

Acicular Ferrite Formation and Its Influencing Factors - A Review

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Abstract

Acicular ferrite is a microstructure nucleating intergranularly on non-metallic inclusions and forming an arrangement of fine, interlocking grains. This structure is known to improve steel properties, especially steel toughness, essentially. The formation of acicular ferrite is mainly affected by steel composition, cooling rate, inclusion landscape and austenite grain size. In recent decades, extensive research has been conducted to investigate these factors. The present paper provides an overview of the impact of published results and the state of knowledge regarding acicular ferrite formation. Special attention is paid to the effect of carbon, manganese and titanium addition to steel, as well as the optimum size, number and composition of non-metallic inclusions. In addition, the reactions during the nucleation and growth of acicular ferrite needles are briefly addressed. Further, characteristics of acicular ferrite and bainite are summarized, which should help to distinguish these similar structures.

Keywords: acicular ferrite, cooling rate, non-metallic inclusion, steel

1. Introduction

At the beginning of the 1990s, Takamura and Mizoguchi (1990) introduced the concept of Oxides Metallurgy, which focuses on the use of oxidic inclusions to improve the quality of the final product and stabilize the production process. They described, inter alia, that by controlling the nature and distribution of the inclusions, the formation of intragranular ferrite, the so-called acicular ferrite, can be promoted, which significantly increases the steel's fracture toughness. Although the clear definition of the term 'Oxides Metallurgy' by Takamura and Mizoguchi (1990) was novel, the idea of using acicular ferrite for the optimization of steel properties was not new. Already in 1956, Aaronson and Wells (1956) described a microstructure of intragranularly nucleated, needle-shaped and chaotically arranged ferrite grains; however, they did not name this structure acicular ferrite, but 'Widmannstätten star'. One of the first publications that designated this characteristic structure as acicular ferrite was by Smith, Coldren and Cryderman in 1971. Since then, comprehensive efforts have been devoted to an explanation of acicular ferrite formation. Most of these early studies focused on weld metals (Abson, Dolby, & Hart, 1978; Bonnet & Charpentier, 1983; Cochrane & Kirkwood, 1978; Devillers, Kaplan, Marandet, Ribes, & Riboud, 1983; Düren, 1983; Evans, 1980, 1982, 1983; Ricks, Barritte, & Howell, 1981; Ricks, Howell, & Barritte, 1982; Saggese, Bhatti, Hawkins, & Whiteman, 1983), so using acicular ferrite to improve the toughness of weld fusion zones is quite popular today. In recent years, acicular ferrite has also been of increasing interest to steel producers; the excellent combination of toughness and strength makes acicular ferrite favorable for HSLA (high-strength low-alloy) steels (Bhadeshia, 2001; Sarma, Karasev, & Jönsson, 2009; M. Song, Song B., Hu, Xin, & G.Y. Song, 2015; Sung, Shin, Hwang, C. G. Lee, & S. Lee, 2013). In addition, acicular ferrite is becoming more and more important as a constituent in line pipe steels because of its good sour gas resistance (Garcia-Mateo, Capdevila, Caballero, & Andrés, 2008; Madariaga, Gutierrez, & Bhadeshia, 2001; Ogibayashi, 1994; Xiao et al., 2006; Xiao, Liao, Ren, Shan, & Yang, 2005; Zhao, Shan, Xiao, Yang, & Li, 2002; Zhao, Yang, & Shan, 2003).

Acicular ferrite formation is influenced by four main parameters (Bhadeshia, 2001; Farrar & Harrison, 1987; Grong & Matlock, 1986; Loder & Michelic, 2016; Sarma et al., 2009).

- Austenite grain size (AGS)
- Cooling rate (CR)
- Steel composition
- Non-metallic inclusions (NMI)

Comprehensive research to evaluate the impact of these parameters has been performed in recent decades. However, the effects are not completely clarified in the literature yet, possibly due to their strong interactions. The present work provides an overview of the state of knowledge on acicular ferrite formation and its four main influencing factors.

2. The Formation of Acicular Ferrite

Acicular ferrite nucleates heterogeneously on the surface of NMI during the austenite-ferrite-transition. As transformation continues, the ferrite grains radiate in various directions, creating a chaotic construction of crystallographically disoriented plates of approximately 5 - 15 μm in length and 1 - 3 μm in width. Thereby, the typical fine-grained and interlocking structure of acicular ferrite is formed. Compared with parallel plates, it is much more difficult for cleavage cracks to propagate across this chaotic structure, which leads to a significant increase in mechanical properties, most notably in toughness (Abson et al., 1978; Bhadeshia, 2001; Cai, Zhou, Tong, Yue, & Kong, 2015; Díaz-Fuentes, Iza-Mendia, & Gutiérrez, 2003; Farrar & Harrison, 1987; Fattahi, Nabhani, Hosseini, Arabian, & Rahimi, 2013; Gourgues, Flower, & Lindley, 2000; Jin, Shim, Cho, & Lee, 2003; Lan, Du, & Liu, 2013; Lee, Kim, Kang, & Hwang, 2000; Madariaga et al., 2001; Nako, Hatano, Okazaki, Yamashita, & Otsu, 2014; Ohkita & Horii, 1995; Ricks et al., 1982; Sarma et al., 2009; Wan, Wang, Cheng, & Wu, 2012; Zhang & Farrar, 1996; Zhang, Shintaku, Suzuki, & Komizo, 2012b, 2012a; Zhang, Terasaki, & Komizo, 2010).

The formation of acicular ferrite is diffusionless, so the acicular ferrite plates become supersaturated with carbon and excess carbon is rejected to the remaining austenite shortly after the transformation. Depending on the CR, the carbon-enriched austenite transforms in the ongoing cooling process to pearlite, bainite or martensite. Pearlite and bainite are formed at low and medium CR when the austenite becomes saturated in carbon and cementite precipitates. At a high CR, the remaining austenite transforms to martensite. Occasionally, the austenite does not convert, so islands of retained austenite are found in the final microstructure. In addition to the CR, carbon, silicon and nickel were found to influence the transition of the remaining austenite between the acicular ferrite grains. With increasing carbon content, the fraction of intergranular phases between acicular ferrite needles increases, as observed by Evans (1982, 1983). Increasing the silicon and nickel contents leads to a higher tendency of the intergranular region to transform into martensite, as asserted by Shim et al. (2001) and Evans (1990b). They found that these elements suppress the precipitation of cementite and, consequently, the formation of bainite and pearlite (Bhadeshia, 2001; Capdevila et al., 2006; Capdevila, García-Mateo, Chao, & Caballero, 2009; Evans, 1982, 1983, 1990b; Farrar & Harrison, 1987; Grong & Matlock, 1986; Hossein Nedjad, Zahedi Moghaddam, Mamdouh Vazirabadi, Shirazi, & Nili Ahmadabadi, 2011; Huo, Liu, Zhang, Yan, & Gao, 2013; Kim, Lee, & Kim, 2008; Lan et al., 2013; Madariaga et al., 2001; Madariaga, Gutiérrez, García-de Andrés, & Capdevila, 1999; Rees & Bhadeshia, 1994; Ricks et al., 1982; Shim, Cho et al., 2001; Strangwood & Bhadeshia, 1986; Sugden & Bhadeshia, 1989; Xiao et al., 2005; Yang, Liu, Sun, & Li, 2010; Zhao, Yang, Xiao, & Shan, 2003; Zuo & Zhou, 2015).

