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Mechanical Properties of Additively Manufactured Duplex Stainless Steels: A Review

Hassan Saadawi¹, Kâzım Tur², Erkan Konca²

Modeling and Design of Engineering Systems PhD Program, School of Natural and Applied Sciences, Atilim University, Ankara, Turkey¹

Department of Metallurgical and Materials Engineering, Atilim University, Ankara, Turkey²

ABSTRACT: Additive manufacturing (AM) has risen in popularity as a viable option for producing components in a short period of time, paving the way for it in a growing number of industries. Today, additive manufacturing is used to manufacture a variety of engineering materials, including titanium, aluminum, nickel alloys, and steels. More recently, there has been increasing interest in applying additive manufacturing to duplex stainless steels (DSSs) due to the greater demand for DSSs in the offshore equipment, since duplex stainless steels have excellent mechanical properties and corrosion resistance such that they are suitable for use in harsh corrosive environments containing chlorides such as seawater. Mechanical properties of duplex stainless steels are influenced considerably by additive manufacturing techniques, heat input, post heat treatment and the resulting microstructure. Understanding the interaction effects of these factors on duplex stainless steels is essential to achieve high quality products with better mechanical properties. The aim of this paper is to provide a systematic review on additive manufacturing of duplex stainless steels regarding the mechanical properties, including hardness, tensile strength, and toughness. Some suggestions for the future studies of AM duplex stainless steels are also put forward.

KEYWORDS: Additive manufacturing, Duplex stainless steel, Wire arc additive manufacturing, Selective laser melting.

List of abbreviations.

Abbreviations	Phrases
AM	Additive Manufacturing
BCC	Body Centered Cubic
CAD	Computer Aided Design
CMT	Cold Metal Transfer
CTOD	Crack Tip Opening Displacement
DSS	Duplex Stainless Steel
FCAW	Flux Cored Arc Welding
FCC	Face Centered Cubic
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
SDSS	Super Duplex Stainless Steel
SLM	Selective Laser Melting
TIG	Tungsten Inert Gas
TOPTIG	Robotic Tungsten Inert Gas Welding
UTS	Ultimate Tensile Strength
WAAM	Wire Arc Additive Manufacturing
WM	Weld Metal
YS	Yield Strength



I. INTRODUCTION

Economical, sociopolitical, environmental and technological trends are posing significant challenges to manufacturing processes around the world through its impact on the enterprise behavior in the market [1]. In order to maintain competitive advantages, the companies should follow the developments in the manufacturing technology [2]. Additive Manufacturing refers to several techniques by which CAD model information is used to build a 3-dimensional part by consecutive layering of material [3]. The American Society for Testing and Materials (ASTM International) defines additive manufacturing as—“Process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [4].

Additive manufacturing has been around for almost two decades [5]. Several additive manufacturing techniques have been introduced to fabricate metals, ceramics, polymers, and composites since Chuck Hull proposed the notion of three-dimensional printing in 1986. Among various approaches, AM techniques used to fabricate 3D metal structures can be classified based on the state of the raw material as liquid, powder and wire based techniques [6,7,8]. Compared to the conventional manufacturing processes, including subtractive manufacturing processes and forming process, the main advantage of AM is its ability to manufacture complicated designs with a great accuracy in dimensions without the use of specific tooling or dies [7,8,9,10].

