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Cold bending of advanced ferritic steels: ASTM grades T23, T91, T92

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ABSTRACT

The metallurgical background of advanced ferritic steels must be considered during every stage of fabrication, including forming operations, such as cold bending, because they can negatively affect the high-temperature properties of the material when not performed properly.

In this work, the results of a broad cold bending program carried out on ASTM Grades T23, T91 and T92 tubes in the range $1.0 \leq R/OD \leq 4.5$ are presented; the industrial window for a safe and repeatable cold bending of 9%Cr tubes was defined: ovalisation and thickness variation were measured after the bending; the microstructure, the hardness values and the mechanical properties at extrados and intrados positions were investigated and compared with properties of unbent materials. Optimum post bending heat treatment of most severe bends was defined.

This paper aims to integrate the International Codes for cold bending with recommendations for proper post bending heat treatments, in order to obtain a final component with the desired microstructure, cold workability and mechanical properties. Recommendations for the post bending heat treatment were formulated and compared with the prescriptions given by the relevant International Codes and Standards.

Creep properties of large cold bends were also assessed by means of specimens directly machined from extrados and intrados portions of real bends. Both extrados and intrados areas of T23, T91 and T92 bends exhibited a creep resistance within the lower scatter band of base material isothermal curve. The creep-rupture ductility of the intrados was measured higher than that of the extrados.

1. Introduction

The use of 2.25%Cr and 9%Cr advanced ferritic steels ASTM Grades 23, 91 and 92 for components of Ultra Super Critical power plants is continuously increasing; when produced and processed properly, these steels exhibit excellent high-temperature resistance, much higher than that of the older Grades 22 and 9 [1].

The metallurgical background of advanced ferritic steels must be considered during all stages of fabrication, including forming operations, because these common procedures could negatively affect the high-temperature properties of the material if they are not performed properly.

Cold bends, which are widely used in several high-temperature components (e.g. boilers, headers), are made from straight pipes by a cold-working process using a bending machine.

Lots of efforts have been put worldwide to study the effects of cold bending on large pipes for line pipe applications [2–4]. A cold bending process causes plastic deformation primarily in the longitudinal direction of the pipes. The tensile properties of the cold bends are different from those of the straight pipes due to work hardening and the Bauschinger effect [5].

An influence of cold bending can be also expected in the creep resistance, however a very limited knowledge has been generated about the changes of creep strength in cold deformed high-temperature resistant steels [6].

In this work, the results of a broad cold bending program carried out on tubes of 2.25%Cr and 9%Cr advanced ferritic steels are presented: the microstructure and the mechanical properties at extrados and intrados positions were investigated and compared with properties of unbent materials. Creep properties were assessed by means of specimens directly machined from extrados and intrados positions of real bends.

Tubes of Grades 23, 91 and 92 (according to ASTM A213 Standard) after normalizing and tempering have been used for cold bending operations; Tables 1 and 2 show the characteristics of the materials used in this research program.

This paper aims to integrate the current International Codes for cold bending with recommendations for proper post bending heat

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Table 1
Tubes used for cold bending tests.

Grade	Dimension		Heat Treatment	
	OD [mm]	WT [mm]	Normalizing Temperature [°C]	Tempering Temperature [°C]
ASTM A213 T23	38.0	4.0	1050	760
	51.0	4.0	1050	760
	76.0	12.5	1050	780
ASTM A213 T91	38.1	4.19	1070	780
	44.5	2.67	1070	780
	44.5	3.05	1070	780
	76.0	12.5	1070	780
ASTM A213 T92	44.5	7.1	1070	780
	76.0	12.5	1070	780

treatments, in order to obtain a final component with the desired microstructure and mechanical properties.

2. Cold bending practice

Cold bending of tubular products can lead to a significant level of deformation at extrados and intrados areas. After cold forming, yield and tensile strengths generally change, while elongation decreases. Bending of tube can distort the cross section: the greater the bending radius, the lower the resulting distortion [2,3,7,8].

The intrados of the tube bend undergoes compression that thickens the wall; excessive compression, in the worst case, can fold the material causing wrinkles or waves. The extrados of the tube bend undergoes tension that reduces the wall thickness. The same forces tend to ovalise the tube cross section.

After bending it must be ascertained whether the maximum ovality and the minimum wall thickness are within the requirements of International Codes [9,10].

The main parameter to characterize the cold deformation of a tube is the bending ratio, defined as the *nominal bending radius* (*R*) to the centreline of tube over the *nominal outside diameter* (*OD*) of the tube: (R/OD).

Ovalisation (u) at each section of the bend is measured by the following formula [9]:

$$u(\%) = 2 \times \frac{(Max\ \mathrm{OD} - Min\ \mathrm{OD})}{(Max\ \mathrm{OD} + Min\ \mathrm{OD})} \times 100 \quad (1)$$

where *Max*OD (mm) and *Min*OD (mm) are respectively the maximum and the minimum values of the diameters taken in the same cross section. The ovalisation values at each section of the bend shall be limited within the area of the graph in Fig. 1 (in case of single bending) [9].

After bending a minimum tube thickness is required at each section: the *minimum thickness* value is calculated with the following formula, for tubes with diameter ≤142 mm [9]:

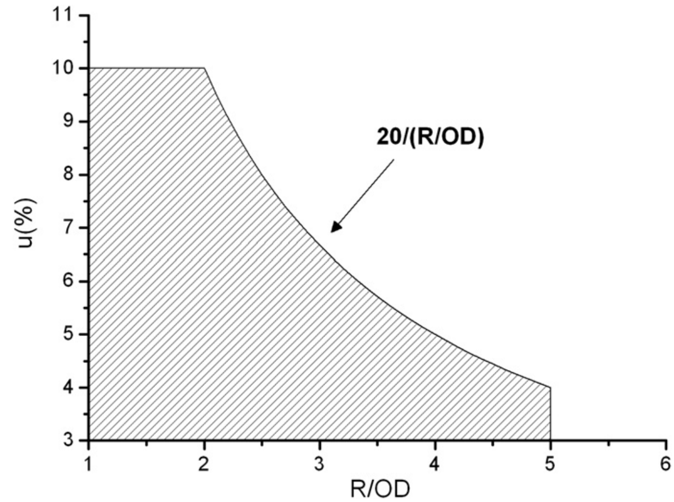

Fig. 1. Limits for ovalisation $u(\%)$ according to EN12952-5 [1].

$$WT_{\min} = WT_0 \cdot \frac{\frac{R}{\mathrm{OD}} + 0.5}{\frac{R}{\mathrm{OD}} + 1} \quad (2)$$

where WT_0 is the nominal wall thickness (mm). The maximum reduction of thickness is found at extrados sections.