Several authors (Aaranson & Wells, 1956; Barbaro, Krauklis, & Easterling, 1989; Díaz-Fuentes et al., 2003; Jin et al., 2003; Madariaga et al., 2001; Ricks et al., 1981; Ricks et al., 1982; Song et al., 2015; Wu, Inagawa, & Enomoto, 2004; Yang et al., 2010; Zhang & Farrar, 1996; Zhang et al., 2010) separate primary and secondary acicular ferrite. According to them, primary acicular ferrite plates nucleate on NMI, while secondary acicular ferrite forms on primary plates by so-called sympathetic nucleation. Although Wu et al. (2004) support the theory of sympathetic nucleation, they noted that it is hardly possible to distinguish between sympathetic nucleation and impingement of plates in many cases. Additionally, Wan et al. (2012) observed in 3-D reconstructed microstructure models that many acicular ferrite plates, classified in the cross-section as secondary plates, are just grains that impinged or intersected their "primary" plates. Additionally, there is no explanation why secondary acicular ferrite should not form a series of laths on the large surface of primary plates, resulting in packages of parallel laths.

Since the 1970s, much research has been performed to determine the mechanism of acicular ferrite formation. It is a common opinion that NMI are essential for nucleation. The literature describes four main mechanisms of how inclusions promote the nucleation of intragranular ferrite:

- Destruction of crystal structure (Barbaro et al., 1989; Bhadeshia, 2001; Gregg & Bhadeshia, 1997; Lee et al., 2000; Ricks et al., 1981; Ricks et al., 1982; Sarma et al., 2009; Shim, Oh et al., 2001; Zhang et al., 2012a; Zhang et al., 2010)
- Creation of dislocation arrays (Bhadeshia, 2001; Furuhashi, Yamaguchi, Sugita, Miyamoto, & Maki, 2003; Grong & Matlock, 1986; Sarma et al., 2009; Zhang et al., 2010)
- Reduction of lattice mismatch (Abson et al., 1978; Cochrane & Kirkwood, 1978; Eijk, Grong, & Hjelen, 1999; Furuhashi, Shinyoshi et al., 2003; Furuhashi, Yamaguchi et al., 2003; Grong, Kluken, Nylund, Dons, & Hjelen, 1995; Jin et al., 2003; Nako, Okazaki, & Speer, 2015; Sarma et al., 2009; Yamamoto,

Hasegawa, & Takamura, 1996; Zhang et al., 2010)

- Chemical changes in the local matrix (Byun, Shim, Cho, & Lee, 2003; Cai et al., 2015; Chai, Su, Yang, & Xue, 2014; Evans, 1980; Farrar & Harrison, 1987; Gregg & Bhadeshia, 1997; Grong & Matlock, 1986; Hui et al., 2014; Kimura, Nakajima, Mizoguchi, & Hasegawa, 2002; Ogibayashi, 1994; Sarma et al., 2009; Seo, Kim, Evans, Kim, & Lee, 2015; Shim, Cho et al., 2001; Shim, Oh et al., 2001; Shim, Byun et al., 2001; Song et al., 2015; Wan et al., 2012; Yang, Ma, Zhu, Wang, & Zheng, 2012a)

Comprehensive information on the state of knowledge regarding these formation mechanisms were published in Koseki & Thewlis, Loder (2016), Sarma et al. (2009), Thewlis, Whiteman, and Senogles (1997). Hence, detailed information about the mechanisms was not included in the present paper.

3. Acicular Ferrite vs. Bainite

When bainite was first discovered by Davenport, Bain, and Kearny, (1930) (reprinted in Bhadeshia (2010), Davenport, Bain, and Kearny (1970), it was defined as acicular-shaped ferrite. Even still, acicular ferrite is often described as intragranularly nucleated bainite. The similar transformation temperature and comparable transformation mechanism are seen as evidence for the connection of acicular ferrite and bainite. According to Bhadeshia and coworkers (Bhadeshia, (1992, 2001), Rees and Bhadeshia (1994), Sugden and Bhadeshia (1989), a change from bainite to acicular ferrite can be achieved by simple control of the nucleation sites. Nevertheless, a clear distinction between acicular ferrite and bainite is essential because these structures show significant differences, which are summarized in Table 1, and consequently result in different mechanical properties. (Byun et al., 2003; Díaz-Fuentes et al., 2003; Eijk et al., 1999; Gourgues et al., 2000; Sarma et al., 2009; Shim, Cho et al., 2001; Smith et al., 1971; Yang et al., 2010)

Table 1. Characteristics of acicular ferrite and bainite (Bhadeshia, 1992, 2001; Byun et al., 2003; Díaz-Fuentes et al., 2003; Gourgues et al., 2000; Sarma et al., 2009; Shim, Cho et al., 2001; Yang et al., 2010)

	Acicular ferrite	Bainite
Nucleation	intragranular	inter- or intragranular
Nucleation site	point sites (surface of NMI)	mostly austenite grain surface
Transition Temp.		similar
Grain form	needle-shaped/lenticular plates	fine laths which form sheaves
Growth direction	various directions (star-like)	parallel laths
Parallelism	cannot form parallel laths	laths are parallel within package
Growth mechanism		diffusionless
Growth stop reason	C-enrichment of austenite or impingement	

Madariaga et al. (1999, 2001) suggested that acicular ferrite plates can grow as so-called morphological packets. These packets are similar to the bainitic morphology, so according to this theory, the only difference between acicular ferrite and bainite is the nucleation site: intragranular particles for acicular ferrite and grain boundaries for bainite. However, this does not conform to the widely used description of acicular ferrite, which includes that acicular ferrite plates radiate in various directions, forming a chaotic structure of crystallographic disoriented plates. Thus, Díaz-Fuentes et al. (2003) recommended that structures of parallel ferrite plates inside the austenite grain should be named intragranularly nucleated bainite and that only chaotically arranged ferrite plates nucleating at point sites should be classified as acicular ferrite.

4. Influence of Austenite Grain Size

During phase transformation, the nucleation of new phases can occur homogeneously or heterogeneously. Generally, heterogeneous nucleation is more likely because of the reduced nucleation energy at interphase surfaces. Hence, during the austenite-ferrite-transition, the ferrite grains tend to nucleate heterogeneously on NMI, like acicular ferrite, or on grain boundaries, like Widmannstätten ferrite and grain boundary ferrite. Which nucleation site will be preferred depends on the ratio between the total surface area of NMI and the total surface area of austenite grains. Intragranular nucleation is preferred with increasing AGS or inclusion number, and grain boundary nucleation becomes more likely with decreasing grain size or inclusion number (see Figure 1). However, the AGS cannot be increased unlimitedly without reducing the inclusion number due to pinning effects. (Adrian & Pickering, 1991; Andersen & Grong, 1995; Bernhard, Bragin, & Vanovsek, 2012; Bernhard, Reiter, & Presslinger, 2008; Garbarz, 1995) However, a decrease in inclusions will reduce the nucleation sites for acicular ferrite, so the fraction of acicular ferrite can decrease or stay stable at larger AGS (Barbaro et al., 1989; Bhadeshia, 2001; Bin & Bo, 2012; Byun et al.,

2003; Cochrane & Kirkwood, 1978; Devillers et al., 1983; Díaz-Fuentes et al., 2003; Farrar, Zhang, Bannister, & Barritte, 1993; Garcia-Mateo et al., 2008; Gregg & Bhadeshia, 1997; Grong & Matlock, 1986; Kikuchi et al., 2011; Lee & Pan, 1995; Liu & Olson, 1986; Rees & Bhadeshia, 1994; Ricks et al., 1982; Sarma et al., 2009; Song et al., 2015; Thewlis, 2006; Vanovsek, Bernhard, Fiedler, & Schnitzer, 2013; Wan, Wu, Cheng, & Wei, 2015; Yang, Ma et al., 2015; Yang et al., 2012a, 2012b; Zhang et al., 2012a; Zhang, Terasaki, & Komizo, 2009, 2010).