Today, AM is used to manufacture products out of a variety of engineering materials, including titanium, aluminum, nickel alloys, and steels. More recently, there has been increasing interest in applying AM to super duplex stainless steels (SDSS) due to greater demand for SDSS in the offshore equipment. Since SDSS have excellent mechanical properties and corrosion resistance, they are suitable for use in harsh corrosive environments containing chlorides such as seawater [10,11,12]. Duplex stainless steel is a general term for stainless steels having an austenitic-ferritic microstructure with ferrite to austenite phase ratio of approximately 1:1. This ferrite/austenite duplex microstructure improves both mechanical properties and corrosion resistance [13], and it is closely related to alloying element content, namely chromium (Cr), molybdenum (Mo), nitrogen (N) and nickel (Ni). Chromium and molybdenum are ferrite stabilizers, which promote the body-centered cubic (BCC) crystal structure of iron and they are used to improve DSS's strength, corrosion resistance, hardenability, and wear resistance. Nickel and nitrogen are austenite stabilizers because they encourage the change of crystal structure from BCC to FCC, which promotes the formation of austenite. These two alloying elements also improve DSS's pitting corrosion resistance, impact toughness, and tensile properties. The ferrite formers, chromium and molybdenum, should be balanced by the austenite formers, nickel and nitrogen, in order to obtain the duplex structure [14,15]. During the additive manufacturing of DSS, the product experience different rates of heating and cooling which leads to expansion and contraction of the part. As a result, high thermal stresses are generated. Reheating of the added layers of DSS can also change the ferrite/austenite ratio and nucleate brittle intermetallic phases within the matrix. Presence of stresses and brittle intermetallic phases with change of microstructure negatively affects the mechanical properties of additively manufactured DSS parts [16, 17].

A review of published values for mechanical properties of DSS parts processed by various AM techniques is therefore essential for researchers in this area, to summarize the state-of-the-art research findings and to point out future research priorities. The aim of this paper is to provide a systematic review on additive manufacturing of duplex stainless steels regarding the mechanical properties, including hardness, tensile strength, and toughness. Some suggestions for the future study of AM duplex stainless steels are also put forward.

II. TENSILE PROPERTIES

The mechanical properties of additively manufactured duplex stainless steels can be significantly influenced by AM techniques, process parameters, post heat treatments, and the microstructure [18]. Zhang et al. [19] investigated the tensile properties of SDSS (ER2594) manufactured by TIG-WAAM in the vertical and horizontal direction, and they observed anisotropy in two orientations, with the difference of 38–86 MPa in UTS and 0–5.3% in elongation. The average values of YS, UTS and elongation obtained in their study were 530 MPa, 852 MPa and 35%, respectively. Similar results were obtained by Kannan et al. when they studied the tensile properties of DSS (ER2209) processed by GMAW-WAAM in different orientations; the differences were 58–74 MPa in the UTS and 2–4.35% in the EL values [20]. They attributed this behavior to the varying austenite/ferrite ratio along the build direction. Figure 1 reports the tensile properties obtained in their study. In the study of Hejripour et al. [21], GMAW was used as WAAM technique to fabricate DSS (ER2209) parts and they reported that the mean values of YS and UTS in layer direction were higher than those of the build one with elongations of 11.5% and 5.3%, respectively. They related this difference to the nonhomogeneous microstructure due to reheating. As stated by



Posch et al.[22] the tensile properties of DSS (ER2209) blades, which was built up by CMT-WAAM, were obtained as 455 MPa (YS), 717 MPa (UTS) and 28% elongation. Jang et al. [23] studied the effect of postweld heat treatment at different temperatures (930, 1080, 1230°C) on the tensile strength of super duplex stainless steel Grade 2507 multipass welds using FCAW. Figure 2 shows that the tensile strength was greatly reduced when the heat treatment was performed at 930°C due to the presence of sigma phase.