The maximum value of *strain* (ε) accumulated by the material fibres during bending corresponds to the elongation of the extrados and characterizes the bend independently of the process used. The strain can be calculated according to the ASME Boiler & Pressure Vessel Code (BPVC), Section I, formula in PG-19, as follows [10]:

$$\varepsilon(\%) = \frac{100}{2 \cdot \left(\frac{R}{\mathrm{OD}}\right)} \quad (3)$$

After cold bending, the following actions are mandatory:

- *Visual examination*: no defects, crushing and wrinkles shall be allowed in the bend;
- *Measurements of ovalisation u(%) and wall thinning* ($WT_{\min}$), according to formulas (1) and (2) (thickness variation is assumed to be maximum at extrados of the bend);
- *Measurements of bending strain* (ε), according to formula (3).

If the visual inspection, ovalisation and thickness variation requirements are fulfilled, then the bend is acceptable.

Cold forming without subsequent heat treatment is generally accepted for limited strain by International Codes, e.g. ASME allows avoiding post bending heat treatment if $\varepsilon \leq 5\%$; for larger deformation the post-production rules depend on the bending conditions (R/OD and/or ϵ and temperature).

In case of a certain level of deformation, Codes prescribe a stress-relieving treatment in order to eliminate the work hardening in severely cold deformed parts. Moreover, in well-defined

Table 2
Chemical compositions (main elements) according to ASTM A213 of the materials used for cold bending tests (mass %).

Grade		C	Mn	P	S	Si	Cr	Mo	W	Nb	V	B	N
23	min	0.04	0.10	–	–	–	1.9	0.05	1.45	0.02	0.20	0.0005	–
	max	0.10	0.60	0.030	0.010	0.50	2.6	0.30	1.75	0.08	0.30	0.0060	0.03
91	min	0. 80	0.30	–	–	0.20	8.0	0.85	–	0.06	0.18	–	0.03
	max	0.012	0.60	0.020	0.010	0.50	9.5	1.05	–	0.10	0.25	–	0.07
92	min	0.07	0.30	–	–	-	8.5	0.30	1.50	0.04	0.15	0.0010	0.03
	max	0.13	0.60	0.020	0.010	0.50	9.5	0.60	2.00	0.09	0.25	0.0060	0.07

Table 3
Vdtüv 511-2 (grade 91) and 552-2 (grade 92): heat treatment rules after cold bending.

Equivalent Strain ε % [eq. 3]		R/OD < 1.8	1.8 ≤ R/OD < 3	R/OD ≥ 3
		ε > 27.8	27.8 ≥ ε > 16.7	ε ≤ 16.7
VdTÜV 511-2 / 522-2	OD ≤ 76.1	PBHT	No HT	No HT
	OD > 76.1	N + T	N + T	No HT

Table 4
En12952-5 code: heat treatment rules after cold bending of t23, t91 and t92.

Equivalent Strain ε% [eq. 3]		R/OD < 1.3	1.3 ≤ R/OD < 2.5	R/OD ≥ 2.5
		ε > 38.5	38.5 ≥ ε > 20	ε ≤ 20
EN12952-5	OD ≤ 142	PBHT	No HT	No HT
	OD > 142	PBHT	PBHT	No HT

cases, bends shall undergo a complete normalizing and tempering heat treatment.

Requirements for heat treatment after cold bending are given in National and International Codes [9,11,12]; VdTÜV 511-2 (Grade 91) and VdTÜV 552-2 (Grade 92) prescriptions are shown in Table 3, while EN12952-5 prescriptions are shown in Table 4: as a function of the bending ratio (R/OD) and the tube diameter, a post bending heat treatment (PBHT) may be required, or in more severe bending conditions, a complete normalizing and tempering (N + T) heat treatment shall be mandatory; for small deformation, the heat treatment can be avoided (No HT).

The post-production rules suggested by the ASME Boiler Code for Grade T91 are summarized in Table 5 as a function of bending ratio, bending strain, and operating service temperature [13,14]: if maximum nominal service temperature is lower than 538 °C, no heat treatment is required; for maximum nominal service temperature higher than 538 °C, heat treatment after cold bending depends on the amount of strain deformation (measured at extrados by formula (3)). Since PBHT prescriptions for Grade 92 are not included in the ASME code case, Table 5 has been assumed valid also for Grade 92.

Regarding Grade T23, the ASME proposal is still under discussion, and it has not been reported in this work.

Codes generally allow post bending heat treatment in the temperature range between 650 °C and 760 °C, followed by air cooling. This will be discussed further.

3. Cold bending trials

Tubes of Grades T23, T91 and T92 have been cold bent by industrial rotary bending machines. All bends are "*U*" bends (bending angle: 180°), with bending ratio (R/OD) from 1.0 up to 4.5. Table 6 summarizes the cold bends produced within this research program. Several bends for each testing condition were produced, to guarantee safe and repeatable industrial feasibility. If a bend exhibits defects – e.g. crushing and wrinkles, excessive ovalisation or thickness variation – then it is rejected. As shown in Table 6, most of the bends passed the visual check as well as the control on ovalisation and minimum thickness (at extrados).

Grade T91, OD × WT 38 × 4.19 mm, was successfully cold bent in a very severe condition, with R/OD = 1.0: no visual defects occurred and limited ovalisation and limited wall thinning were measured.