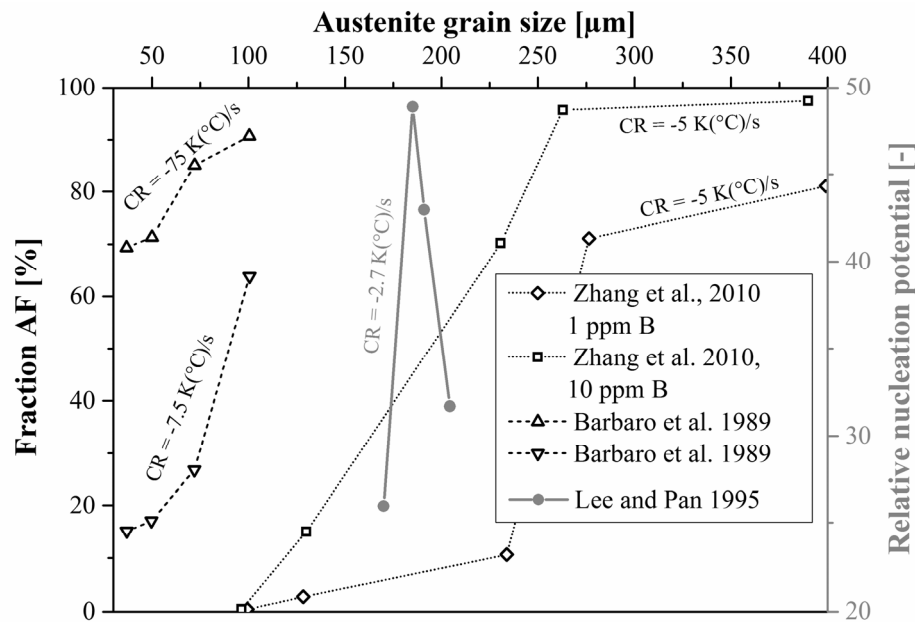


Figure 1. Impact of AGS on the acicular ferrite formation in titanium alloyed low-carbon steels for different CR between 1073,15 K (800 °C) and 773,15K (500 °C) ; adapted from Ref. (Barbaro et al., 1989; Lee & Pan, 1995; Zhang et al., 2010)

Farrar et al. (1993) observed that the AGS also influences the acicular ferrite start temperature. Mostly, ferrite formation starts at austenite grain boundaries. Due to the reduced solubility of carbon in ferrite, the surrounding austenite is enriched in carbon during this transition. In small austenite grains, the intragranular region is also influenced by this effect. The higher carbon content prevents the formation of acicular ferrite and lowers the acicular ferrite start temperature. With increasing AGS, intragranular regions are less enriched in carbon, and the acicular ferrite start temperature remains more stable. The carbon enrichment of austenite grains during grain boundary formation influences the structure of acicular ferrite as well. Due to the larger carbon enrichment of smaller austenite grains, the nucleation rate of acicular ferrite is reduced, and the formed plates can grow larger before they are stopped by impingement. Hence, acicular ferrite grains become coarser with decreasing AGS. (Bhadeshia, 2001; Farrar et al., 1993).

5. Influence of Cooling Rate

It is commonly accepted that the transformation of acicular ferrite is situated between bainite and coarse-grained ferrite; however, the optimum CR to achieve maximum acicular ferrite depends strongly on the production route and the composition of the steel (Farrar & Harrison, 1987; Rees & Bhadeshia, 1994; Sarma et al., 2009; Yang, Wang, Wang, & Song, 2008; Zhang et al., 2012b; Zhao, Yang, Xiao et al., 2003). Due to this strong interaction, a very wide range of CR is described in the literature as suitable for acicular ferrite. Table 2, Table 3 and Table 4 give an overview of recent results in the literature regarding CR for acicular ferrite during heat treatments with or without deformation.

Furthermore, Rees and Bhadeshia (1994) observed that the structure of acicular ferrite becomes finer with increasing CR. A higher CR increases supercooling and therefore the reaction driving force, which leads to a higher nucleation rate. Many acicular ferrite plates nucleate, so the plates have less free space to grow and will become finer.

Table 2. CR between 1073,15 K (800 °C) and 773,15K (500 °C) described in the literature as suitable for the formation of acicular ferrite during heat treatments without deformation

Ref.	CR range	CR opt.	Steel composition
	[K(°C)/min]	[K(°C)/min]	[C, Mn, Si, Al, Cu, Ni, Cr, Mo in wt.-%; Ti, Nb, V, B in wt.-ppm]
(Thewlis, 2006)	6 - 498	6 - 30	0.08 C, 2.00 Mn, 0.40 Si, 0.03 Al, 0.25 Mo, 100 Ti
(Thewlis, 2006)	6 - 540	180	0.05 C, 1.50 Mn, 0.30 Si, 0.03 Al, 400 Nb, 800 V
(Thewlis, 2006)	6 - 540	6	0.08 C, 2.00 Mn, 0.40 Si, 0.03 Al, 0.25 Mo, 100 Ti, 10 B
(Capdevila et al., 2006)	6 - 600	18 - 360	0.38 C, 1.44 Mn, 0.62 Si, 0.03 Al, 0.04 Ni, 0.07 Cr, 0.16 Mo, 160 Ti, 1000 V
(Xiao et al., 2005)	12 - 450	-	0.03 C, 1.56 Mn, 0.24 Si, 0.32 Mo, 390 Nb, 190 V
(Zhao et al., 2003)	24 - 3000	1200	0.05 C, 1.94 Mn, 0.30 Si
(Zhao et al., 2003)	24 - 3000	450 - 600	0.08 C, 1.28 Mn, 0.25 Si, 270 Ti, 450 Nb, 530 V
(Capdevila et al., 2006)	30 - 1200	120 - 600	0.36 C, 1.44 Mn, 0.63 Si, 0.02 Al, 0.13 Ni, 0.17 Cr, 0.02 Mo, 220 Ti, 900 V
(Yang et al., 2008)	90 - 150	120	0.39 C, 1.14 Mn, 0.16 Si, 0.01 Al, 250 Ti
(Capdevila et al., 2009)	120 - 360	360	0.10 C, 1.54 Mn, 0.20 Si, 0.22 Cu, 20 Ti, 20 Nb, 600 V
(Lan et al., 2013)	180 - 600	300	0.08 C, 1.59 Mn, 0.25 Si, 0.46 Cr, 0.11 Mo, 1000 Ti+Nb+V, 10 B
(Capdevila et al., 2009)	240 - 600	360	0.08 C, 1.46 Mn, 0.02 Al, 10 Ti, 2500 V
(Jin et al., 2003)	300	-	0.07 C, 1.90 Mn, 160 Ti
(Huo et al., 2013)	400 - 1500	800	0.09 C, 1.29 Mn, 0.29 Si, 0.03 Al, 0.13 Cu, 0.15 Ni, 0.06 Cr, 0.18 Mo, 10 Ti, 300 Nb, 500 V

