechanical cycles to study the underlying mechanism to liquation and provide quantitative information on the weldability of materials. The traditional hot ductility type of test, Fig. 20 [82], can be used to gain insight into the HAZ and corresponding liquation mechanisms and to derive criteria for ranking materials against one another. The ductility signature measured in Fig. 20 shows a rapid ductility loss during on-heating curve, which is related to the onset of liquation in the material [42]. The on-cooling tests are executed by first heating a test specimen

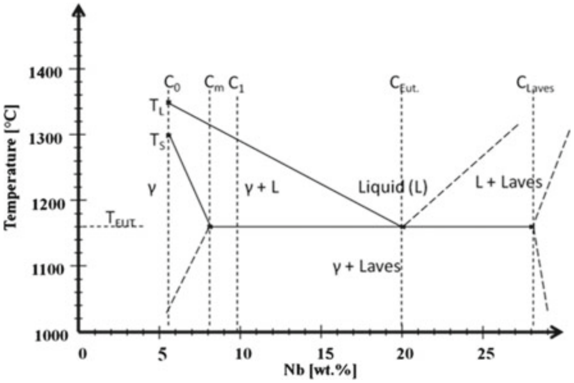


Fig. 18 Pseudo-binary phase diagram of ATI®718Plus™ [89]

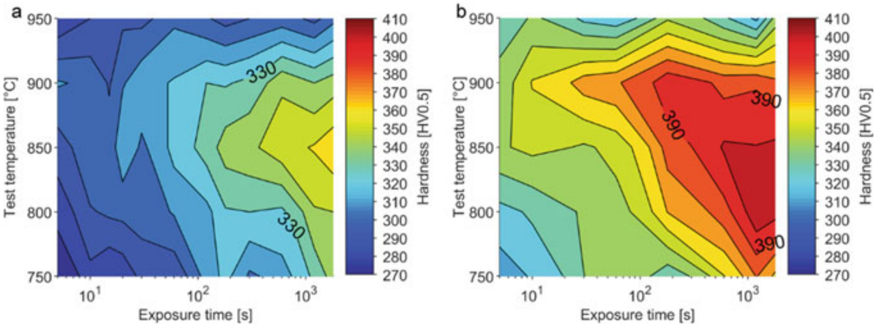


Fig. 19 TTH diagrams for Haynes® 282® (**a**) and Waspaloy (**b**) for exposure times up to 1800s [67]

to a peak temperature (T_{Peak}), derived from the nil-strength temperature (NST), typically 50 °C below. Other parameters and criteria such as the nil-ductility temperature (NDT), ductility recovery temperature (DRT), the ductility recovery rate (DRR), the ratio of ductility recovery (RDR), and the brittle temperature range can be used as measures for how susceptible a material would be towards HAZ liquation cracking. The method allows studying the liquation behavior in the HAZ during welding and can be used to compare different materials [50].

There is also a great potential in utilizing the tool to gain insight to SAC [60] where tests such as constant load rupture tests, stress relaxation tests, stress to fracture tests, and tests measuring ductility have been tried in the past [60]. Another frequently used approach follows the rationale of simulating the PWHT, and to evaluate how the ductility is affected in the temperature range where SAC occurs. This type of test approach is referred to as constant heating rate test (CHRT) [74]. Since the CHRT uses a constant heating rate to the different test temperatures, the effect of hardening reactions cannot be investigated. This has led to the development of a new approach