Table 5
ASME code: Heat treatment rules after cold bending of T91 (applicable to T92 also).

ε [%] ASME,BPVC, Sec. I, PG-19	ε > 30	30 ≥ ε > 20	20 ≥ ε > 5	ε ≤ 5
R/OD	R/OD < 1.7	1.7 ≤ R/OD < 2.5	2.5 ≤ R/OD < 10	R/OD ≥ 10
T°C ≤ 538	No HT	No HT	No HT	No HT
538 < T°C ≤ 593	N + T	PBHT	PBHT	No HT
593 < T°C	N + T	N + T	PBHT	No HT

Table 6
Cold bends manufactured with different R/OD ratios (n.a. means *not available*).

Grade	Dimension OD × WT (mm × mm)	R/OD	Ovalisation (%)		Thickness at extrados (mm)		Quality Check
			Measured	Required EN12952	Measured	Required EN12952	
Grade 23	38 × 4.0	1.0	n.a.	<10	n.a.	≥3.3	*Failed*
		1.18	4.5	<10	3.6	≥3.4	Passed
	51 × 4.0	1.30	8.2	<10	3.7	≥3.4	Passed
		1.56	6.3	<10	3.9	≥3.5	Passed
	76 × 12.5	2.69	4.3	<7.5	12.4	≥11.5	Passed
		3.55	3.4	<5.6	12.5	≥11.7	Passed
		4.50	2.5	<4.45	12.4	≥11.9	Passed
Grade 91	38 × 4.19	1.00	7.1	<10	3.6	≥3.5	Passed
		1.18	5.5	<10	3.7	≥3.6	Passed
	44.5 × 2.67	1.14	n.a.	<10	2.0	≥2.3	*Failed*
		1.40	n.a.	<10	2.2	≥2.3	*Failed*
		1.64	3.5	<10	2.4	≥2.3	Passed
		1.79	6.5	<10	2.5	≥2.4	Passed
	44.5 × 3.05	1.14	n.a.	<10	2.5	≥2.6	*Failed*
		1.40	7.2	<10	2.7	≥2.6	Passed
		1.64	6.2	<10	2.7	≥2.7	Passed
		1.80	5.6	<10	2.9	≥2.7	Passed
	76 × 12.5	2.69	5.5	<7.5	12.3	≥11.5	Passed
		3.55	3.4	<5.6	12.4	≥11.7	Passed
		4.50	2.3	<4.45	12.4	≥11.9	Passed
Grade 92	44.5 × 7.1	1.14	8.1	<10	6.8	≥6.0	Passed
		1.49	6.7	<10	6.3	≥6.2	Passed
	76 × 12.5	2.69	5.1	<7.5	12.1	≥11.5	Passed
		3.55	3.2	<5.6	12.2	≥11.7	Passed
		4.50	2.1	<4.45	12.4	≥11.9	Passed

Grade T92, OD × WT 44.5 × 7.1 mm, was cold bent with R/OD = 1.14 with no problems.

Large bends of T23, T91 and T92 OD × WT 76 × 12.5 mm tubes were successfully performed with very limited ovalisation and wall thinning at extrados with R/OD ratios 2.69, 3.55 and 4.5.

A few bends, in the most severe bending conditions (small R/OD ratio) failed due to crushing and wrinkle formation at intrados: bends of Grade T91 OD × WT 44.5 × 2.67 mm with R/OD ratios 1.14 and 1.40 were both rejected; on the contrary the same tube dimension was cold bent without defects at higher R/OD ratios 1.64 and 1.79.

Pictures of a T91 bend, OD × WT 44.5 × 2.67 mm, R/OD = 1.40, is shown in Fig. 2.

This broad bending program on Grades T91 and T92 has allowed to define an industrial window for successful cold bending of 9%Cr tubes: ovalisation and wall-thinning values after bending are shown in Fig. 3 as a function of R/OD radius.

4. Microstructure of the bend

After visual examination, the microstructure of each bend was investigated at intrados and extrados, and it was compared with the microstructure of the unbent portion of the tube: hardness measurements and investigations by Light Microscopy (LM) and Scanning Electron Microscopy (SEM) were carried out.

By LM investigation, microstructure of the bends appears stretched at extrados, while compressed at intrados areas, especially in the case of bends with severe bending ratios; no recrystallization phenomenon was observed on as-bent Grades T23, T91 and T92.

SEM investigations of extrados samples of the bends confirmed that no micro-voids are present in tubes after cold bending, even in the most severe bending conditions.

Fig. 2. GRADE T91, OD×WT 44.5 × 2.67 mm, $\theta = 180°$, R/OD = 1.40 (accepted).

Fig. 4A–C show the microstructure of T92 OD × WT 44.5 × 7.1 mm bend, R/OD = 1.14, respectively at unbent, intrados and extrados portions, with correspondent average hardness values.

Fig. 5A–C show the microstructure of T23 OD × WT 38 × 4 mm bend, R/OD = 1.18, respectively at unbent area, intrados and extrados portions, with correspondent average hardness values.

All the bends examined show similar microstructural characteristics: at intrados the grains appear deformed and compressed (stretched in radial direction) with an evident hardness increase; at extrados the grains appear deformed and stretched in the longitudinal direction with a limited hardness increase.

Table 7 summarizes the average hardness values of as-bent tubes at extrados, intrados and unbent portions. International Codes in specific cases require a stress-relieving heat treatment or a complete normalizing and tempering heat treatment as a function of the cold deformation level.

On the basis of the present work, the authors recommend to perform the PBHT if the hardness at any portion of the bend exceeds 265HV (250HBW; 25HRC) for Grades T91 and T92, or if it exceeds 230HV (220HBW; 97HRB) for Grade T23; these hardness requirements are prescribed by ASTM A213 Standard for the unbent material. Table 7 also reports the heat treatment prescriptions after bending according to EN, VdTÜV and ASME Codes, compared with the author's recommendations based on the metallographic and mechanical investigations carried out on bends.