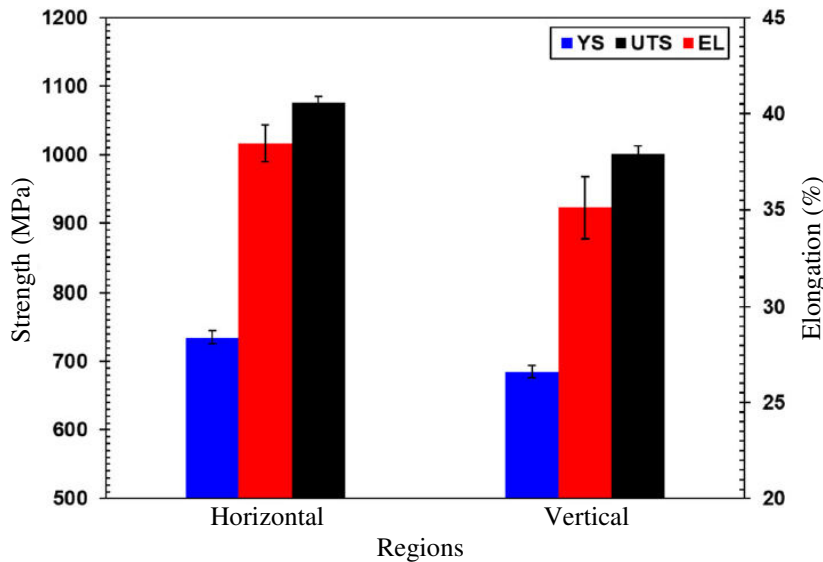


Figure 1. Tensile properties of WAAM processed SDSS at different orientations. Adapted from Ref. [20]

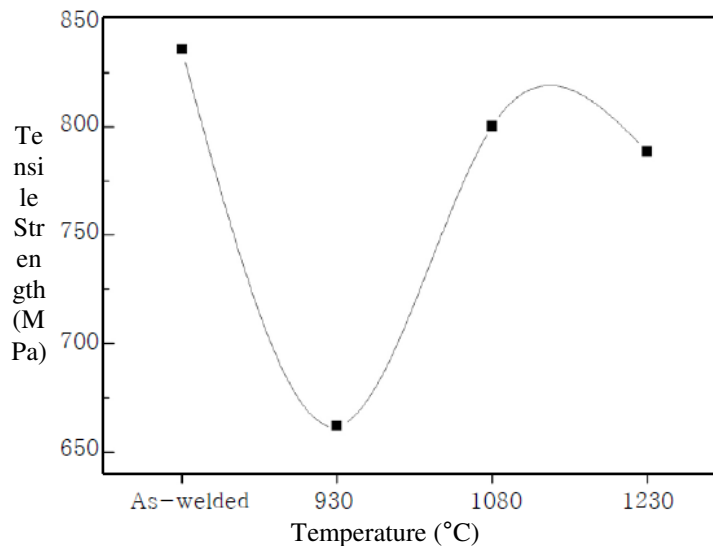


Figure 2. Tensile strength of weld metal. Adapted from Ref. [23]

Hengsbach et al. [24] investigated the tensile properties of Grade 2205 DSS parts built by SLM and treated in different annealed conditions (900, 1000, 1200°C). They reported that the ultimate strength of the annealed specimens varied between 720 MPa to 770 MPa which was considered good compared to the high ultimate strength of 940 MPa in the as-built condition. Similarly, Papula et al. [25] studied the effect of different annealing conditions (950, 1000, 1050, 1100°C) on the tensile properties of Grade 2205 DSS. Annealing decreased the high yield and tensile strengths of the as-built material, but significantly increased the ductility. In their study, Saeidi et al. [26] measured a low elongation value of 1.8% and a high tensile strength of 920 MPa for the Grade 2507 SDSS additively manufactured by SLM and post heat treated at 1200°C, and the authors correlated these results to the presence of brittle phases. Lervag et al. [27] used CMT-WAAM to build-up SDSS (ER2509) wall with different heat input and investigated the



tensile properties in the vertical and horizontal directions. They observed reductions in the yield and tensile strength values with increasing heat input, as seen in Figure 3.