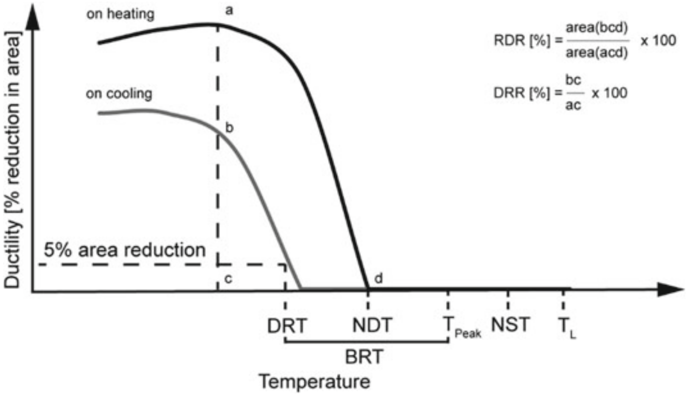


Fig. 20 Schematic hot ductility signature curve from the hot ductility test with corresponding test temperatures indicated in the graph [82]

that utilizes fast heating of 1000 °C/s and subsequent isothermal exposure to obtain microstructures with varying precipitation structure [66, 67, 82].

Variable restraint (Varestraint) weldability testing is a method that can be used to investigate susceptibility towards hot cracking [42, 85]. The test is carried out by applying an external load to a specimen at the same time as it is being welded. Varestraint testing provides a way to rank materials, conditions, welding processes, and parameters against one another. In Fig. 21, an example is presented regarding Varestraint testing of cast Alloy 718 in three different conditions, as cast, hot isostatic pressing (HIP)-1120 °C-4 h and HIP-1190 °C-4 h. [87]. The scatter in cracking response is unfortunately normally large when dealing with cast materials, however, the average data indicate the condition of HIP-1190 °C-4 h being the worst of the investigated conditions, which, despite the large scatter, have been also observed for other alloys [49, 56]. So, scattering in test data and other types of factors that add uncertainties to the understanding of cracking behavior is just another proof of the importance of not relying on single type of test method, one should utilize a wide portfolio of methods to successively build a comprehensive and reliable understanding of the underlying mechanisms.

Conclusions

Research within AM technology has increased exponentially since 2010, dating back to ~1985, however, the number of publications for “welding” and “superalloys” has had a more modest increase dating back to ~1950s. The top-ten countries as well as affiliations regarding the greatest number of publications within the field of “welding AND superalloys” coincide to a large extent to the top-ten countries in the field of “additive manufacturing AND superalloys” with few exceptions. Fabrication can

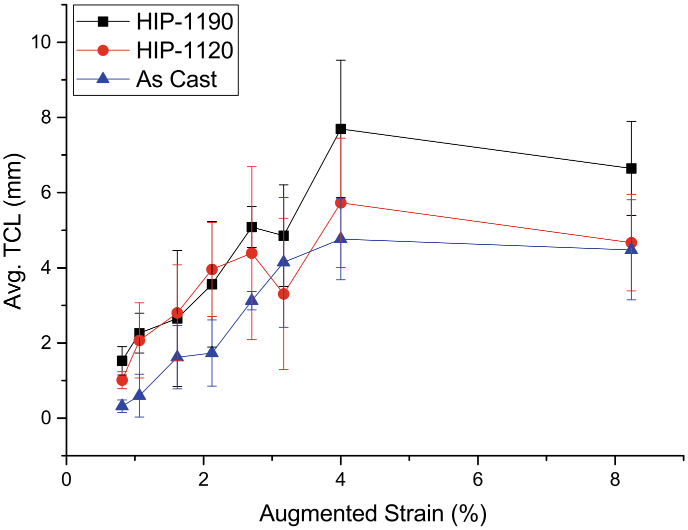


Fig. 21 HAZ liquation cracking response with standard deviations for Varestraint testing of cast Alloy 718 in the as cast, HIP-1120 °C-4 h and HIP-1190 °C-4 h conditions [87]

