Broj rada: 3.3
DOI: 10.65156/wws.sjdp.si.013

UPOREDNA ANALIZA ZAHTEVA STANDARDA ISO 15614-1 I VGB-S-013 ZA ZAVARENE SPOJEVE ČELIKA X10CrMoVNb9-1

COMPARATIVE STUDY OF ISO 15614-1 AND VGB-S-013 REQUIREMENTS FOR WELDED JOINTS OF STEEL X10CrMoVNb9-1

Aleksandra Krstevska[1] 0000-0002-5596-6596, Filip Zdraveski[1] 0009-0008-9189-0753, Marjan Gavriloski[1] i Martin Petreski[1] 0000-0001-6308-3366

[1] University „Ss. Cyril and Methodius“ in Skopje, Faculty of Mechanical Engineering – Skopje, Rugjer Boshkovikj 18, P.O. Box 464, MK-1000 Skopje, R. Makedonija

E-mail: aleksandra.krstevska@mf.edu.mk, filip.zdraveski@mf.edu.mk, marjan.gavriloski@mf.edu.mk, martin.petreski@mf.edu.mk

Rezime: Martenzitni čelik X10CrMoVNb9-1 se široko koristi u komponentama visokih temperatura u elektranama gde su strogi zahtevi za zavarivanje i termička obrada (PWHT) važni kako bi se osigurao dugoročni bezbedan rad. Međunarodni standardi i tehnički propisi definišu različite kriterijume kvalifikacije za zavarene spojeve i parametre PWHT. Ovaj rad predstavlja uporednu analiza zahteva navedenih u ISO 15614-1 i VGB-S-013 za kvalifikaciju zavarenih spojeva od čelika X10CrMoVNb9-1. Analiza se fokusira na temperaturne opsege PWHT, vremena zadržavanja, kriterijume prihvatanja za mehanička svojstva i opšte specifikacije postupaka zavarivanja. Rad ističe kako različiti normativni pristupi mogu uticati na kvalifikaciju zavarenih spojeva u komponentama elektrana i pruža praktičan uvid u izbor i odobravanje postupaka zavarivanja. Predstavljena analiza pruža osnovu za dalje istraživanje metalurških i mehanički svojstva koji proizilaze iz standarda kvalifikacija postupka zavarivanja i zahteva tehničkih propisa.

Ključne reči: Čelik X10CrMoVNb9-1, standard ISO 15614-1, standard VGB-S-013, procedure zavarivanja, kriterijumi prihvatanja

Abstract: The martensitic steel X10CrMoVNb9-1 is widely used in high temperature components in power plants where strict welding and post weld heat treatment (PWHT) requirements are important to ensure long term safe operation. International standards and technical regulations define different qualification criteria for welded joints and PWHT parameters. This paper presents a comparative analysis of the requirements specified in ISO 15614-1 and VGB-S-013 guidelines for the qualification of welded joints in X10CrMoVNb9-1 steel. The analysis focuses on PWHT temperature ranges, holding times, acceptance criteria for mechanical properties and overall welding procedures specifications. The paper highlights how varying normative approaches can influence the qualification of welded joints in power plant components and provides practical insight involved in welding procedure selection and approval. The presented study provides a foundation for further investigation of the metallurgical and mechanical properties resulting from the standard that defines welding procedure specifications and technical regulations requirements.

Key words: X10CrMoVNb9-1 steel, ISO 15614-1 standard, VGB-S-013 standard, welding procedures, acceptance criteria

1. INTRODUCTION

Martensitic steel X10CrMoVNb9-1, commonly referred as P91, is one of the most widely used materials in high-temperature components of supercritical and ultra supercritical power plants due to its excellent creep resistance, high-temperature strength and long-term service stability. It is commonly used in superheaters, reheaters and steam pipelines operating under severe thermal and mechanical loading conditions, [1], [2]. Under such service environments, the quality of welded joints becomes one of the most important factors affecting component reliability and service life. Welding of X10CrMoVNb9-1 steel requires strict control of preheating, interpass temperature and post-weld heat treatment (PWHT) in order to avoid the formation of brittle martensitic structures in HAZ, high hardness and possibility to cracking, [3], [4]. Therefore, welding procedure qualification plays a key role in ensuring the integrity of welded joints.

