

High Strength Austenite for Additive Manufacturing

Dr. Andreas Mohr
Deutsche Edelstahlwerke Specialty Steel
GmbH & Co. KG
Oberschlesienstr. 16
Krefeld, NRW, 47807
Germany

Dr. Horst Hill
Deutsche Edelstahlwerke Specialty Steel
GmbH & Co. KG
Oberschlesienstr. 16
Krefeld, NRW, 47807
Germany

Dipl.-Ing. Karlheinz P.J. Hoeren
Deutsche Edelstahlwerke Specialty Steel
GmbH & Co. KG
Oberschlesienstr. 16
Krefeld, NRW, 47807
Germany

M.sc. Janosch Conrads
Deutsche Edelstahlwerke Specialty Steel
GmbH & Co. KG
Oberschlesienstr. 16
Krefeld, NRW, 47807
Germany

ABSTRACT

Stainless austenitic steels are widely applied in the field of classic mechanical engineering. An important representative of these grades is the material 316L (S31603), which is well established as a standard steel in Additive Manufacturing (AM). Typical austenitic stainless steels contain some main alloying elements, which are described in the following: The formation of an austenitic microstructure is achieved by nickel (Ni). The addition of chromium (Cr) lead to the corrosion resistance of these materials. For resistance to localized corrosion, molybdenum (Mo) can be added. However, this requires full dissolution of Cr and Mo in the steel matrix. As a consequence, stainless austenites usually exhibit very low carbon and nitrogen contents to prevent chromium carbides and nitrides. But, both alloying elements cannot be classified as being detrimental in stainless austenites in general. In contrast, C and N can also be used to improve mechanical and corrosion resistance.

Based on this knowledge, a high-strength austenite was developed particularly tailored for AM. The mechanical properties of the new development, determined by tensile tests, show twice as high characteristic values (yield strength, Rp0.2, and ultimate tensile strength, Rm) compared to 316L, with simultaneously increased corrosion resistance against chloride ions.

Keywords: Stainless steels, Austenite, Corrosion Resistance, Additive Manufacturing, Mechanical Properties, Chemical Properties, High Strength,

INTRODUCTION

Typical austenitic stainless steels like 316L (S31603) contain chromium, nickel, and, optionally, molybdenum as major alloying elements. These are required to provide their beneficial properties, which include e.g. very high corrosion resistance and high ductility and toughness, yet showing comparably low strength and hardness. General corrosion resistance is primarily achieved by the element chromium, which causes formation of a thin but dense chromium oxide layer on the surface, when the amount of chromium dissolved in the metallic matrix is larger than approximately 10.5 wt%. This corrosion-preventing oxide layer can be further stabilized by the addition of molybdenum, which results in improved resistance to localized corrosion, that is induced e.g. by chloride ions. Since both Cr and Mo are prone to form carbides or nitrides, austenitic stainless steels are usually characterized by very low carbon ($C \leq 0.03$ wt%) and nitrogen contents ($N \leq 0.11$ wt%), because precipitation of Cr- or Mo-rich carbides or nitrides reduces the corrosion resistance due to depletion of the matrix. However, since both alloying elements tend to stabilize a ferritic body-centered cubic (bcc) microstructure, the addition of sufficient amounts of nickels is required in order to ensure stable faced-centered cubic (fcc) austenite.¹ Despite this, interstitial elements carbon and especially nitrogen cannot generally be classified as being detrimental to austenitic stainless steels. In contrast, they can also be used to enhance mechanical and chemical properties. On the one hand, dissolved, interstitial elements, in particular nitrogen and especially in combination with molybdenum increase the resistance against localized corrosion induced by chloride ions. On the other hand, they cause a distinct increase in strength of austenitic steels compared to substituted elements by provoking solid solution strengthening.²

Based on these benefits of N and C+N in austenitic steels, the so-called high nitrogen steels (HNS) and high interstitial steels (HIS) were developed. They feature (C+N) contents of approximately 0.6 - 1.2 wt% and contain Cr and Mn of 16 – 20 wt% each. Furthermore, Mo can be added up to approximately 3 wt%. The C+N alloyed austenitic steels due to their special alloying system, including the interstitially dissolved elements, exhibit the following advantages compared to conventional stainless austenitic steels like 316L:

- Increased strength (solid solution strengthening) combined with still very high toughness and ductility.
- Higher tendency to work-harden.
- Improved corrosion resistance, in particular against localized corrosion.