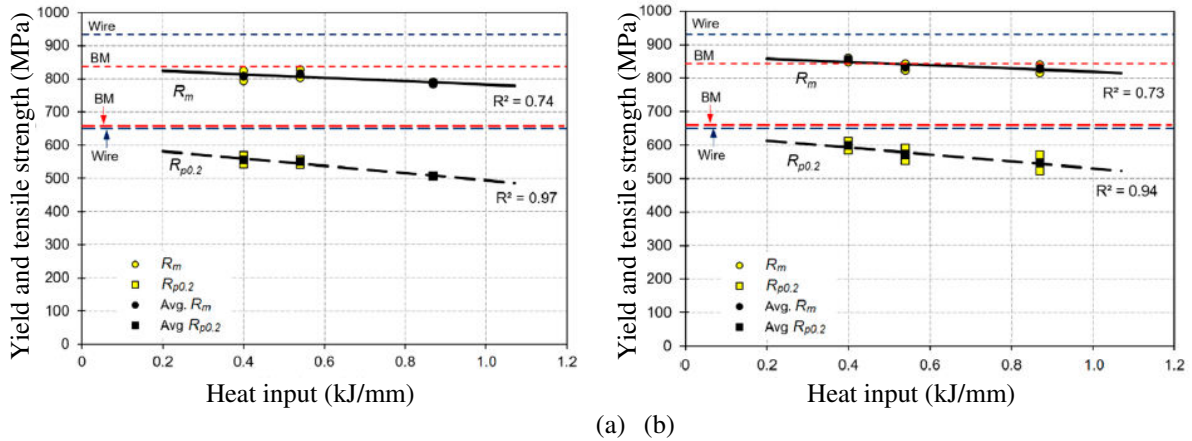


Figure 3. Effect of heat input on yield and tensile strength for (a) vertical samples and (b) horizontal samples. Adapted from Ref. [27]

Lacerda et al.[28] studied the effect of volume fraction of ferrite and austenite phases on the mechanical behavior of duplex stainless steel Grade 2205. Samples were annealed at 1060, 1200, and 1300°C. They found the variation of the ferrite/austenite proportion with different annealing temperatures as shown in Figure 4. They also reported the influence of annealing temperature on strength values. Figure 5 shows that the YS and UTS decrease with the increasing annealing temperatures. By comparing Figures 4 and 5, it can be concluded that the increase of ferrite volume fraction resulted in reduced strength values of duplex stainless steel.

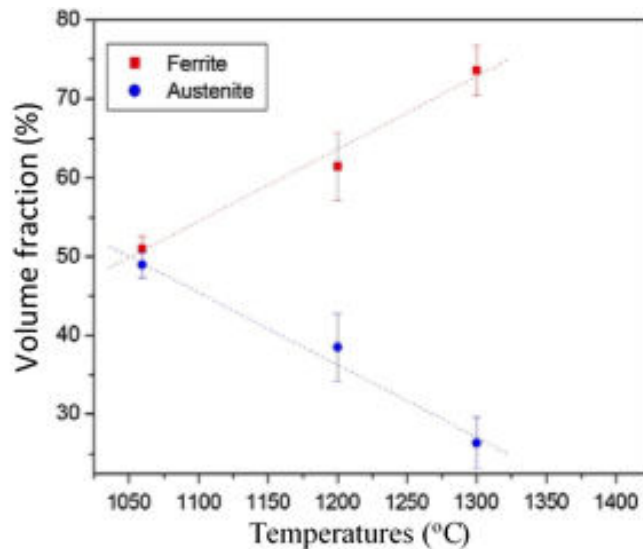


Figure 4. Variation of volume fraction of phases for different annealing temperatures. Adapted from Ref. [28]

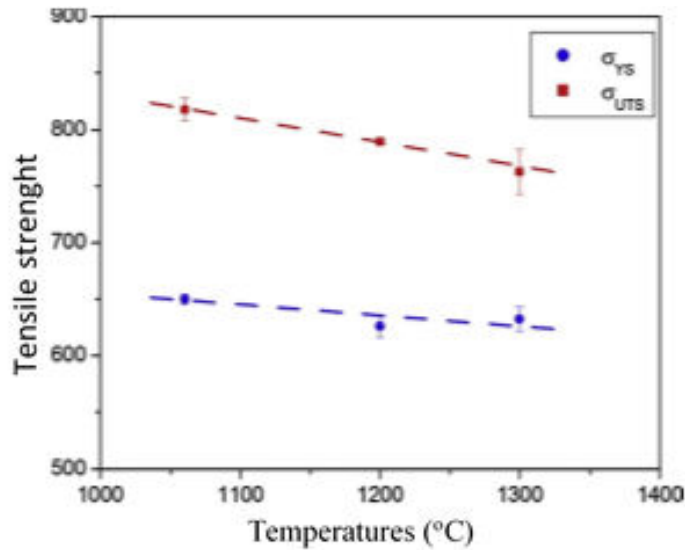


Figure. 5. Effect of annealing temperatures on the strength of DSS. Adapted from Ref. [28]

In summary, due to the reheating of additively manufactured DSS beads, the ferrite/austenite ratio changes. The effect of reheating and cooling varies with the change of AM technique and the amount of heat input. The change of ferrite/austenite ratio leads to anisotropic behavior of tensile properties which affects the performance of additively manufactured component. Table 1 lists the tensile strengths of DSSs produced by different AM processes.