be seen as an enabler for more efficient aero-engines by reducing the weight of structural components. It is dependent on know-how of metallurgical aspects of different material forms, i.e., sheet, forging, and casting as well as their implications on welding. Additive manufacturing is an additional recent tool that can potentially further enhance the fabrication concept of hot structural components. The aerospace sector dominates the total market share (70%) with respect to superalloy usage. Weldability as a concept can be defined as a measure of the ease with which a metal or an alloy can be welded or joined without degradation to the weldment microstructure or properties during or after welding and for the duration of its intended service. In this context, susceptibility towards cracking during welding and post-weld heat treatment (PWHT) is of major importance. Weld cracking in Ni- and Ni–Fe-based precipitation hardening superalloys is predominantly related to hot cracking and strain age cracking (SAC), which are of high importance especially for hot structural applications in aero-engines. There has been significant development on gas metal arc welding processes such as pulsed mode of GMAW, cold metal transfer, keyhole, and high frequency, which provide deeper penetration and a more robustness, however, laser beam welding despite being significantly more capital intensive still possesses advantages regarding automation and control, not at least of high importance in directed energy deposition type of processes.

Ni- and Ni–Fe-based superalloys will always be at some risk of solidification cracking where welding procedure and parameters combined with the chemical composition determine the susceptibility of an alloy. High heat input, in general, aggravates cracking since it decreases the temperature gradient which in turn increases the region of solid–liquid where cracking can take place. Certain elements such as B, C, Si, Mo, and Nb are more important than others when it comes to the influence of solidification temperature range and formation of terminal eutectic at the end of solidification.

Heat-affected zone liquation cracking on the other hand is very much related to grain boundary liquation, where trace elements such as B, P, S, and Nb are important. The actual liquation mechanism is triggered by two different types: penetration mechanism and segregation mechanism. Trace elements such as B are of crucial importance in the segregation mechanism, where it segregates via non-equilibrium or equilibrium mechanisms, whereas the penetration mechanism primarily is claimed to be governed by eutectic melting, and constitutional liquation.

Strain age cracking (SAC) occurs in the solid state, without any prerequisite of liquid phase, and occurs when hardening takes place in the alloy. It is closely related to the kinetics of hardening in superalloys, and it is primarily of concern for γ' hardening superalloys. SAC occurs during the post-weld heat treatment (PWHT) and is consequently sometimes referred to as "PWHT cracking" or "Reheat cracking" because of the high welding stresses that develop at the same time that hardening occurs in γ' precipitation hardening Ni-based superalloys. The main factors that influence susceptibility towards SAC are related to induced strain, stress localization at grain boundaries, precipitation kinetics, and the ability for stress relaxation.

Weldability testing is necessary to account for the aforementioned concerns related to cracking, however, weldability, as such, is quite a broad concept that covers everything from actual welding to service performance and should therefore be treated with care to avoid misunderstanding of its meaning. A proposed procedure in assessing susceptibility toward cracking is to utilize a variety of tools, where each one of them provides insightful knowledge on the specific material's behavior. The proposed procedure involves systematic work of metallography, thermal analysis, hardness testing in combination with thermal treatments, hot ductility testing, welding using different processes, as well as Varestraint testing.