This paper presents a comparative study of two different documents related with the qualification of welded joints. ISO 15614-1 is international standard for qualification of welding procedures for metallic materials, WPQR, [5]. VGB-S-013 is technical standard for construction and installation supervision in the manufacture and assembly of water-tube boilers and associated systems in thermal power plants [6]. VGB-S-013 cannot replace the requirements of ISO 15614-1, instead, it refers to them and complements the specific requirements for water-tube boilers in power plants. ISO 15614-1 specifies general hardness limits of the weld and impact energy requirements based on material grouping according to ISO 15608. Guidelines for power plant components like VGB-S may require more strict limits to ensure creep resistance and precent premature failure under high-temperature service conditions, [7], [8], [9]. The presented experimental results from dissimilar metal welds (DMW) between X10CrMoVNb9-1 martensitic steel and 12X18H12T austenitic stainless steel are used to discuss the two documents. Special attention is given to the use of PWHT and discussion of mechanical and microstructural properties of the welds [3], [10], [11].

Several researchers have investigated the welding behaviour and service performance of X10CrMoVNb9-1 steel and other creep-resistant steels used in thermal power plants. Klueh and Nelson reported that the long-term reliability of X10CrMoVNb9-1 welded joints is strongly influenced by the microstructural changes occurring in the heat-affected zone during welding and subsequent heat treatment,[8], [12]. Shibli and Starr demonstrated the importance of appropriate PWHT for achieving acceptable hardness levels and improved creep resistance in welded X10CrMoVNb9-1 components, [13]. Pandey et al. examined the microstructural evolution and mechanical properties of dissimilar welds between ferritic and austenitic steels, highlighting the beneficial role of nickel-based filler metals in reducing metallurgical incompatibilities, [14]. Recent studies investigated the mechanical properties, structural integrity, and repair welding procedures of dissimilar welded joints between X10CrMoVNb9-1 and 12X18H12T steels used in boiler components, [10] . These studies confirmed that thermal treatment significantly affects tensile strength, toughness, hardness distribution, and microstructural stability, indicating the need for a comprehensive evaluation of qualification requirements and acceptance criteria for such welded joints.

The aim of this paper is to compare the requirements of ISO 15614-1 and VGB-S-013 for welded joints in X10CrMoVNb9-1 steel with austenitic steel using experimental results obtained from mechanical and microstructural investigations of dissimilar welded joints between X10CrMoVNb9-1 and 12X18H12T stainless steel.

2. STANDARDS REQUIREMENTS

The experimental data is discussed according to ISO 15614-1 standard that specifies the requirements for the specification and qualification of welding procedures for metallic

materials. The martensitic steel X10CrMoVNb9-1 is classified in material group 6.4, according to ISO/TR 15608 and the hardness distribution in the welded joint should not exceed 350 HV. For dissimilar metal joints the tensile strength shall not be less than the minimal value specified for the parent material having the lowest tensile strength. The impact test shall be carried out on specimens from the HAZ in each parent metal and the absorbed energy shall be in accordance with the appropriate parent metal standard.

The VGB-S-013-00-2024-12-EN document is a technical standard developed by VGB PowerTech and serves as a guideline for quality assurance in the manufacture, inspection, and installation of water-tube boilers and their associated systems. The standard gives maximum HV10 hardness values in order to ensure adequate toughness and minimize the risk of brittle fracture during operation. For X10CrMoVNb9-1 steel, the maximum permissible hardness of the welded joint is ≤ 300 HV10, while the hardness in the heat-affected zone must not exceed ≤ 320 HV10. For the base material, the permissible hardness range is 200–260 HV10. These limits serve as acceptance criteria for evaluating the quality of the joint and indicate that the heat treatment has successfully reduced brittleness and residual stresses while ensuring adequate toughness of the component. Compliance with these limits minimizes the risk of cracking and contributes to the reliable long-term operation of components exposed to elevated temperatures and stresses.

ISO/TR 14745:2015 provides steps for the selection of post-weld heat treatment (PWHT) parameters for steels, including the holding temperature and holding time, depending on the material group and thickness, [15]. The martensitic creep-resistant steel X10CrMoVNb9-1 belongs to material group 6.4 according to ISO/TR 15608. For this material, ISO/TR 14745 recommends a PWHT holding temperature in the range of 730–770 °C. The required holding time depends on the thickness of the X10CrMoVNb9-1 component: 30 min for material thicknesses ≤ 12mm, $2t_{min}$, with a minimum holding time of 60 min, for 12 < t ≤ 60mm, and 90+ t_{min} for thicknesses exceeding 60 mm. In this study, PWHT was applied only to X10CrMoVNb9-1 side of the dissimilar welded joint. Therefore, considering the investigated material thickness of 5 mm, the recommended minimum holding time according to ISO/TR 14745 is 30 min. The applied PWHT temperature of 760 °C is within the recommended temperature range for X10CrMoVNb9-1.