III. HARDNESS PROPERTIES

Jang et al. [23] studied the effect of post heat treatment at different temperatures (930, 1080, 1230°C) on the hardness of FCAW multipass samples and found that the hardness values of super duplex stainless steel Grade 2507 weldment post treated at 930°C were higher than the values at other temperatures due to the formation of the sigma phase (see Figure 6).

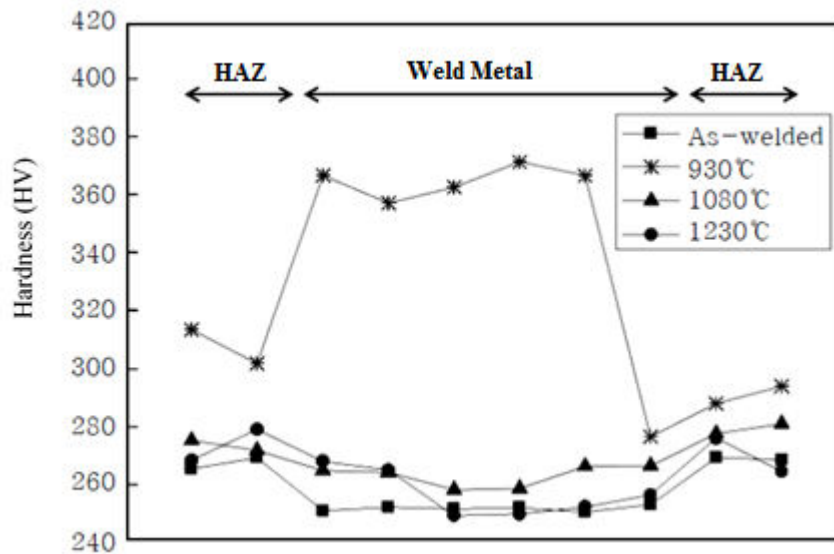


Figure 6. Hardness data of weld metal. Adapted from Ref. [23]



Table 1. Tensile strength of DSS with different AM processes.

Materials	AM Process	Orientation	Post Heat Treatment	Heat input kJ/mm	YS MPa	UTS MPa	% EL	Reference
SDSS ER2509	TIG-WAAM	Vertical	As deposited		515	820	36	[19]
		Horizontal			545	885	33	
DSS ER2209	GMAW-WAAM	Vertical	As deposited		685	1001	35	[20]
		Horizontal			736	1075	38	
DSS ER2209	GMAW-WAAM	Vertical	As deposited		480	682	--	[21]
		Horizontal			509	771	35	
DSS ER2209	CMT-WAAM		As deposited		455	717	28	[22]
SDSS Grade 2507	FCAW		As deposited		835	--	--	[23]
			930°C		662	--	--	
			1080°C		800	--	--	
			1230°C		788	--	--	
DSS Grade 2205	SLM		As deposited		940	--	--	[24]
			900°C		770	--	--	
			1000°C		770	--	--	
			1200°C		720	--	--	

Table 1. Continued.

Materials	AM Process	Orientation	Post Heat Treatment	Heat input kJ/mm	YS MPa	UTS MPa	% EL	Reference
DSS Grade 2205	SLM		As deposited		590	1071	7	[25]
			950°C		561	869	23	
			1000°C		549	848	24	
			1050°C		536	837	24	
			1100°C		524	813	24	
SDSS Grade 2507	SLM		1200°C					[26]
SDSS ER2509	CMT-WAAM	Vertical		0.40	554	812	--	[27]
				0.54	540	815	--	
				0.87	504	788	--	
		Horizontal		0.40	593	862	--	
				0.54	571	833	--	
				0.87	542	827	--	



Zhang et al. [19] concluded that the hardness values of SDSS (ER2594) processed by TOPTIG-WAAM decreased from the last layer to the wall-body as seen in Figure 7, and linked this change to the varying ferrite/austenite ratios at different positions.