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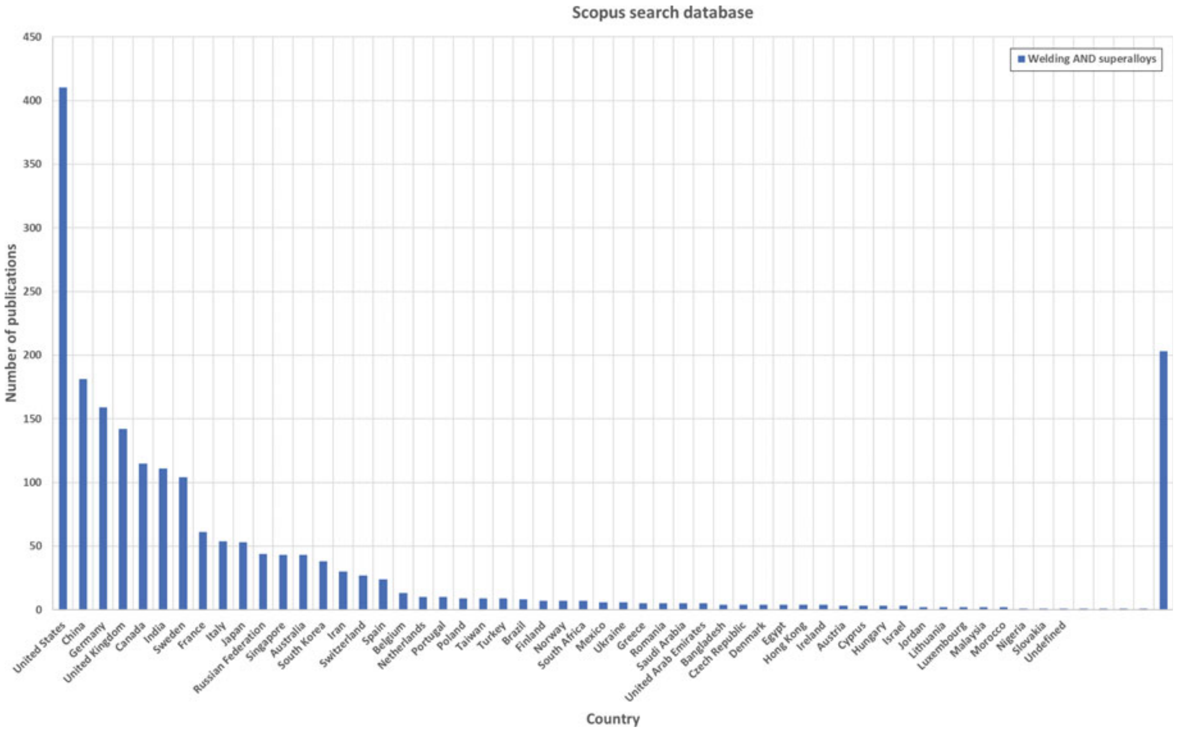
Appendix 1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