Comparing PBHT prescriptions given by EN, VdTÜV and ASME Codes with the author's recommendations, the following considerations can be made:

- The EN and VdTÜV Codes generally give similar prescriptions for heat treatment; the ASME Code is generally more conservative than the EN and VdTÜV Codes: in several cases ASME prescribes PBHT when EN and VdTÜV prescribe no HT for the same cold deformation; moreover ASME prescribes N + T where EN and VdTÜV prescribe simple stress-relieving (PBHT).
- ASME prescriptions are a function of the service temperature.
- In one case, for T91 OD × WT 44.5 × 2.67 mm, R/OD = 1.79, the different Codes gives differing prescriptions: EN prescribes no HT, VdTÜV prescribes a PBHT, while ASME takes into considerations all possibilities (No HT, PBHT, N + T) depending on the service temperature.
- Recommendations by metallographic investigations are generally in line with the prescriptions from EN and VdTÜV Codes; more discrepancies are reported with ASME Code.
- Differences between Code prescriptions and recommendations are noticed for the most critical bends: for example, T92 OD × WT 44.5 × 7.1 mm bend, R/OD = 1.49, shows very

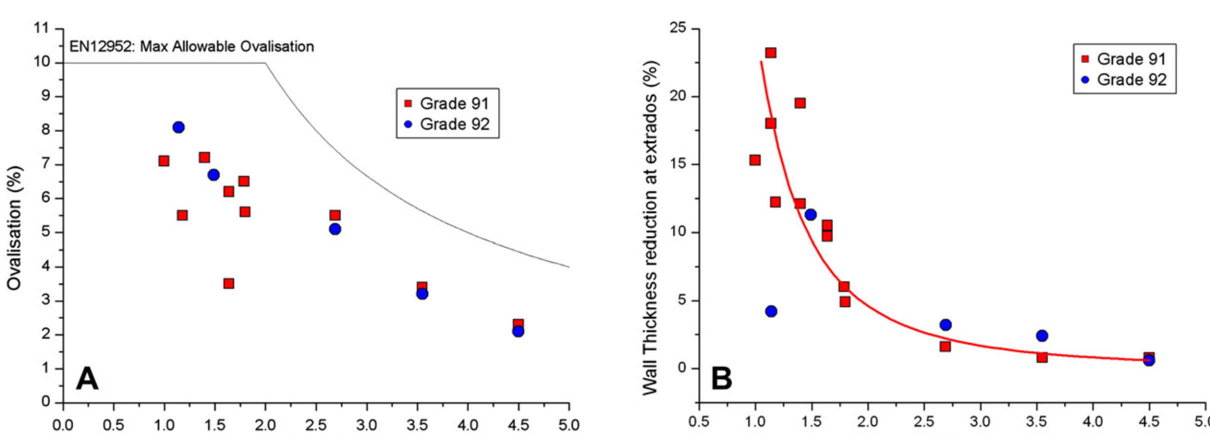

Fig. 3. Industrial bending window of T91 and T92: obtained values of ovalisation (A) and wall thickness reduction (B) at extrados after cold bending.

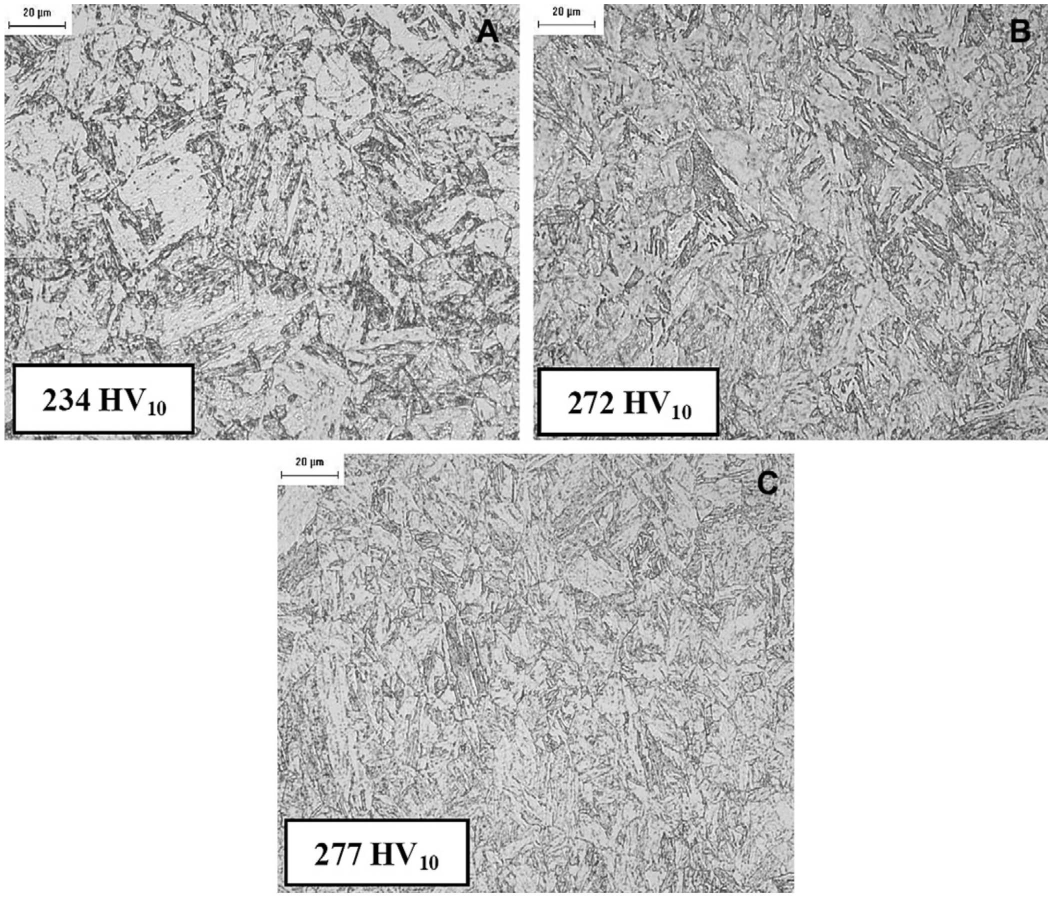

Fig. 4. Grade 92, OD×WT 44.5×7.1 mm , R/OD = 1.14; (A) unbent zone, transverse section; (B) intrados, longitudinal section; (C) extrados, longitudinal section.