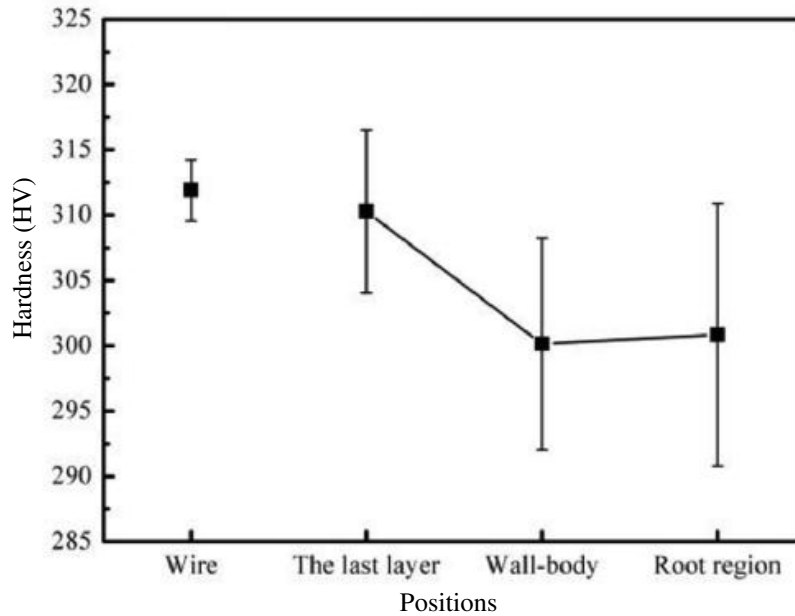


Figure 7. Hardness distribution. Adapted from Ref. [19]

Hejripour et al. [21] also showed that the hardness of 340 HV at the first layer is higher than the hardness of 316 HV at the top layer, whereas, at the middle layers, the average hardness was 293 HV. Lervag et al. [27] have observed that the hardness changes with different heat inputs. They reported that the maximum hardness in the HAZ and weld metal (WM) were reduced by increasing the heat input as shown in Figure 8.

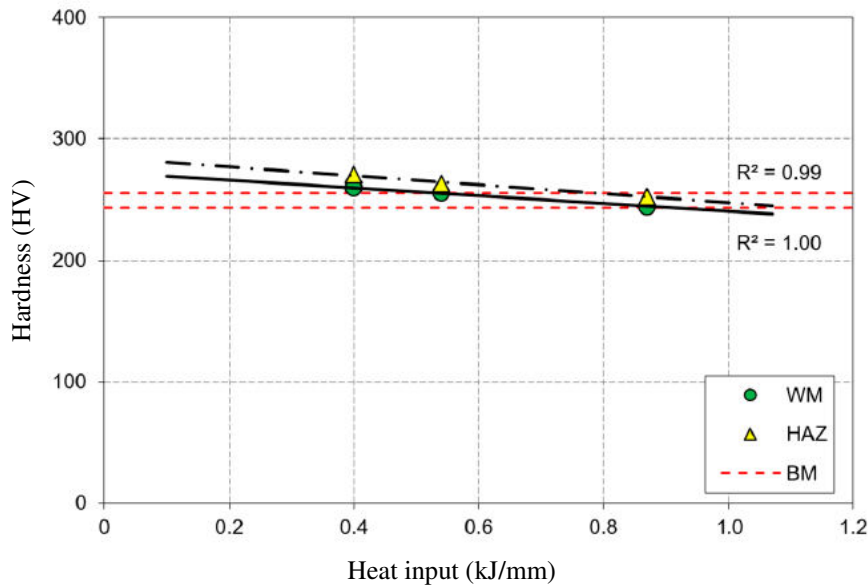


Figure 8. Effect of heat input on hardness in deposited layers (WM) and heat affected zone (HAZ). Adapted from Ref. [27]

Papula et al. [25] investigated the hardness of Grade 2205 DSS additively manufactured by SLM and annealed at different temperatures (950, 1000, 1050, 1100°C). The highest hardness was obtained in the as-built condition as 337 HV. Microhardness was reduced after various heat treatments. Gederberg et al. [29] found that the hardness of the

deposited ER2509 SDSS increased with increasing number of reheating cycles. The multiple reheating resulted in higher hardness values. Similarly, Kannan et al. [20] reported that the hardness of the SDSS (ER2594) wall was higher at the top (310 HV) as compared to the other places (281 HV at the bottom and, 295 HV in the middle).