Table 3. CR between 1073,15 K (800 °C) and 773,15K (500 °C) described in the literature as suitable for the formation of acicular ferrite during heat treatments by HT-LSCM

Ref.	CR range	CR opt.	Steel composition
	[K(°C)/min]	[K(°C)/min]	[C, Mn, Si, Al, Cu, Ni, Cr, Mo in wt.-%; Ti, Nb, V, B in wt.-ppm]
(Zhang et al., 2012b)	60 - 240	-	0.15 C, 1.48 Mn, 0.20 Si, 100 Ti, 2 B
(Zhang et al., 2012b)	60 - 240	240	0.15 C, 1.48 Mn, 0.20 Si, 100 Ti, 12 B
(Wang et al., 2012)	300	-	0.07 C, 1.10 Mn, 0.14 Si, 46-240 Ti
(Wan, Wu, Huang, & Wei, 2014)	300	-	0.06 C, 1.60 Mn, 0.21 Si, 0.02 Al, 0.25 Cu+Ni+Cr+Mo, 400 Ti, 390 Nb, 220 V, 5 B
(Wan et al., 2015)	300	-	0.06 C, 1.62 Mn, 0.30 Si, 0.70 Ni+Cr+Mo, 150 Ti+Zr, 550 Nb, 12-20 B, 8-35 Ca

Table 4. CR between 1073,15 K (800 °C) and 773,15K (500 °C) described in the literature as suitable for the formation of acicular ferrite during thermo-mechanical treatments

Ref.	CR range	CR opt.	Steel composition
	[K(°C)/min]	[K(°C)/min]	[C, Mn, Si, Al, Cu, Ni, Cr, Mo in wt.-%; Ti, Nb, V, B in wt.-ppm]
(Li, Min, Liu, & Jiang, 2015)	60 - 600	300 - 600	0.05 C, 1.55 Mn, 0.22 Si, 0.03 Al, 0.31 Ni, 140 Ti, 24 Mg, 30 Zr
(Capdevila et al., 2006)	60 - 1200	-	0.36 C, 1.44 Mn, 0.63 Si, 0.02 Al, 0.13 Ni, 0.17 Cr, 0.02 Mo, 220 Ti, 900 V
(Capdevila et al., 2006)	60 - 1200	240 - 600	0.38 C, 1.44 Mn, 0.62 Si, 0.03 Al, 0.04 Ni, 0.07 Cr, 0.16 Mo, 160 Ti, 1000 V
(Wu, Lee, Kim, & Kim, 2012)	60 - 1800	600	0.06 C, 1.80 Mn, 0.25 Si, 0.02 Al, 0.30 Cu, 0.30 Ni, 0.31 Mo, 140 Ti, 400 Nb, 400 V, 10 B
(Xiao et al., 2005)	60 - 2400	300 - 2400	0.03 C, 1.56 Mn, 0.24 Si, 0.32 Mo, 390 Nb, 190 V
(Zhao, Yang, Xiao et al., 2003)	60 - 3000	600	0.03 C, 1.56 Mn, 0.24 Si, 0.32 Mo, 400 Nb, 200 V
(Zhao, Yang, Xiao et al., 2003)	120 - 2400	1200 - 2400	0.08 C, 1.28 Mn, 0.25 Si, 270 Ti, 450 Nb, 530 V
(Shim, Byun et al., 2001)	180	-	0.06 C, 2.46 Mn, 0.20 Si, 90 Ti
(Lan et al., 2013)	180 - 600	300	0.08 C, 1.59 Mn, 0.25 Si, 0.46 Cr, 0.11 Mo, 1000 Ti+Nb+V, 10 B
(Zhao, Yang, Xiao et al., 2003)	210 - 1800	1800	0.05 C, 1.94 Mn, 0.30 Si
(Shim, Byun et al., 2001)	300	-	0.14 C, 1.84 Mn, 0.18 Si, 110 Ti
(Rees & Bhadeshia, 1994)	300	-	0.05 C, 1.08 Mn, 0.46 Si, 2.20 Ni, 0.65 Cr, 0.41 Mo, 220 V
(Rees & Bhadeshia, 1994)	300	-	0.06 C, 2.02 Mn, 0.48 Si, 2.20 Ni, 0.65 Cr, 0.41 Mo, 250 V
(Yang et al., 2010)	300	-	0.03 C, 0.17 Mn, 1.80 Si, 0.02 Al, 0.25 Cu, 0.18 Ni, 0.26 Cr, 110 Ti, 1200 Nb

6. Influence of Steel Composition

Alloying elements can affect the formation of acicular ferrite as solute element in the matrix or because they form active NMI. Table 5 gives an overview of the most important alloying elements' effects. Elements can enhance (\uparrow), not influence (\leftrightarrow) or decrease (\downarrow) the amount of acicular ferrite. Some elements are described to have a positive effect on the formation of acicular ferrite at low contents (L), but a negative one with higher additions (H). About the impact of carbon and aluminium contradictory opinions (?) can be found in literature. An extensive discussion of the listed elements' effects can be found in Loder (2016).

Table 5. Influence of alloying elements on the formation of acicular ferrite

Element	Acts as solute	Acts as NMI	Effect on AF	Literature
C	x	x	? (\uparrow / \downarrow)	(Düren, 1983; Evans, 1982, 1983; Farrar & Harrison, 1987; Mu, Mao, Jönsson, & Nakajima, 2016)
O		x	\uparrow	(Abson et al., 1978; Düren, 1983; Fox & Evans, 2012; Grong & Matlock, 1986; Liu & Olson, 1986; Saggese et al., 1983)
S		x	L: \uparrow H: \downarrow	(Evans, 1986b; Lee & Pan, 1995; Mu, Jönsson, & Nakajima, 2014, 2015)
Ca		x	\uparrow	(Lee & Pan, 1995)
Ti		x	\uparrow	(Evans, 1986a, 1991b, 1993, 1995; Fox & Evans, 2012; Grong et al., 1995; Ilman, Cochrane, & Evans, 2014, 2015; Saggese et al., 1983; Seo et al., 2015; Vanovsek et al., 2013)
Mn	x	x	L: \uparrow H: \downarrow	(Byun et al., 2003; Chai et al., 2014; Chen, Zhang, Liu, Li, & Xu, 2013; Cochrane & Kirkwood, 1978; Evans, 1980; Farrar & Harrison, 1987; Grong & Matlock, 1986; Liu, Kobayashi, Yin, Kuwabara, & Nagai, 2007)
Al		x	? ($\downarrow / \leftrightarrow$)	(Bhadeshia, 2001; Evans, 1990a; Huang, Wang, Jiang, Hu, & Yang, 2016; Inoue et al., 1993; Ogibayashi, 1994; Shim, Cho et al., 2001; Yamada, Terasaki, & Komizo, 2008)
Mg	?	?	\uparrow	(Min, Li, Yu, Liu, & Jiang, 2016; Song et al., 2015)
Si	x		\downarrow	(Evans, 1986a; Shim, Cho et al., 2001)
B	x		L: \uparrow H: \downarrow	(Bhadeshia, 2001; Düren, 1983; Evans, 1996; Grong & Matlock, 1986; Ilman, Cochrane, & Evans, 2012, 2015; Peng, Chen, & Xu, 2001; Takamura & Mizoguchi, 1990; Yamamoto et al., 1996; Zhang et al., 2010)
Nb		x	\uparrow	(Chen et al., 2013; Evans, 1991a)
V		x	\uparrow	(Capdevila et al., 2009; Evans, 1991c; Garcia-Mateo et al., 2008; Mu et al., 2016)
Cr	x		L: \uparrow H: \downarrow	(Bhadeshia, 2001; Capdevila et al., 2006; Evans, 1987, 1989, 1990b; Smith et al., 1971)
Mo	x		L: \uparrow H: \downarrow	(Bhadeshia, 2001; Capdevila et al., 2006; Evans, 1987, 1989, 1990b; Smith et al., 1971)
Ni	x		L: \uparrow H: \downarrow	(Bhadeshia, 2001; Capdevila et al., 2006; Evans, 1987, 1989, 1990b; Smith et al., 1971)