3. MATERIALS AND METHODS

Two different parent materials were part of the experimental work. A dissimilar weld was created between martensitic steel X10CrMoVNb9-1 and austenitic stainless steel 12X18H12T with dimensions ø32 mm × 5 mm. TIG 141 welding process was used with nickel-based filler metal NiCr20Mn3Nb (Thermanit Nicro 82).

The main investigation was carried on the martensitic pipe with small dimensions in addition to analyze the hardness distribution and microstructural characterization of the DMW. The preparation of the welds is given in Table 1.

Table 1 Preparation of parent material X10CrMoVNb9-1 and creating DMW

X10CrMoVNb9-1	Preheating (°C)	Buttering layer	PWHT (°C)	Welding process	DMW
Group A	20	NiCr20Mn3Nb	20	TIG 141 (NiCr20Mn3Nb)	12X18H12T
Group B	250	NiCr20Mn3Nb	760	TIG 141 (NiCr20Mn3Nb)	12X18H12T

On Figure 1 is graphically presented the DMW. The length of the buttered layer after machining is about 5mm in order to avoid the carbon migration and hardness variations in the heat affected zone. The post-weld heat treatment was carried out in accordance with the

recommended procedures for welding martensitic steel X10CrMoVNb9-1, at a temperature of 760°C with a holding time of 30 min, according to ISO/TR 14745. Cooling was carried out by gradually reducing the temperature in the furnace at a rate of approximately 150° per hour until reaching 400°, and then the samples were cooled in air, [9]. The TIG 141 process was used for welding the steels, performed at parameters of 90 A and 10 V.

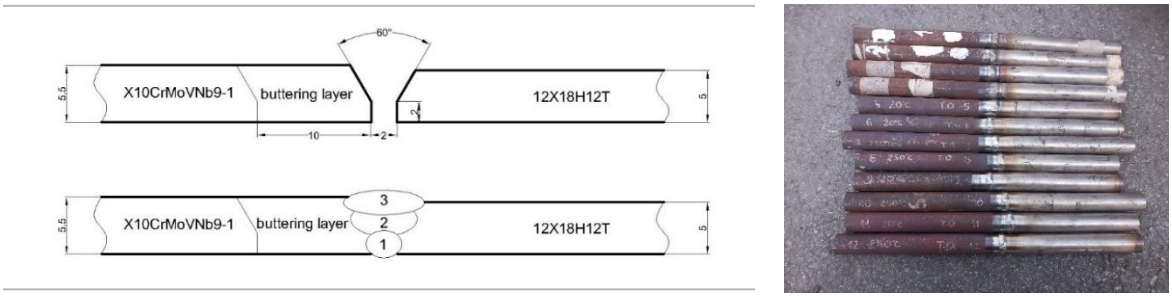


Figure 1 Dissimilar metal welds of X10CrMoVNb9-1 and 12X18H12T

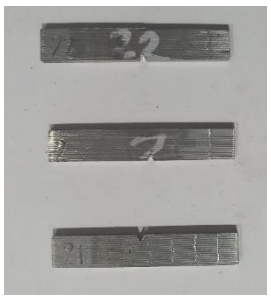
3. EXPERIMENTAL RESULTS

In Table 2 are presented the mechanical properties of DMWs, toughness in the weld metal and HAZ in both parent materials, hardness in HAZ1 (parent material X10CrMoVNb9-1) in upper and lower zone in the HAZ and tensile strength.