Saeidi et al. [26] suggested that the high hardness of 400 HV of Grade 2507 SDSS additively manufactured by SLM and post heat treated at 1200°C was possibly due to the presence of brittle phases. Tavares et al. [30] studied the hardness of super duplex stainless steel Grade 2507 multipass welds using GMAW. They observed an increase of hardness in the root pass and attributed this to the precipitation of Cr₂N and/or ε-phase. Table 2 lists the hardness values of the additively manufactured DSSs with different techniques.

IV. FRACTURE TOUGHNESS

Jang et al. [23] investigated the effect of different postweld heat treatment temperatures (930, 1080, 1230°C) on the impact toughness and found that at 930°C the sigma phase existed resulting in brittle fracture and lower impact value. Zhang et al. [19] studied the impact toughness of SDSS (ER2594) processed by TOPTIG-WAAM and concluded that the values of impact toughness in the head (109.21 J/cm²) and the root (104.21 J/cm²) were lower than the value in the wall-body (121.74 J/cm²) due to the non-uniform balance of austenite and ferrite. Lervag et al. [27] have studied the impact toughness and fracture toughness (CTOD) values using different heat inputs. As shown in Figure 9, with increasing of heat input, a slight reduction in impact toughness occurs. They related it to the coarsening of the microstructure with increasing heat input. On the other hand, an enhancement in the CTOD fracture toughness was found with increasing heat input, as shown in Figure 10.

Tavares et al. [30] studied the toughness of super duplex stainless steel Grade 2507 multipass welds using GMAW. They observed that the root pass has a substantially higher toughness than both the filler passes and the base metal when tested at room temperature (25°C). Table 3 lists the impact toughness values of the additively manufactured DSSs with different techniques.

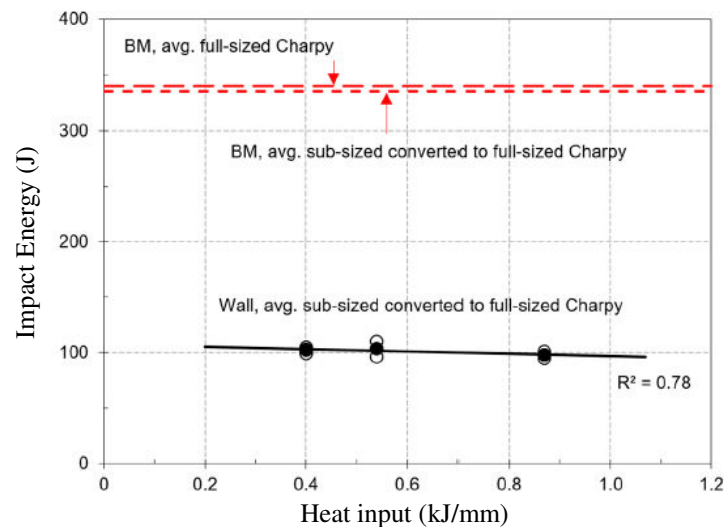


Figure 9. Charpy V-notch impact energy of walls and base metal. Adapted from Ref. [27]



Table 2.The hardness of DSS additively manufactured with different techniques.