6.1 Carbon

To date, several publications about the interaction of carbon and acicular ferrite have emerged, but they describe divergent effects: (Düren, 1983; Evans, 1982, 1983; Farrar & Harrison, 1987; Mu et al., 2016)

- Evans (1982, 1983) found a steady increase in the amount of acicular ferrite with increasing carbon content from 0.05 to 0.15 wt.-% when investigating weld metals with 0.65 - 1.72 wt.-% manganese and approximately 0.30 wt.-% silicon.
- Mu et al. (2016) investigated the influence of carbon between 0.01 and 0.40 wt.-% using thermodynamic calculations. The other alloying elements were kept constant at 1.00 wt.-% manganese, 0.40 wt.-% silicon, 100 wt.-ppm titanium and 20 wt.-ppm aluminum. They calculated the driving force for ferrite nucleation and showed a steady decrease with rising carbon content. Furthermore, they demonstrated that the nucleation capability of inclusions is reduced by higher carbon contents; subsequently, the minimum size of the inclusions to act as nuclei is significantly increased (see Figure 2).

- Düren (1983) studied weldments with 0.03 - 0.13 wt.-% carbon, 1.30 wt.-% manganese, 0.35 wt.-% silicon, 0.70 wt.-% nickel, 0.02 wt.-% aluminum, 0.30 wt.-% molybdenum, 250 wt.-ppm niobium and 400 wt.-ppm vanadium. He observed an optimum carbon content for acicular ferrite of 0.07 wt.-%. Below, the acicular ferrite is substituted by coarser ferrite veins, and above, it is substituted by martensite.

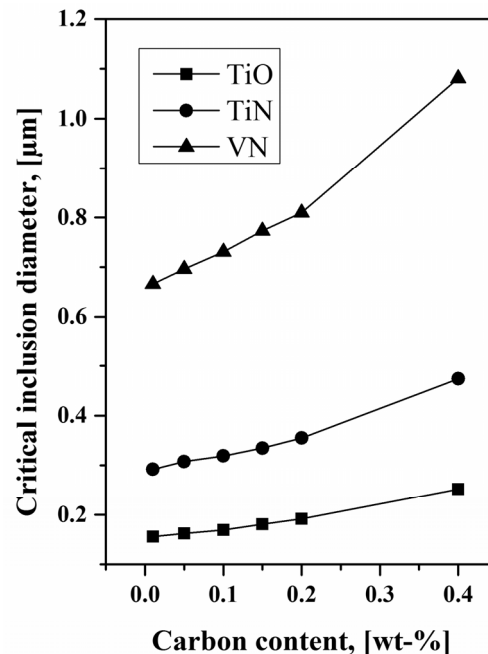


Figure 2. Influence of carbon content on the acicular ferrite formation: increase in the critical inclusion diameter for acicular ferrite nucleation; adapted from (Mu et al., 2016)

Some authors (Chai et al., 2014; Furuhashi, Yamaguchi et al., 2003; Gregg & Bhadeshia, 1997) reported that carbon-depleted zones promote acicular ferrite formation. Carbon is an austenite-stabilizing element, so zones with reduced carbon content tend to transform to ferrite. On the one hand, carbon depletion can result from the precipitation of carbide particles, such as VC. On the other hand, Gregg and Bhadeshia (1997) suggested that oxygen, which can be released by oxide particles, e.g., TiO₂ inclusions, reacts with carbon in the surrounding matrix and removes it from solution (Chai et al., 2014; Furuhashi, Yamaguchi et al., 2003; Gregg & Bhadeshia, 1997).

6.2 Manganese

The literature describes four main effects of manganese in acicular ferritic steels:

- Suppression of polygonal ferrite and pearlite: Solute manganese suppresses the formation of polygonal ferrite and pearlite, which enhances the acicular ferrite formation. (Farrar & Harrison, 1987)
- Formation of manganese-depleted zones around inclusions: Manganese can be merged in NMI, so manganese-depleted zones around inclusions are formed. These manganese-depleted zones are often described as essential for the nucleation of acicular ferrite. (Chai et al., 2014; Farrar & Harrison, 1987)
- Depression of the austenite-ferrite-transition temperature: Solute manganese decreases the austenite-ferrite-transition temperature. Low phase transition temperatures reduce the driving force for ferrite nucleation. Hence, Chai et al. (2014) asserted that manganese contents that are too high may lead to the suppression of acicular ferrite formation. (Chai et al., 2014)
- Augmentation of yield strength: Solute manganese increases the steel's yield strength. Regarding toughness, this increase in yield strength by manganese can counteract the positive effect of acicular ferrite. Therefore, Grong and Matlock (1986) defined a manganese content of 1.5 wt.-% as optimum for mild and low-alloy steel weld metals.

Thus, it can be concluded that solute manganese negatively influences the formation of acicular ferrite, but if it is bonded in NMI, it becomes supporting. Manganese contents below 1.5 - 2.0 wt.-% are mostly seen as beneficial for acicular ferrite formation, while higher contents are described as having a negative effect on the mechanical properties (Chai et al., 2014; Evans, 1980; Farrar & Harrison, 1987; Grong & Matlock, 1986).

Generally, the formation of manganese-depleted zones is seen as the most important effect of manganese in acicular ferritic steels. Notwithstanding, there are still controversial opinions how this chemical fluctuations in the matrix form. Some authors (Chai et al., 2014; Hui et al., 2014; Kimura et al., 2002; Sarma et al., 2009; Song et al., 2015; Yang et al., 2012a) report that MnS, which precipitates and grows during cooling owing to the change in sulfur solubility, creates such manganese-depleted zones. Others (Byun et al., 2003; Cai et al., 2015; Chai et al., 2014; Gregg & Bhadeshia, 1997; Huang et al., 2016; Ogibayashi, 1994; Seo et al., 2015; Shim, Cho et al., 2001; Shim, Oh et al., 2001; Shim, Byun et al., 2001; Wan et al., 2012) argue that manganese is absorbed by titanium containing inclusions; although, the reason for this manganese absorption is hardly discussed in the literature. One suggestion offered by Gregg and Bhadeshia (1997) asserted that the manganese absorption is associated with the transformation of inclusions from Ti_2O_3 to Ti_3O_5 . Another explanation is provided by Shim et al. (2001), who stated that the manganese absorption is caused by the large amount of cation vacancies in titanium oxide and the high solubility of manganese in these cation sites [e.g., > 10 mol.-% at 1473,15 K (1200 °C) in Ti_2O_3]. Seo et al. (2015) described Ti_2O_3 particles as especially favorable for manganese absorption because Ti_2O_3 provides many cation vacancies. Ti^{3+} ions have a similar radius to Mn^{3+} ions, and Ti_2O_3 has nearly the same crystal structure as $MnTiO_3$.