The latter can be estimated by use of the following empirical equations, Pitting Resistance Equivalent Number (PREN) and MARC Measure of Alloying for Resistance to Corrosion (MARC).^{3,4}

$$\text{PREN} = \text{wt\% Cr} + 3.3 * \text{wt\% Mo} + 16 * \text{wt\% N} \quad (1)$$

$$\text{MARC} = \text{wt\% Cr} + 3.3 * \text{wt\% Mo} + 20 * \text{wt\% C} + 20 * \text{wt\% N} - 0.5 * \text{wt\% Mn} - 0.25 * \text{wt\% Ni} \quad (2)$$

However, the conventional production of C+N austenitic steels is challenging due to different points. First, nitrogen features a limited solubility in liquid iron. It is increased by the addition of chromium, while nickel is detrimental. Ni can be replaced by manganese (Mn), which acts as fcc-stabilizing element as well yet increasing N solubility. However, high amounts of nitrogen require expensive metallurgical techniques such as pressurized remelting (PESR). More recently it has been shown, that the joint addition of carbon and nitrogen to FeCrMn-alloyed austenitic stainless steels (HIS) enables cost-effective melting at ambient pressure while at the same time even improving mechanical properties (e.g. strength and work-hardening ability) compared to austenitic HNS with similar content of interstitials.² Furthermore, the combination of Cr with C+N, precipitation of chromium-rich carbides and nitrides, which act detrimental to corrosion resistance, is more likely to occur during cooling after casting or heat treatment. Thus, the conventional heat treatment of austenitic stainless steels (solution annealing aiming at dissolution of any undesired second phase followed by rapid quenching in water in order to avoid re-precipitation) becomes even more important.²

Finally, the intense work-hardening ability of austenitic stainless steels featuring large amounts of interstitial elements yet showing very high toughness and ductility result in a challenging machinability of such alloys.

Most of these difficulties can be avoided by using powder atomization and applying Additive Manufacturing (AM) as an alternative production route. In the field of AM, Laser Powder Bed Fusion (LPBF) is one of the most widely used processes. In Laser Beam Melting or Laser Powder Bed Fusion, a metal powder is melted by means of a laser beam in the areas that will form the future part. This allows components to be built up successively by repeating the steps of melting and adding a new layer of powder. This process enables very fast heating and cooling speeds, which prevents the precipitation of carbides and nitrides. In this way, near-net-shape components can be produced from C+N steels, which require no further processing steps like forging, extensive machining or a difficult heat treatment and offering a very good corrosion resistance with superior mechanical properties.

EXPERIMENTAL PROCEDURE

Based on this knowledge, Deutsche Edelstahlwerke (DEW) has developed a **High Strength Austenite (HSA)** for Additive Manufacturing showing high PREN- and MARC-numbers. The chemical composition of the new alloy HSA compared to the reference steel 316L is shown in **Table 1**.

Table 1: Chemical composition of 316L and HSA in mass%.

	C+N	Mn	Cr	Mo	Ni	Fe	PREN	MARC
316L	<0.15	1.0	17.0	2.0	13.0	bal.	26	20
HSA	1.0	21.0	18.0	2.0	< 0.1	bal.	36	34

For laboratory tests, both 316L and HSA were atomized at DEW. Subsequently, both materials were processed in a grain size of 10 – 53 µm (0.0003937008 in - 0.0021259843 in) on an EOS¹ M290 LPBF-system.

Typical processing parameters for 316L were used for LPBF of both materials. For the tensile tests, specimens were prepared and tested according to DIN 50125 form B.⁵ The specimens for the notch impact test were prepared and tested according DIN 148.⁶ The tensile and notched bar impact specimens were printed vertical with an allowance of 1 mm and then mechanically machined to the required final geometry. The corrosion resistance of both materials was analyzed by current density potential curves according to ASTM G 150.⁷ The surface corrosion resistance was tested in H₂SO₄, while the resistance against pitting corrosion was analyzed using 3.56% sodium chloride solution. The specimens for corrosion test were also printed in vertical direction.

All investigations were performed in the “as printed” condition without any additional heat treatment.

¹ Tradename