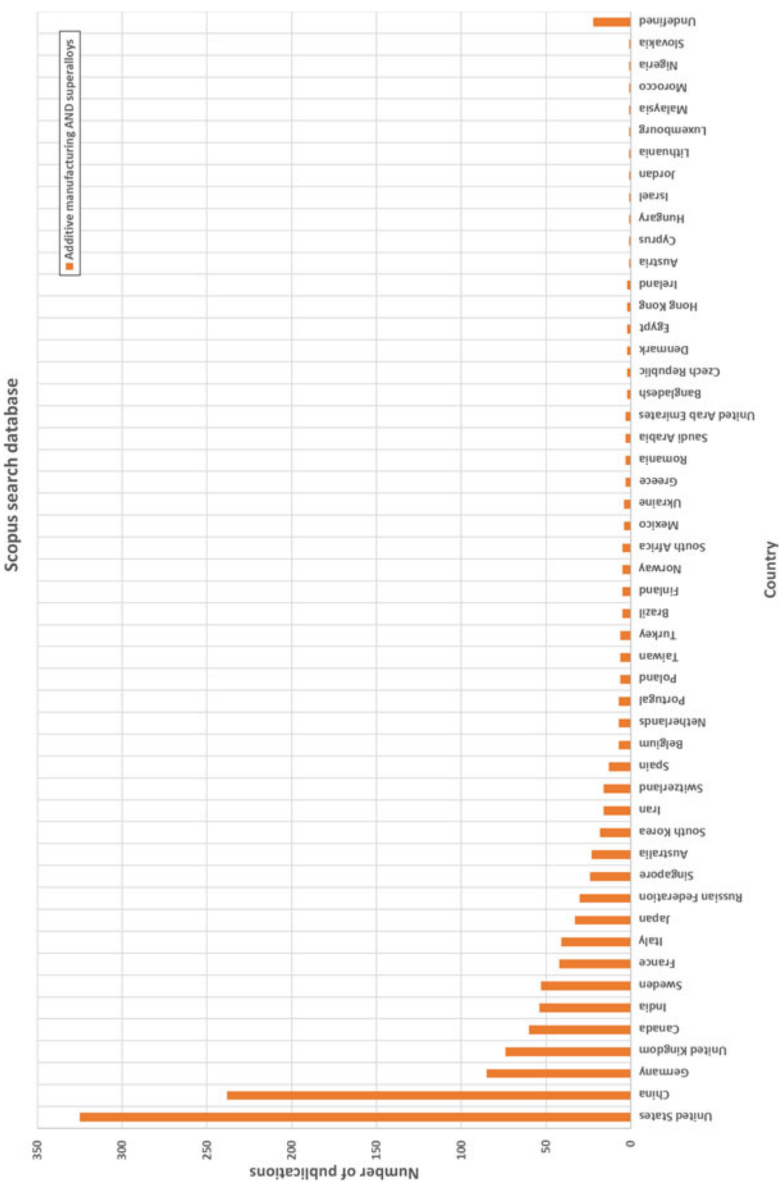
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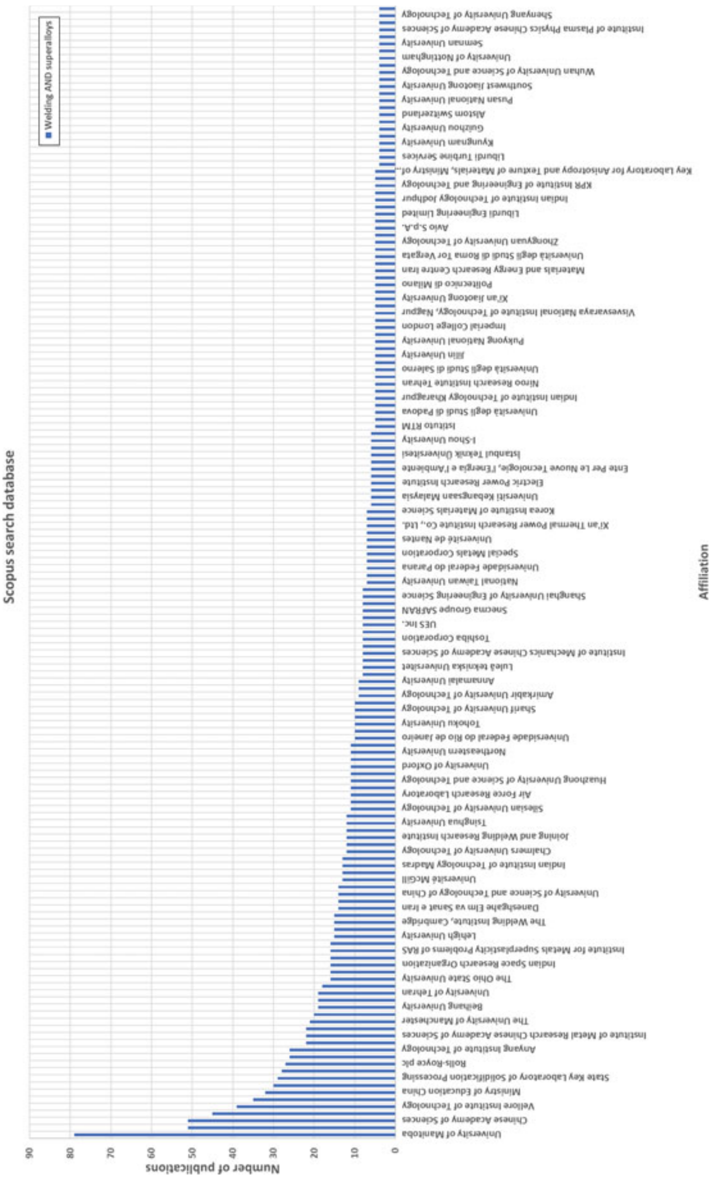
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