There are two possibilities described in the literature regarding how manganese-depleted zones promote acicular ferrite formation: (Byun et al., 2003; Chai et al., 2014; Chen et al., 2013; Cochrane & Kirkwood, 1978; Liu et al., 2007).

- Reduction of austenite stabilization: Because manganese is an austenite-stabilizing element, the nucleation energy for ferrite is reduced in areas with lower manganese contents.
- Increase in the austenite-ferrite-transition temperature: Composition fluctuations support acicular ferrite nucleation because of a change in the austenite-ferrite-transition temperature. Austenite-stabilizing elements decrease the transition temperature and therefore lead to a reduction in the nucleation driving force. If depleted zones of austenite-stabilizing elements form, the transition temperature is increased, and the driving force for acicular ferrite nucleation is also increased.

6.3 Titanium

Generally, an increase in acicular ferrite with the addition of titanium has been reported in the literature. (Evans, 1986a, 1993, 1995; Fox & Evans, 2012; Grong et al., 1995; Ilman et al., 2015; Saggese et al., 1983; Seo et al., 2015; Vanovsek et al., 2013) The main influence of titanium is to form titanium-containing inclusions, which provide active nucleation sites for acicular ferrite. Bonnet and Charpentier (1983) conducted a comprehensive study of weld metals with 0.04 - 0.09 wt.-% carbon, 0.80 - 2.00 wt.-% manganese, 0.20 - 0.75 wt.-% silicon, 0.05 - 0.15 wt.-% copper, 30 - 140 wt.-ppm titanium and 60 - 120 wt.-ppm vanadium. They found a critical titanium content of 40 - 50 ppm below which it is not possible to form acicular ferrite independent of other conditions (see Figure 3). Similar observations were made by Byun et al. (2003), who determined that without titanium addition, bainite is formed instead of acicular ferrite. With increasing titanium content, the microstructure changed from bainite to acicular ferrite. Additionally, Evans (1991b) and Ilman et al. (2014) reported that without titanium, nearly no acicular ferrite forms in welds with approximately 0.07 wt.-% carbon, 1.50 wt.-% manganese, 0.35 wt.-% silicon and 6 - 255 wt.-ppm titanium. However, a slight increase in the titanium content leads to a boost in acicular ferrite, as shown in Figure 3. The depression of the acicular ferrite at approximately 80 ppm titanium is the result of changes in inclusion morphology.

Nevertheless, deoxidation with titanium is not popular due to its high price. Deoxidation with cheaper elements, such as aluminum, manganese or silicon, and the modification of deoxidation products by titanium are more common in secondary refining. Hui et al. (2014) and Yamada et al. (2008) also proved that inclusions that only show thin layers of TiOx can act as active nuclei. Saggese et al. (1983) demonstrated that only 2 % TiOx in inclusions is necessary to maximize acicular ferrite.

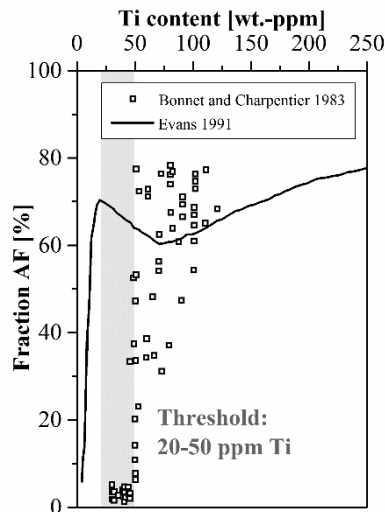


Figure 3. Influence of titanium content on the fraction of acicular ferrite in weld deposits; adapted from Bonnet and Charpentier, (1983) and Evans (1991b)

7. Influence of Non-Metallic Inclusions

7.1 Inclusion Size

The capability of NMI to act as nuclei increases with increasing particle size. This is because the nucleation energy is significantly reduced and larger stress fields, which initiate the austenite-ferrite-transition, are formed. (Abson et al., 1978; Bhadeshia, 2001; Bin & Bo, 2012; Grong & Matlock, 1986; Ricks et al., 1981; Ricks et al., 1982; Sarma et al., 2009). Recent observations (Huang et al., 2016; Lee et al., 2000; Mu et al., 2014, 2015; Mu et al., 2016; Seo et al., 2015; Song et al., 2015) have determined the probability of acicular ferrite nucleation on particles with varying sizes according to:

$$\text{Nucleation probability} = \frac{\text{Number of active inclusions}}{\text{Total number of inclusions}} \quad (1)$$

As illustrated in Figure 4, these authors described a boost in nucleation potential with increasing inclusion size, which is in good accordance with earlier findings of Ricks et al. (1981, 1982). However, it should be noted that in the literature, lower and upper critical sizes for active inclusions are commonly described. The lower critical value is the minimum size beneath which particles are too small to act as active nuclei. The lower critical size was determined to be 0.3 - 0.5 μm in various studies. (Barbaro et al., 1989; Huang et al., 2016; Lee et al., 2000; Mu et al., 2014; Mu et al., 2016) Above the upper critical value, no further significant improvements in the nucleation probability are observable. Ricks et al. (1981, 1982), Lee et al. (2000) and Mu et al. (2014, 2016), who investigated inclusions smaller than 1.5 μm , defined 1 μm as the upper critical value. Above 1 μm , the probability curve flattens out. Huang et al. (2016), who considered inclusions up to 7 μm , observed 1.5 μm as the upper critical value but described a sharp decrease in the nucleation probability above 4 μm , resulting in inert behavior of inclusions larger than 6.5 μm . Similar results were gained by Song et al. (2015) and Wang et al. (2012), who found inclusions with sizes of 1 - 3 μm and 1 - 2 μm , respectively, as the most appropriate nuclei. Inclusions below or above these ranges were less active. Seo et al. (2015) determined the upper critical value to be approximately 0.6 - 0.7 μm and showed that the value decreased with increased titanium contents, which may result from the high nucleation potential of titanium-containing inclusions (Barbaro et al., 1989; Huang et al., 2016; Lee et al., 2000; Liu & Olson, 1986; Mu et al., 2014, 2015; Mu et al., 2016; Ricks et al., 1981; Ricks et al., 1982; Seo et al., 2015; Song et al., 2015; Wang et al., 2012).