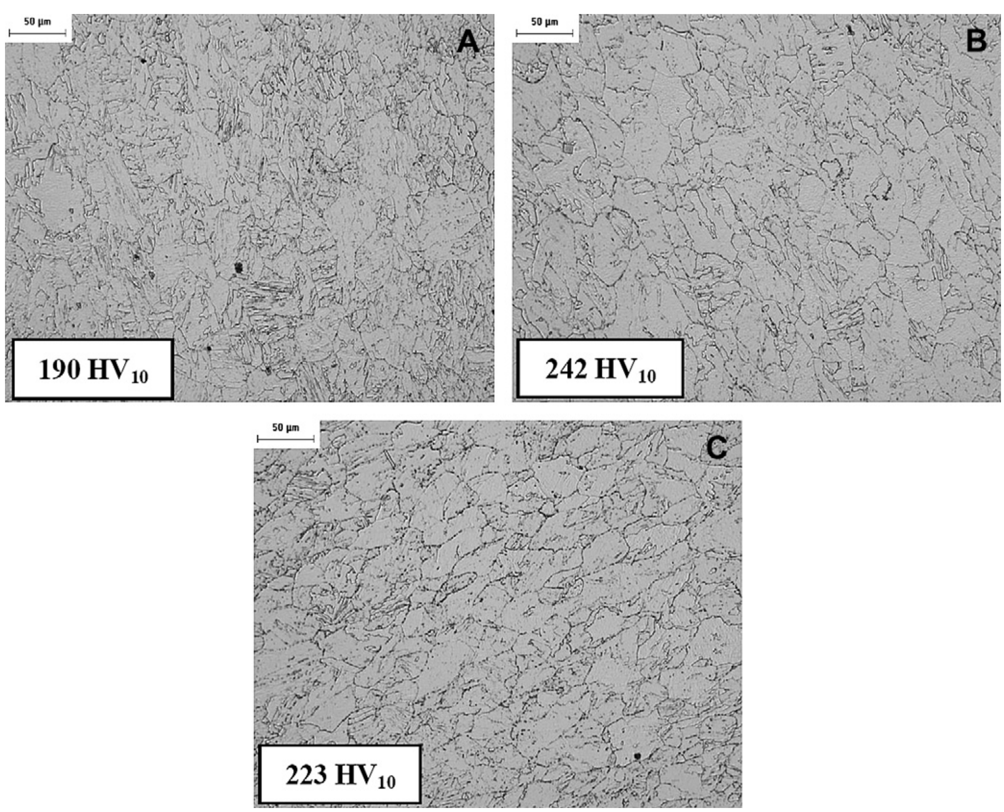

Fig. 5. Grade T23, OD×WT 38×4.0 mm, R/OD = 1.18; (A) unbent zone, transverse section; (B) intrados, longitudinal section; (C) extrados, longitudinal section.

Table 7
Average hardness values of the bends at extrados, intrados and unbent portions. Prescriptions for heat treatments after bending by international codes, in comparison with author's recommendations (n.a. means *not applicable*).

Grade/(maximum hardness)	Dimension OD × WT (mm × mm)	R/OD	Strain (%)	Average hardness		Heat treatment prescriptions after cold bending			
				Position	HV_{10}	EN	VdTÜV	ASME	Recommendations
T23 (230HV)	38 × 4.0	1.18	42.3	Intrados	242	PBHT	n.a.	n.a.	PBHT
				Extrados	223				
				Unbent	190				
	51 × 4.0	1.30	38.5	Intrados	244	PBHT	n.a.	n.a.	PBHT
				Extrados	230				
				Unbent	200				
		1.56	32.0	Intrados	235	No HT	n.a.	n.a.	No HT/PBHT
				Extrados	223				
				Unbent	196				
	76 × 12.5	4.5	11.1	Intrados	213	No HT	n.a.	n.a.	No HT
				Extrados	213				
				Unbent	210				
T91 (265HV)	38 × 4.2	1.0	50	Intrados	290	PBHT	PBHT	T ≤ 538 °C → No HT	PBHT
				Extrados	255			T > 538 → N + T	
				Unbent	220				
	44.5 × 2.67	1.64	30.5	Intrados	273	No HT	PBHT	T ≤ 538 °C → No HT	PBHT
				Extrados	262			T > 538 °C → N + T	
				Unbent	221				
		1.79	27.9	Intrados	263	No HT	PBHT	T ≤ 538 °C → No HT	No HT/PBHT
				Extrados	258			538 < T ≤ 593 °C → PBHT	
				Unbent	217			T > 593 °C → N + T	
	44.5 × 3.05	1.64	30.5	Intrados	265	No HT	PBHT	T ≤ 538 °C → No HT	No HT/PBHT
				Extrados	253			T > 538 °C → N + T	
				Unbent	217				
		1.80	27.7	Intrados	266	No HT	No HT	T ≤ 538 °C → No HT	No HT/PBHT
				Extrados	244			538 < T ≤ 593 °C → PBHT	
				Unbent	223			T > 593 °C → N + T	
	76 × 12.5	4.5	11.1	Intrados	240	No HT	No HT	T ≤ 538 °C → No HT	No HT
				Extrados	245			T > 538 °C → PBHT	
				Unbent	235				
T92 (265HV)	44.5 × 7.1	1.49	33.5	Intrados	272	No HT	No HT	T ≤ 538 °C → No HT	PBHT
				Extrados	277			T > 538 °C → N + T	
				Unbent	234				
	76 × 12.5	4.5	11.1	Intrados	260	No HT	No HT	T ≤ 538 °C → No HT	No HT
				Extrados	260			T > 538 °C → N + T	
				Unbent	240				

high hardness values at intrados (272HV) and extrados (277HV); a PBHT would be recommended but the EN and VdTÜV Codes do not prescribe any heat treatment, while the ASME Code prescribes a complete normalizing and tempering (N + T) of the bend, if service temperature exceeds 538 °C.