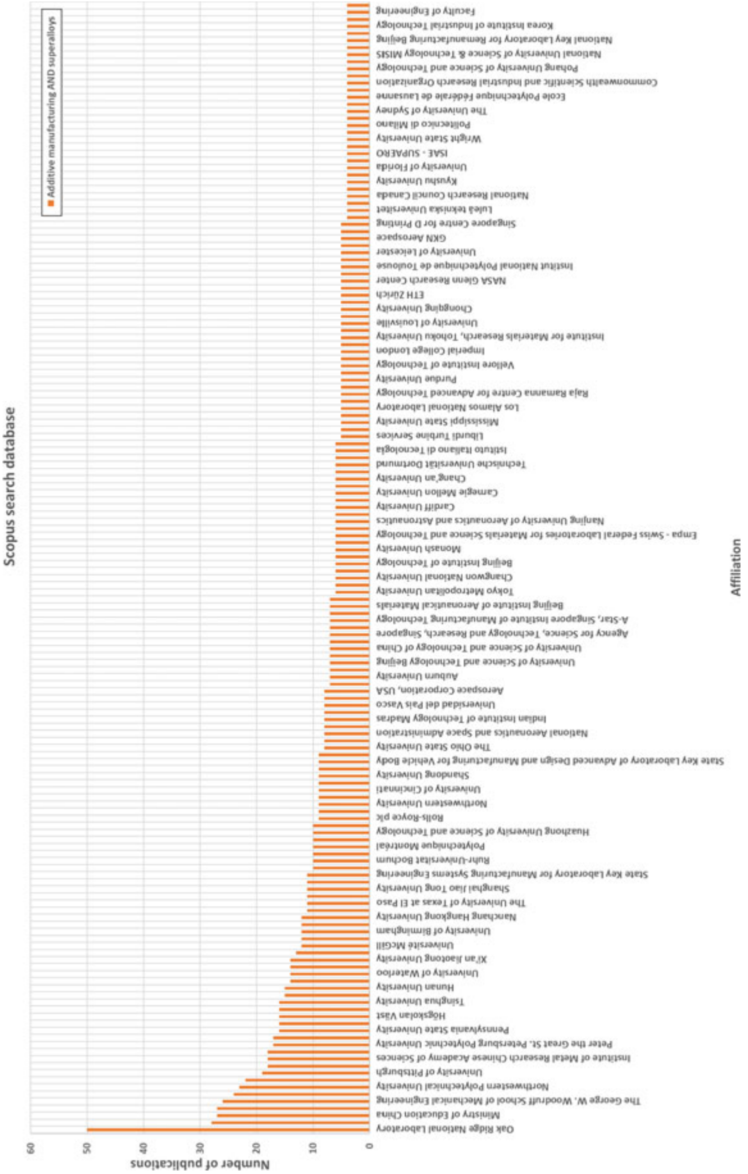
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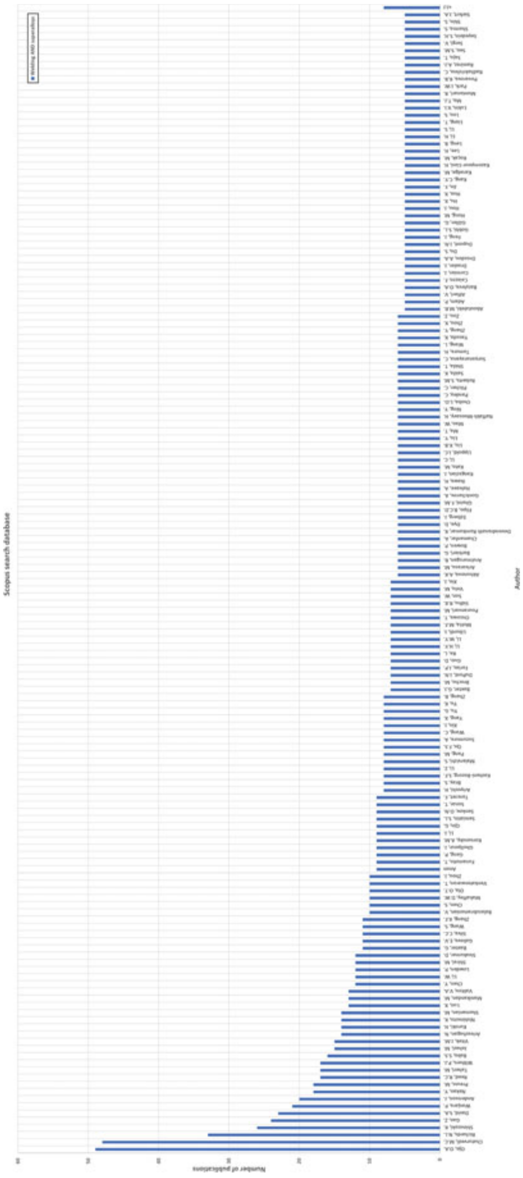