The demand for larger inclusions is in contrast to the requirements of high-toughness steels in which inclusions should be as small as possible. On the one hand, it is therefore important to consider the findings of Ref. (Huang et al., 2016; Lee et al., 2000; Mu et al., 2014; Ricks et al., 1981), which showed that an increase in inclusion size above 1.0 - 1.5 μm does not have a further beneficial effect on the nucleation probability of acicular ferrite. Hence, an inclusion size of 1 μm can be suggested as optimum for acicular ferrite because the nucleation energy is minimized, but the material properties are not degraded by large inclusions. On the other hand, the nature of

inclusions is much more important than their size or number, so acicular ferrite microstructures can also be produced by appropriate modifications of the inclusions' composition without increasing their content (Bhadeshia, 2001; Huang et al., 2016; Lee et al., 2000; Mu et al., 2014, 2015; Sarma et al., 2009).

Several authors reported that the inclusion size also affects the structure of nucleating ferrite grains: Song et al. (2015) observed, for example, that decreasing the inclusion size also decreased the size of the acicular ferrite laths. Fattahi et al. (2013) and Zhang and Farrar (1996) described that the inclusion size influences how ferrite nucleates on NMI: Smaller inclusions are engulfed by the ferrite plates ('boxing in'). With increasing inclusion size, more needle-shaped ferrite grains will emanate from the particle. Large inclusions act as nuclei for several acicular ferrite laths, and the typical star-like structure of acicular ferrite is developed (Fattahi et al., 2013; Zhang & Farrar, 1996).

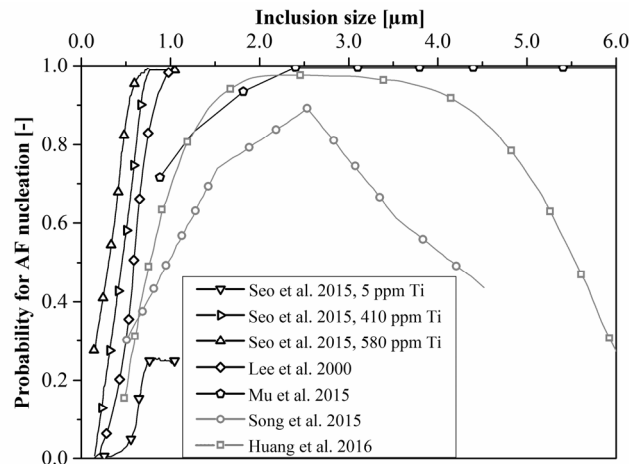


Figure 4. Impact of inclusion size on the probability for acicular ferrite nucleation; adapted from Ref. (Huang et al., 2016; Lee et al., 2000; Mu et al., 2015, 2015; Seo et al., 2015; Song et al., 2015)

7.2 Inclusion Number

NMI are indispensable for acicular ferrite. Several authors (Abson et al., 1978; Bin & Bo, 2012; Garcia-Mateo et al., 2008; Thewlis, 2006) reported that few active inclusions inhibit the nucleation of acicular ferrite. Andersson et al. (2011) calculated that at least ten active inclusions have to be inside an austenite grain of 10 μm in size to provide efficient conditions for acicular ferrite. Nevertheless, higher numbers of inclusions limit the AGS by pinning effects. This worsens the conditions for acicular ferrite nucleation and downgrades the steel's mechanical properties. (Abson et al., 1978; Andersson et al., 2011; Bin & Bo, 2012; Cochrane & Kirkwood, 1978; Garcia-Mateo et al., 2008; Grong & Matlock, 1986; Kikuchi et al., 2011; Lee & Pan, 1995; Liu & Olson, 1986; Sarma et al., 2009; Thewlis, 2006).

Liu and Olson (1986) reported that the number of active inclusions influences the structure of acicular ferrite. If the density of active particles is low, fewer ferrite plates are formed, so they can grow continuously before their growth is stopped by impingement with other plates. With an increasing amount of active particles more acicular ferrite needles are nucleated, so the free space for growth is reduced, and the growing plates are stopped earlier, which results in a finer structure.

7.3 Inclusion Type

Barbaro et al. (1989) asserted that all types of inclusions became active at a critical particle size, but almost all other research has come to the conclusion that the potential of NMI strongly depends on chemical composition. Some inclusion types are seen as active, and some as inactive, strongly dependent on the observed system of the inclusion landscape, steel composition, CR and AGS.

Table 6 - Table 10 give an overview of inclusion types described as active or inactive in the literature. The listed types are divided into three classes: inclusions that are generally described as active, inclusions that are generally described as inactive and inclusions whose effect is seen contradictory in the literature. There are several reports in the literature (e.g., Bin & Bo, 2012; Nako et al., 2015; Thewlis, 2006) about the use of rare earth elements to create active nuclei for acicular ferrite, but rare earth inclusions are not considered in this overview.

Table 6. Literature review on the potential of oxidic inclusions

	ACTIVE	INACTIVE	
OXIDES	(Al,Mg,Zr)O _x	(Li et al., 2015; Min et al., 2016)	
	(Al,Si)O _x	(Sarma et al., 2009)	
	(Mn,Al,Si)O _x	(Devillers et al., 1983; Inoue et al., 1993; Sarma et al., 2009; Zhang & Farrar, 1996)	
	(Ti,Mn)O _x	(Byun et al., 2003; Fox & Evans, 2012; Kikuchi et al., 2011; Lee & Pan, 1995; Nako et al., 2014; Shim, Oh et al., 2001; Shim, Byun et al., 2001)	
	(Ti,Mn,Al)O _x	(Huang et al., 2016; Ilman et al., 2015; Inoue et al., 1993; Lee & Pan, 1995; Yamada et al., 2008)	
	(Ti,Mn,Al,Si)O _x	(Wan et al., 2012; Wang et al., 2012; Zhang & Farrar, 1996)	
	(Ti,Mn,Si)O _x	(Nako et al., 2014; Zhang & Farrar, 1996)	
	(Ti,Si)O _x	(Zhang & Farrar, 1996)	
	TiO _x	(Bhadeshia, 2001; Fox & Evans, 2012; Gregg & Bhadeshia, 1997; Hossein Nedjad & Farzaneh, 2007; Ilman et al., 2012, 2015; Kikuchi et al., 2011; Lee & Pan, 1995; Mu et al., 2016; Shim, Cho et al., 2001; Zhang & Farrar, 1996; Zhang et al., 2010)	(Düren, 1983; Shim, Oh et al., 2001)
	(Ti,Al)O _x	(Ilman et al., 2015; Wang et al., 2012)	(Huang et al., 2016; Wang et al., 2012)
	SiO ₂	(Zhang & Farrar, 1996)	(Liu et al., 2007; Shim, Oh et al., 2001)
	Al ₂ O ₃		(Bhadeshia, 2001; Devillers et al., 1983; Evans, 1990a; Fox & Evans, 2012; Gregg & Bhadeshia, 1997; Huang et al., 2016; Kikuchi et al., 2011; Min et al., 2016; Shim, Cho et al., 2001; Shim, Oh et al., 2001; Wang et al., 2012; Yamada et al., 2008; Zheng, Wang, Li, Shang, & He, 2012)
FeO _x		(Sarma et al., 2009)	
(Mn,Al)O _x		(Gregg & Bhadeshia, 1997; Yamada et al., 2008)	
(Mn,Si)O _x		(Byun et al., 2003; Shim, Oh et al., 2001)	
(Mn,Si,Fe)O _x		(Liu et al., 2007)	

Table 7. Literature review on the potential of sulfidic inclusions.