- Regarding T23 OD × WT 51 × 4.0 mm bend, R/OD = 1.56, the hardness values at intrados after bending are slightly over 230HV, so the recommendation takes into consideration both PBHT and no HT.

5. Post bending heat treatment

In all the cases where the hardness measurements exceed the maximum limits (265HV for Grades 91 and 92, 230HV for Grade 23),

Table 8
Hardness values of samples of T91, T92 and T92 before and after PBHT.

		Grade T23 OD×WT 51×4 mm R/OD = 1.30	Grade T91 OD×WT 38×4.2 mm R/OD = 1.0	Grade T92 OD×WT 44.5×7.1 mm R/OD = 1.49
Base material		200 HV_{10} (max 230 HV)	220 HV_{10} (max 265 HV)	234 HV_{10} (max 265 HV)
After bending	Intrados	244 HV_{10}	290 HV_{10}	272 HV_{10}
	Extrados	230 HV_{10}	255 HV_{10}	277 HV_{10}
Tempered 650 °C × 60 min	Intrados	220 HV_{10}	253 HV_{10}	/
	Extrados	225 HV_{10}	258 HV_{10}	/
Tempered 700 °C × 60 min	Intrados	/	/	248 HV_{10}
	Extrados	/	/	257 HV_{10}
Tempered 750 °C × 10 min	Intrados	226 HV_{10}	248 HV_{10}	250 HV_{10}
	Extrados	210 HV_{10}	248 HV_{10}	247 HV_{10}
Tempered 750 °C × 20 min	Intrados	220 HV_{10}	240 HV_{10}	242 HV_{10}
	Extrados	202 HV_{10}	238 HV_{10}	245 HV_{10}
Tempered 750 °C × 60 min	Intrados	/	212 HV_{10}	/
	Extrados	/	228 HV_{10}	/
Tempered 760 °C × 60 min	Intrados	/	/	233 HV_{10}
	Extrados	/	/	239 HV_{10}

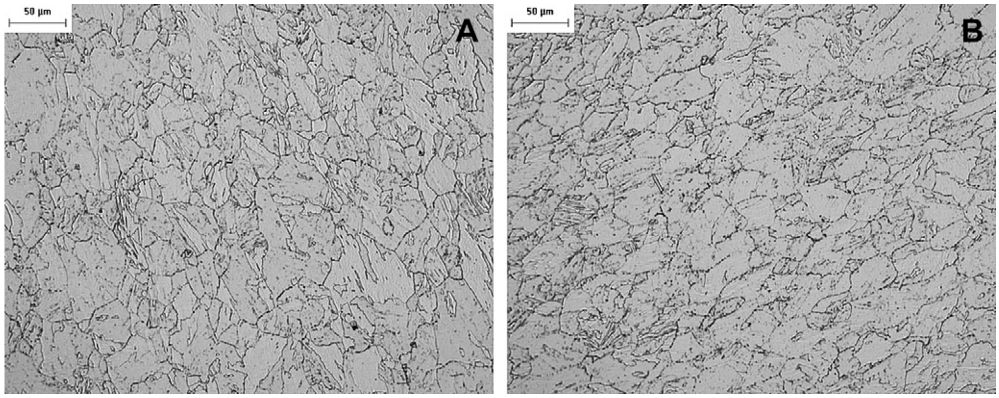

Fig. 6. Grade 23, OD×WT 51×4.0 mm, R/OD = 1.30, (A) intrados, (B) extrados after stress relieving 750°C/10min. Longitudinal sections. Nital etching.

a post bending heat treatment is recommended by the authors, Table 7.

International Codes generally allow PBHT in a wide range of times and temperatures; for example, VdTÜV prescribes 60 min minimum in the temperature range 650–750 °C for Grade 91 and 700–760 °C for Grade 92.

Trial post bending heat treatments on T23, T91 and T92 severe bends (T23, OD × WT 51 × 4 mm, R/OD = 1.3; T91, OD × WT 38 × 4.2 mm, R/OD = 1.0; T92, OD × WT 44.5 × 7.1 mm, R/OD = 1.49) were performed with 10, 20 and 60 min soaking times at 750 °C, Table 8; the minimum duration of 60 min, as prescribed by VdTÜV 511/2 and 552/2 material datasheets, is considered too long at 750 °C and the reduction of hardness values below maximum level is obtained already after 10 min at 750 °C.

Trial PBHT showed that a reduction of the hardness values below maximum limits was obtained by means of 650 °C/60 min on T23 and T91, as well as by means of 700 °C/60 min on T92 bend.

No traces of recrystallization on investigated bends have been found after PBHT.

The microstructure of the T23 bend after stress-relieving at 750 °C/10 min is shown in Fig. 6.

6. Mechanical properties of R/OD = 4.5 bends

A broad mechanical characterization has been performed on large bends with R/OD = 4.5 made from OD × WT 76 × 12.5 mm T23, T91 and T92 tubes. The mechanical properties were assessed at intrados, extrados and in the unbent area. The bends did not receive post bending heat treatment, as their hardness values fulfilled material requirements. Tensile and Charpy-V notch (CVN) specimens as well as sub-size creep specimens were machined directly from the bend portions.

Table 9 shows tensile properties at room temperature. Results show evident differences between properties of extrados and intrados: at extrados, where positive strain deformation (tensile) occurs during bending, the Y/T ratio (ratio between yield strength (YS) and ultimate tensile strength (UTS)) is greater than 0.97; this result is expected because of the large amount of plastic strain accumulated during bending. On the other hand, at intrados, where a negative strain deformation (compression) occurs during bending, the YS value is lower than the YS value of the unbent material. This mechanical behavior is well known as Bauschinger effect [5]. In all cases, the requirements on mechanical resistance given by ASTM A213 were fulfilled. Elongation is negatively affected by cold bending: the values at intrados and extrados were lower than ASTM A213 minimum requirements for unbent tubes.