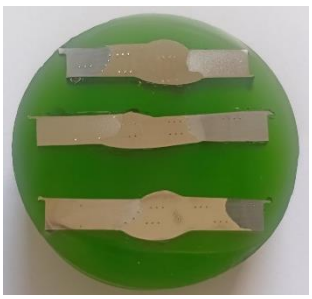
Table 2 Mechanical properties of the DMWs

DMW	Toughness HAZ2 [J]	Toughness WM [J]	Toughness HAZ1 [J]	Hardness HAZ1 HV10 (lower zone)	Hardness HAZ1 HV10 (upper zone)	Tensile strength [MPa]
Group A	25,17	34,87	24,23	263,471	234,385	637,00
Group B	25,13	38,27	33,10	230,249	251,124	640,00

The toughness was tested according to ISO 9016 and ISO 148-1 on probes with V-notch and reduced dimensions 10x2,5x55 mm, [16], [17]. Hardness values were determined according to EN ISO 9015-1 with Vickers method HV10, [18]. The hardness was measured through the weld, parent material, HAZ, buttered layer, weld metal. Due to susceptibility of cracking of martensitic steel X10CrMoVNb9-1 in this paper will be analyzes the hardness values in HAZ 1 (parent material X10CrMoVNb9-1). The tensile test was performed in accordance with EN ISO 4136 [19] where the results of tensile strength are given in the paper. On Figure 2 are presented the experimental probes.



Reduced V-notch probe



Measurement points for hardness



Tensile test – fracture of welded joints

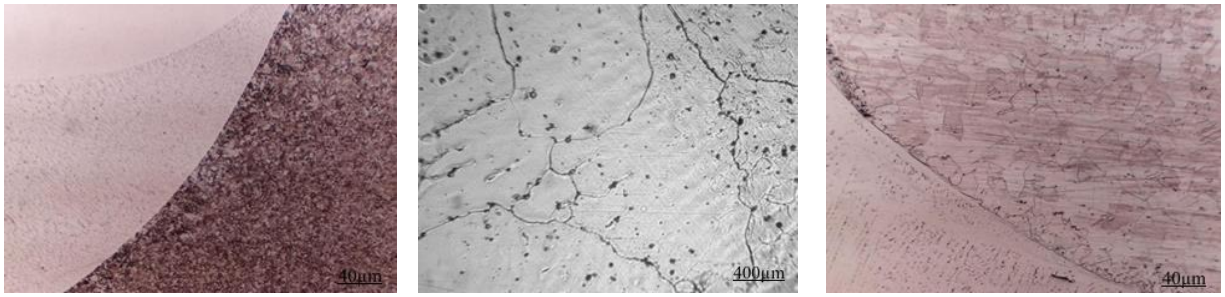
Figure 2 Probes for mechanical testing

A comparative study of the mean values of toughness, hardness and microstructure of the welded joints obtained with two different combinations of preheating and heat treatment is made in Table 3. The toughness of the base material X10CrMoVNb9-1 is 23 J in conditions without heat treatment, while after the applied heat treatment it increases to 27.8 J. Similar trend is observed in HAZ1 where toughness is around 24 J in joints without heat treatment, and after treatment it increases to approximately 33 J, which is clear evidence of structural stabilization and improved toughness.

The hardness of the base material is 241 HV before heat treatment and decreases to 231 HV after PWHT, which is expected due to the tempering of the martensite needles. In both cases hardness varies between 230 ÷ 263 HV10 and both groups show tempered martensite, which shows satisfactory hardness below the range of 350 HV for welded joints of X10CrMoVNb9-1 (group 6.4) and toughness higher than parent material or bellow 320 HV as required in VGB-S-013.

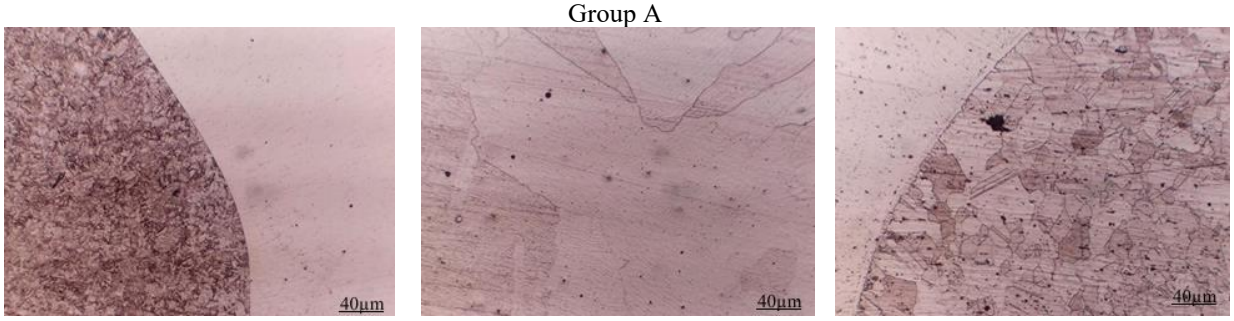
Table 3 Comparative analysis of hardness and toughness of DMW