	ACTIVE	INACTIVE	
SULPHIDES	CuS _y	(Zhang & Farrar, 1996)	
	(Mn,Cu)S _y	(Capdevila et al., 2006; Díaz-Fuentes et al., 2003; Madariaga et al., 2001; Zhang & Farrar, 1996)	
	FeS	(Liu et al., 2007)	
	(Fe,Cu)S _y	(Liu et al., 2007)	
	(Mn,Fe,Cu)S _y	(Liu et al., 2007)	
	MnS	(Bhadeshia, 2001; Kikuchi et al., 2011; Lee & Pan, 1995; Sarma et al., 2009; Yang, Xu et al., 2015; Zhang & Farrar, 1996; Zhang et al., 2012a; Zhang et al., 2010)	(Furuhara, Yamaguchi et al., 2003; Gregg & Bhadeshia, 1997; Huang et al., 2016; Hui et al., 2014; Mu et al., 2014; Sarma et al., 2009; Shim, Oh et al., 2001; Zheng et al., 2012)

Table 8. Literature review on the potential of oxysulfidic inclusions

	ACTIVE	INACTIVE	
OXYSULPHIDES	(Al,Mn,Si)O _x S _y	(Inoue et al., 1993)	
	(Mn,Al,Mg)O _x S _y	(Min et al., 2016)	
	(Mn,Al,Mg,Zr)O _x S _y	(Li et al., 2015; Min et al., 2016)	
	(Mn,Al,Si,Cu)O _x S _y	(Zhang & Farrar, 1996)	
	(Ti,Mn)O _x S _y	(Andersson et al., 2011; Bhadeshia, 2001; Fattahi et al., 2013; Huang et al., 2016; Lee & Pan, 1995; Mu et al., 2014, 2015; Wang et al., 2012; Zheng et al., 2012)	
	(Ti,Mn,Al)O _x S _y	(Cai et al., 2015; Lee & Pan, 1995; Yang et al., 2008)	
	(Ti,Mn,Al,Ca)O _x S _y	(Lee & Pan, 1995)	
	(Ti,Mn,Al,Mg)O _x S _y	(Song et al., 2015)	
	(Ti,Mn,Al,Si)O _x S _y	(Barbaro et al., 1989)	
	(Ti,Mn,Al,Si,Zr)O _x S _y	(Wan et al., 2015)	
	(Ti,Mn,Ca)O _x S _y	(Lee & Pan, 1995)	
	(Ti,Mn,Si)O _x S _y	(Hui et al., 2014)	
	(Ti,Mn,Si,Cu)O _x S _y	(Evans, 1991b; Ilman et al., 2012, 2014)	
	(Mn,Al)O _x S _y	(Yang et al., 2008)	(Li et al., 2015; Min et al., 2016; Wang et al., 2012; Yamada et al., 2008)
	(Ti,Mn,Cu)O _x S _y	(Diaz-Fuentes et al., 2003)	(Diaz-Fuentes et al., 2003)
	(Al,Ca)O _x S _y		(Eijk et al., 1999)
	(Mn,Al,Si)O _x S _y		(Devillers et al., 1983)
	(Mn,Si)O _x S _y		(Byun et al., 2003; Seo et al., 2015)
	(Mn,Si,Cu)O _x S _y		(Evans, 1991b; Ilman et al., 2014)
(Si,Cu)O _x S _y		(Liu et al., 2007)	

Table 9. Literature review on the potential of nitridic and oxynitridic inclusions

	ACTIVE	INACTIVE	
(OXY)NITRIDES	TiO _x N	(Jin et al., 2003)	
	(Ti,Al)O _x N	(Ilman et al., 2015)	
	(Ti,B)O _x N	(Ilman et al., 2012; Zhang et al., 2012a)	
	VN	(Capdevila et al., 2009; Garcia-Mateo et al., 2008; Mu et al., 2016)	
	TiN	(Bhadeshia, 2001; Grong et al., 1995; Ilman et al., 2014, 2015; Jin et al., 2003; Kikuchi et al., 2011; Mu et al., 2016; Zhang et al., 2010)	(Düren, 1983; Shim, Oh et al., 2001; Zheng et al., 2012)

Table 10. Literature review on the potential of other inclusion types in addition to those mentioned before

	ACTIVE	INACTIVE	
OTHERS	(Mn,Al,V)O _x S _y N	(Ogibayashi, 1994)	
	(Ti,Mn,Al)O _x S _y N	(Eijk et al., 1999; Wan et al., 2014)	
	(Ti,Mn,Cu,B)O _x S _y N	(Ilman et al., 2012)	
	(Ti,Mn,Al,Si)O _x S _y N	(Barbaro et al., 1989; Mu et al., 2016)	
	(Mn,V)S _y CN	(Capdevila et al., 2009; Furuhashi, Shinyoshi et al., 2003)	
	(Ti,Mn)O _x S _y N	(Mu et al., 2014; Ogibayashi, 1994)	
	(Ti,Mn)S _y N	(Jin et al., 2003)	
	V(C,N)	(Capdevila et al., 2009; Garcia-Mateo et al., 2008)	(Capdevila et al., 2009)
	VC		(Capdevila et al., 2009)

8. Conclusions

The formation of acicular ferrite is mainly influenced by austenite grain size, cooling rate, steel composition and non-metallic inclusions. In recent decades, extensive work was conducted to evaluate the impact of these parameters, and important knowledge was gained. The present work aimed at displaying the current state of knowledge regarding acicular ferrite formation and its influencing factors. The key aspects can be summarized as follows:

- Austenite grain size: A steel's capability for acicular ferrite increases with increasing austenite grain size. However, the positive effect of large austenite grains is diminished at austenite grain sizes above 150 μm .
- Cooling rate: The optimum cooling rate to produce a maximum fraction of acicular ferrite essentially depends on the steel's composition and its production route. Deformation and thermomechanical treatment significantly change the optimum cooling rates compared to the cooling without deformation.
- Steel composition:
 - The addition of titanium and manganese is essential to the production of acicular ferrite. Titanium forms titanium oxides, which were found to be highly active nucleation sites for acicular ferrite. Manganese merges in inclusions and forms manganese-depleted zones, which stimulate the nucleation of acicular ferrite.
 - The adjustment of appropriate carbon, oxygen and sulfur contents is important to provide sufficient conditions for acicular ferrite.
 - Low to moderate concentrations of manganese, boron, chromium, nickel and molybdenum are described in the literature to promote the formation of acicular ferrite, while higher amounts of these elements negatively influence the formation of acicular ferrite.
 - Magnesium, niobium, vanadium and calcium are asserted to enhance the formation of acicular ferrite.
 - Additions of aluminum and silicon are generally seen as negative for acicular ferrite.
- Non-metallic inclusions:
 - The nucleation potential of acicular ferrite significantly increases with inclusion size. Nevertheless, an inclusion size of 1 μm is defined as optimum because of mechanical properties.
 - The number of inclusions should be high enough to provide a sufficient number of nucleation sites, but with respect to the requirements of high-quality steels, it should be as low as possible.
 - Various inclusion types have already been investigated in the literature, but inconsistent information about some inclusion types still prevails. This may result from the interaction between inclusion type and steel composition. Generally, titanium- and manganese-containing inclusions are described in particular as favorable for acicular ferrite nucleation.

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