Table 10 shows the results of CVN tests at room temperature from sub-size specimens (10 mm × 10 mm × 7.5 mm) machined from extrados, intrados and unbent portions of T91, T92 and T23 large bends.

T91 bends show absorbed energies greater than 230 J/cm^2 at both extrados and intrados; T92 bends toughness is greater than 140 J/cm^2 at both extrados and intrados. No traces of brittle rupture were observed on fracture surfaces of both grades. No significant differences of absorbed energies before and after bending are noticed on T91 and T92.

Results of CVN impact tests from T23 bends show lower values of absorbed energies at room temperature compared to Grades 91 and 92. However, the results achieved comply with Pressure Equipment Directive (PED) requirements (impact toughness >27 J at RT) [14].

Creep specimens with 5 mm diameter were machined from extrados, intrados and unbent portions of and T23, T91 and T92

Table 9
Tensile properties at room temperature of T91, T92 and T23 large bends at room temperature.

Tensile tests at room temperature		Grade T23 OD×WT 76×12.5 mm, R/OD = 4.50				Grade T91 OD×WT 76×12.5 mm, R/OD = 4.50				Grade T92 OD×WT 76×12.5 mm, R/OD = 4.50			
		YS (MPa)	UTS (MPa)	E (%)	RoA (%)	YS (MPa)	UTS (MPa)	E (%)	RoA (%)	YS (MPa)	UTS (MPa)	E (%)	RoA (%)
ASTM A213 Minimum requirements		400	510	20	–	415	585	20	–	440	620	20	-
Unbent		560	730	22	71	630	780	21	66	540	620	21	76
Bent	Extrados	820	835	15	60	860	870	19	40	660	670	15	68
	Intrados	480	690	20	65	505	760	18	55	458	623	19	63

Table 10
Impact properties at room temperature of T91, T92 and T23 large bends.

Impact tests at room temperature		Grade T23 OD×WT 76×12.5 mm, R/OD = 4.50	Grade T91 OD×WT 76×12.5 mm, R/OD = 4.50		Grade T92 OD×WT 76×12.5 mm, R/OD = 4.50	
		Energy (J/cm^2)	Energy (J/cm^2)	Brittle (%)	Energy (J/cm^2)	Brittle (%)
Unbent		52; 45	250; 260	0; 0	205; 185	0; 0
Bent	Extrados	63; 56	236; 263	0; 0	140; 166	0; 0
	Intrados	36; 30	253; 256	0; 0	186; 190	0; 0

bends. Creep tests were performed at 550 °C for Grade T23 and at 600 °C for Grades T91 and T92.

Fig. 7A shows the creep-rupture properties of T23 bends at 550 °C, compared with the creep resistance of the unbent material [15]. Fig. 7B shows the reduction of area to rupture of specimens taken from extrados and intrados; the comparison with the ductility to rupture of unbent material is not given as all specimens from unbent zone are running.

Figs. 8A and 9A show respectively the creep-rupture behavior of T91 and T92 bends at 600 °C, compared with calculated isothermal reference lines for unbent material, as assessed by European Creep Collaborative Committee (ECCC) [16,17]. Figs. 8B and 9B show respectively the ductility to rupture of T91 and T92 bends, compared with ductility to rupture of specimens taken from unbent portions.

All creep specimens broke within gauge length, without anomalous failures.

The creep-rupture strength of intrados and extrados is similar, even if intrados areas of the bends offer a slighter higher creep resistance. Both extrados and intrados areas exhibited a creep resistance within the −20% scatter band of base material isothermal curve. The differences of creep-rupture ductility between extrados and intrados are evident: intrados portions of the bends reach higher values of reduction of area to rupture with respect to extrados portions of the same bend.

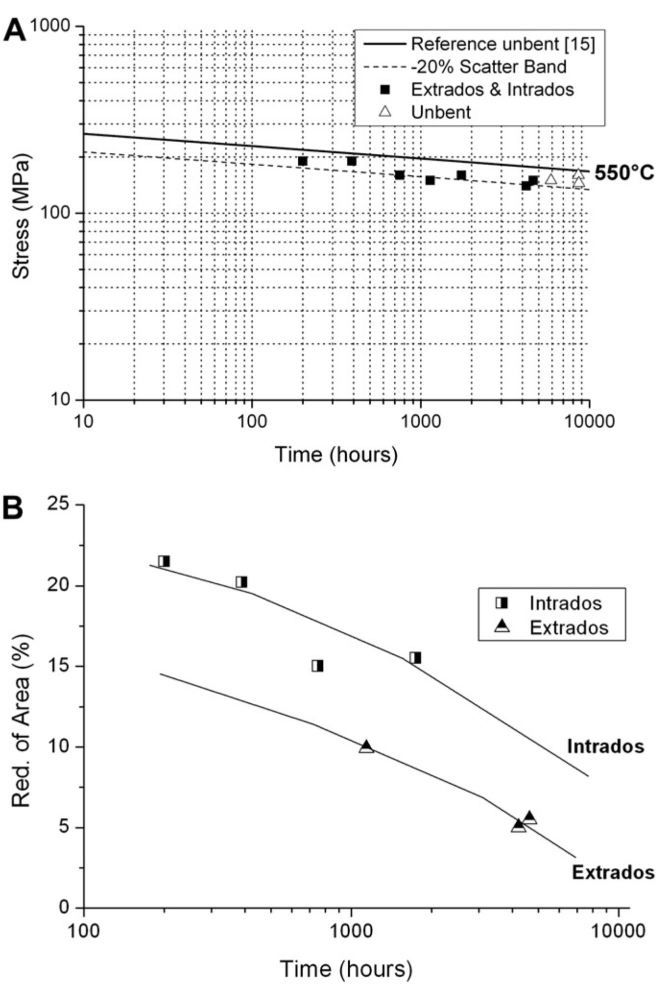

Fig. 7. Creep properties of T23 cold bend, OD×WT 76×12.5 mm, R/OD = 4.5, 180°, at 550 °C. Open points are running tests.