Appendix 5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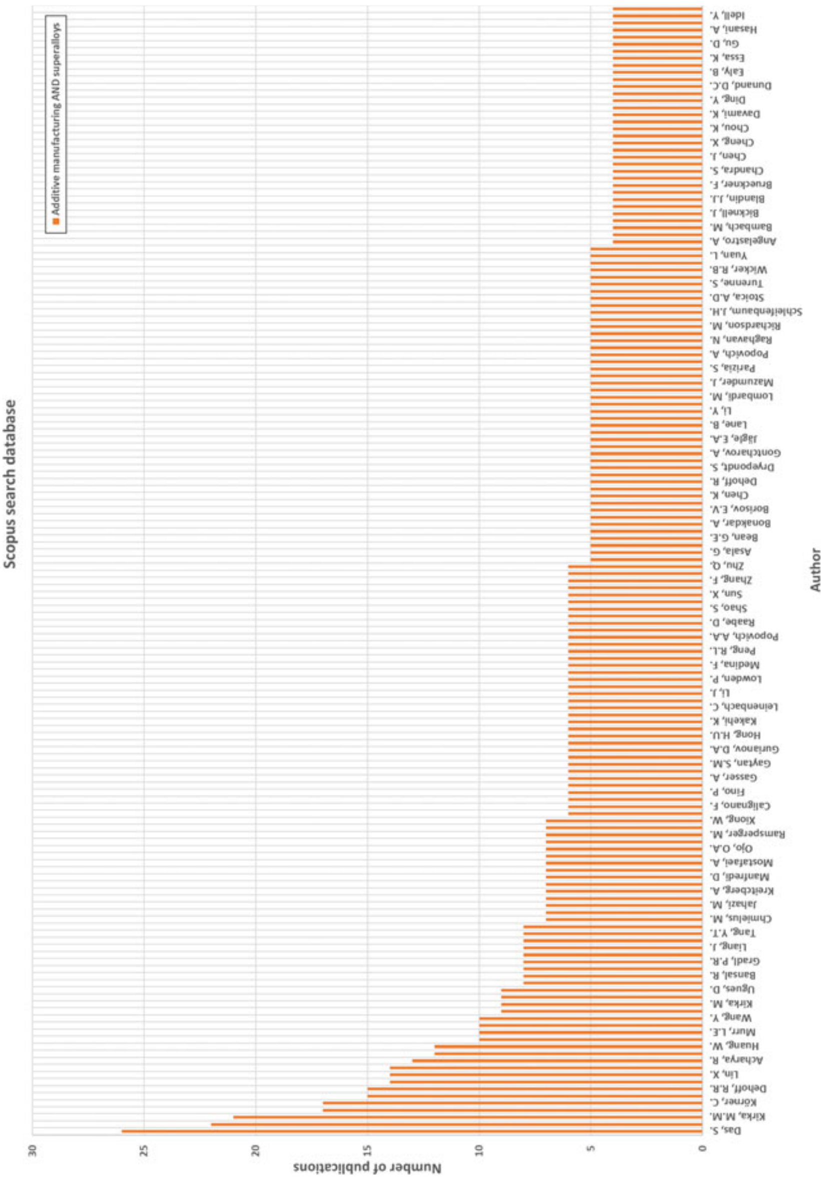
Appendix 6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