DMW	**Toughness X10CrMoVNb9-1**	**Toughness HAZ1**	**Hardness X10CrMoVNb9-1**	**Hardness HAZ1 lower zone**	**Hardness HAZ1 upper zone**	**Microstructure**
Group A	23	24,23	241	263,471	234,385	Tempered martensite
Group B	27,8	33,10	231	230,249	251,124	Tempered martensite



a) HAZ1 (X10CrMoVNb9-1) b) Weld metal c) HAZ2 (12X18H12T)

Group A



a) HAZ1 (X10CrMoVNb9-1) b) Weld metal c) HAZ2 (12X18H12T)

Group B

Figure 3 Metallographic analysis of welded joints

A martensitic matrix with prior-austenite grains is shown in Figure 3a. The typical structure of this steel consists of a tempered martensitic lattice containing finely dispersed precipitates, including carbides. Regarding the butter layer and the weld metal, Figure 3b), it can be

observed that the weld consists of a coarse-grained austenitic structure, Figure 3c) which is characteristic of austenitic stainless steels. Metallographic analysis of the austenitic steel reveals a characteristic granular structure with clearly defined grain boundaries and a relatively homogeneous matrix, free of carbide precipitates.

4. COMPARATIVE STUDY OF THE RESULTS

The analysis of mechanical properties was performed to evaluate the influence of PWHT to mechanical properties of DMW of X10CrMoVNb9-1 of small dimensions tubes. The hardness distribution of the probes shows lower variation of the values in upper and lower zone of HAZ1 which indicated stable microstructure. The highest value of 263 HV10 of the probe without PWHT does not indicate brittle martensitic structure and is in the acceptable range according to ISO 15614-1, bellow 350 HV. According to VGB-S technical standard the hardness for HAZ is below 320 HV10 which is still in the permissible range. It can be notable that the combination with PWHT shows smaller hardness values which is in accordance with the tempered martensitic structure and highest toughness.

The toughness has highest value in Group B combination in all analyzed zones and especially in HAZ1 which indicates stable microstructure. The probes without PWHT show same toughness in HAZ1 as parent material X10CrMoVNb9-1. Tensile strength in both combinations is according to the parent material and is with acceptable values according to the requirements of ISO 15614-1. From the obtained results can be concluded that both experimental combinations have acceptable value according to both standards especially in the limitations of hardness in HAZ.

From the experimental work can be concluded that both combinations give acceptable values especially in limitations in hardness in HAZ and tensile strength. Group A also meets the requirements of the standard including the hardness limit but shows lower values for toughness in HAZ1 compared to the other combination. The most suitable combination, group B, provides highest toughness, lower hardness values and good mechanical properties, indicating a stable microstructure and lowest risk of brittle fracture. The hardness and toughness of welded joints represent an indirect but important parameter for characterizing the microstructure in different zones.

5. CONCLUSION

A comparative study of the requirements defined in ISO 15614-1 and VGB-S-013 is related to hardness limits where ISO 15614-1 permits a maximum hardness of 350 HV for material group 6.4, while VGB-S-013 limits the weld metal hardness to 300 HV10 and the HAZ hardness to 320 HV10. Therefore, while ISO 15614-1 provides general qualification requirements applicable to a wide range of welded structures, VGB-S-013 as technical standard complement the requirements aimed only to increase operational safety and durability of critical power plant components.

The obtained results show that all tested combinations are within the permissible limits for mechanical properties under considered standards. Although heat treatment is expected to contribute to the most favorable properties primarily by reducing the hardness and stabilizing the microstructure, the welds made without heat treatment also demonstrate mechanical characteristics that remain within acceptable limits. The fact that the welds without heat treatment also achieve hardness values similar to those with heat treatment, and their toughness in HAZ remains within the limits of the base material, is an important indication that the investigated DMW with small wall thickness can be applied as temporary repair solution. This is of particular interest for industrial practice, where performance without heat treatment may be sometimes necessary for certain temporary repairs or limited operating conditions.