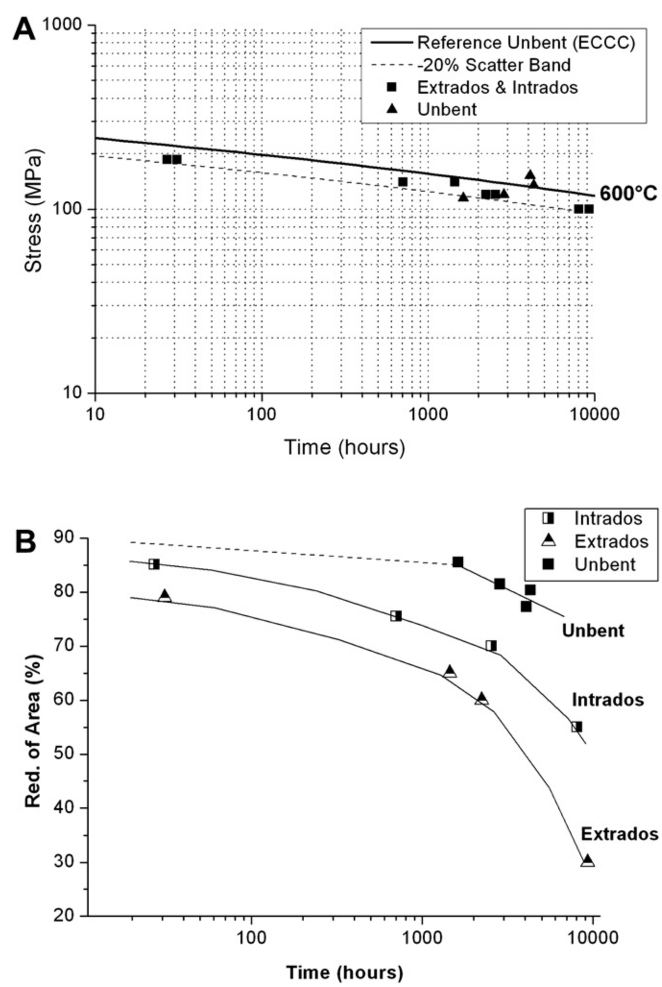

Fig. 8. Creep properties of T91 cold bend, OD×WT 76×12.5 mm, R/OD = 4.5, 180°, at 600 °C.

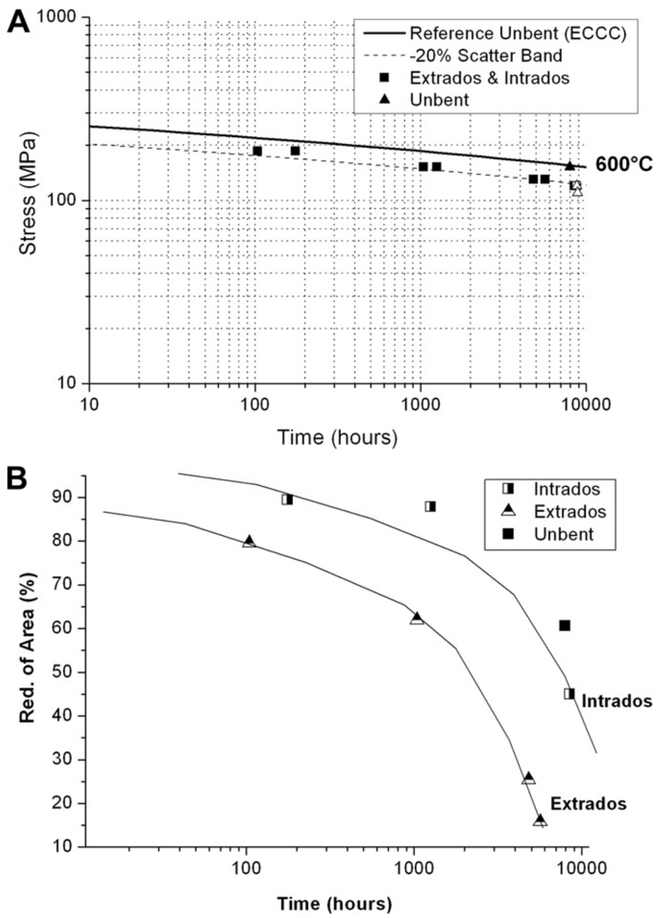

Fig. 9. Creep resistance of T92 cold bend, OD×WT 76×12.5 mm, R/OD = 4.5, 180°, at 600 °C. Open points are running tests.

7. Conclusions

A broad industrial cold bending program of tubes of Grades T23, T91 and T92 was performed in the range $1.0 \leq R/OD \leq 4.5$; the industrial window for a safe and repeatable cold bending of 9%Cr tubes was defined.

This paper integrates the current Codes for cold bending with recommendations for proper post bending heat treatments, in order to obtain a final component with the desired microstructure and mechanical properties, including optimum creep resistance.

PBHT parameters for severe cold bending conditions were defined and recommendations on temperatures and time were given.

Microstructural and mechanical properties at extrados and intrados positions were assessed and compared with properties of unbent materials.

Results from tensile tests showed differences between properties of extrados and intrados: the positive plastic deformation at extrados increases the Y/T ratio, while the plastic compression at intrados causes a reduction of the YS value compared with that of unbent material.

In all cases, the YS and UTS comply with ASTM A213 requirements. The high strain caused by cold bending affects negatively the rupture elongation.

Impact properties were also assessed. In all cases the cold deformed material impact toughness exceeds the PED requirements of 27 J at RT. The impact toughness of Grades 91 and 92 bends exceeds 140 J/cm^2.

Creep properties were assessed by means of specimens directly machined from extrados and intrados positions of real industrial bends. Creep-rupture strengths of intrados and extrados are similar, even if intrados areas of the bends offer a slighter higher creep resistance. Both extrados and intrados areas exhibited a creep resistance within the −20% scatter band of base material isothermal curve. In all cases, the creep-rupture ductility at the intrados was measured higher than that at the extrados.

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