Materials	AM Process	Position	Post Heat Treatment	Heat input kJ/mm	Hardness (HV)	Reference
SDSS Grade 2507	FCAW	HAZ	As deposited		264	[23]
			930°C		313	
			1080°C		273	
			1230°C		267	
		WM	As deposited		251	
			930°C		363	
			1080°C		257	
			1230°C		247	
SDSS ER2504	TIG-WAAM	First layer			129	[19]
		Middle layer	As deposited		122	
		Top layer			206	
DSS ER2209	GMAW-WAAM	HAZ			325	[21]
		First layer	As deposited		340	
		Top layer			316	
SDSS ER2509	GMAW-WAAM	Deposited layers			298	[29]
SDSS Grade 2507	SLM	Deposited layers			448	[30]
SDSS Grade 2507	SLM	Deposited layers	1200°C		400	[26]

Table 2. Continued

Materials	AM Process	Position	Post heat treatment	Heat input kJ/mm	Hardness (HV)	Reference
SDSS ER2509	CMT-WAAM	HAZ	As deposited	0.40	269	[27]
				0.54	260	
				0.87	250	
		WM		0.40	260	
				0.54	254	
				0.87	244	
DSS Grade 2205	SLM	Deposited layers	As deposited		337	[25]
			950°C		280	
			1000°C		280	
			1050°C		271	
			1100°C		255	
DSS ER2209	GMAW-WAAM	First layer			281	[20]
		Middle layer	As deposited		295	
		Top layer			310	
SDSS Grade 2507	GMAW	WM			326	[30]
		Root pass			337	

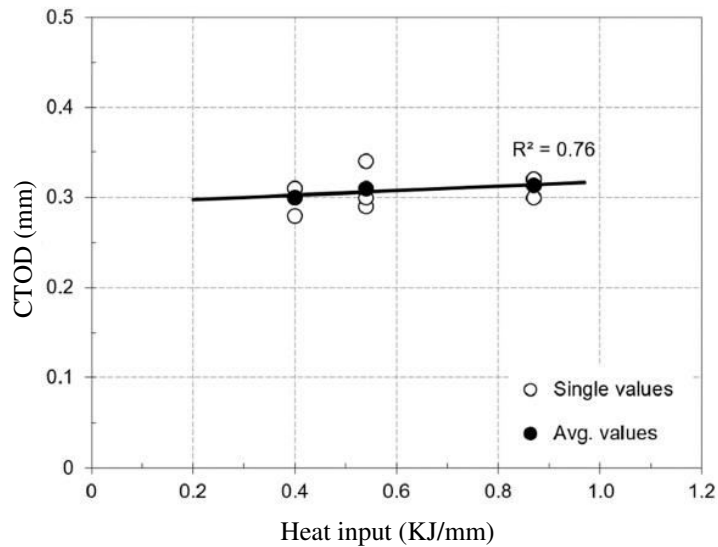


Figure 10. CTOD fracture toughness of walls. Adapted from Ref. [27]

Table 3. The impact toughness values of additively manufactured DSSs with different techniques.

Materials	AM Process	Position	Post Heat Treatment	Heat Input kJ	Impact Energy J/cm ²	Reference
SDSS Grade 2507	FCAW		As deposited		8.62	[23]
			930°C		72.5	
			1080°C		95	
SDSS ER2594	TIG-WAAM	First layer			104.21	[19]
		Middle layer			121.47	
		Top layer			109.21	
SDSS ER2509	CMT-WAAM			0.40	100	[27]
				0.54	100	
				0.87	94.9	
SDSS Grade 2507	GMAW	WM			10	[31]
		Root pass			57	
DSS ER2209	CMT-WAAM				129	[22]

V. SUMMARY AND OUTLOOK

- The advantageous properties of DSSs are due to their dual phase microstructure with an optimized ratio of ferrite to austenite phases. The ferrite/austenite ratio changes due to the reheating of DSS beads during additively manufacturing.



- The degree of change in the ferrite/austenite ratio is dependent on the extent of reheating and cooling which vary with the choice of AM process, and the amount of heat input.
- The change of ferrite/austenite ratio leads to anisotropic behavior of tensile properties which affects the performance of additively manufactured component.
- Post heat treatment can significantly influence the hardness of additively manufactured DSS beads. Hardness is reduced after various heat treatments as compared to the as-deposited condition.
- There is a lack of information about the effects of anisotropy on the fracture behavior, fatigue properties, and corrosion behavior of additively manufactured SDSSs. Further studies and investigations should be made to gain more knowledge about this subject.
- Additionally, further efforts should be made to use numerical modeling to improve AM process.

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