REFERENCES

[1] J. Parker, “EPRI Project Guidelines and Specifications for High-Reliability Fossil Power Plants Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel Components,” 2011. [Online]. Available: www.epri.com

[2] J. Pecha, D. Stano, and O. Peles, “Welding Of 9% Cr Creep Resisting Steels for Power Engineering Equipment.”

[3] A. Krstevska, F. Zdraveski, M. Gavriloski, E. Doncheva, and M. Petreski, “Review of current welding technology and literature review of weld repair without post-weld heat treatment for X10CrMoVNb9-1 steel in dissimilar metal welds,” *Procedia Structural Integrity*, vol. 72, pp. 172–180, 2025, doi: 10.1016/j.prostr.2025.08.089.

[4] M. Consonni and D. J. Abson, “INVESTIGATION OF WELD REPAIR WITHOUT POST-WELD HEAT TREATMENT FOR P91 ISTRAŽIVANJE REPARATURE ZAVARENOG SPOJA BEZ NAKNADNE TERMIČKE OBRADE NA ČELIKU P91 Originalni naučni rad / Original scientific paper.”

[5] International Organization for Standardization, “ISO 15614-1 Specification and qualification of welding procedures for metallic materials-Welding procedure test-Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys,” 2017. [Online]. Available: www.iso.org

[6] VGB PowerTech, “Construction and installation supervision in the manufacture and assembly of water-tube boilers and associated systems in thermal power plants,” 2014.

[7] F. Khan, S. Mahajan, W. N. Khan, and R. Chhibber, “Mechanical, microstructure, and hot corrosion investigations on P22/P91 dissimilar tungsten inert gas weld,” *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 235, no. 9, pp. 2128–2141, Oct. 2021, doi: 10.1177/14644207211021941.

[8] R. L. Klueh, “Elevated temperature ferritic and martensitic steels and their application to future nuclear reactors,” Oct. 2005. doi: 10.1179/174328005X41140.

[9] A. Krstevska, M. Poser, and F. Zdraveski, “Weldability between steel type 304H and steel type P91 for high temperature applications,” *Zavarivanje i zavarene konstrukcije*, vol. 68, no. 4, pp. 29–36, 2023, doi: 10.5937/zzk2301029K.

[10] A. Krstevska, F. Zdraveski, M. Gavriloski, and M. Petreski, “Mechanical properties of steel P91 and steel 12X18H12T in dissimilar pipe welds used in boiler components,” 2023.

[11] A. Krstevska, D. Runchev, and F. Zdraveski, “Welding technology of martensitic steel P91 and austenitic steel 304H-State of the art,” 2023, doi: 10.1007/978-981-16-3641.

[12] R. L. Klueh *et al.*, “Ferritic/martensitic steels – overview of recent results,” *Journal of Nuclear Materials*, vol. 307–311, no. 1 SUPPL., pp. 455–465, Dec. 2002, doi: 10.1016/S0022-3115(02)01082-6.

[13] A. Shibli and F. Starr, “Some aspects of plant and research experience in the use of new high strength martensitic steel P91,” *International Journal of Pressure Vessels and Piping*, vol. 84, no. 1–2, pp. 114–122, Jan. 2007, doi: 10.1016/j.ijpvp.2006.11.002.

[14] C. Pandey and M. Mahapatra, “Evolution of phases during tempering of P91 steel at 760°C for varying tempering time and their effect on microstructure and mechanical properties,” *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 231, no. 6, pp. 1141–1161, Dec. 2017, doi: 10.1177/0954408916656678.

[15] European Commitee for Standardization, “ISO/TR 14745 Welding - Post-weld heat treatment parameters for steels,” 2015.

[16] International Organization for Standardization: ISO/DIS 4063:2020, “ISO 148-1:2016 Metallic materials - Charpy pendulum impact test,” 2016. [Online]. Available: www.iso.orgiTehSTANDARDPREVIEW

[17] International Organization for Standardization: ISO/DIS 4063:2020, “ISO 9016:2022 Destructive tests on welds in metallic materials — Impact tests — Test specimen location, notch orientation and examination,” 2022.

[18] International Organization for Standardization: ISO 9015-1, “Destructive tests on welds in metallic materials — Hardness testing,” 2001. [Online]. Available: www.iso.ch

[19] International Organization for Standardization: ISO 4136:2022, “Destructive tests on welds in metallic materials-Transverse tensile test,” 2022. [Online]. Available: www.iso.org