Association of Metallurgical Engineers of Serbia
AMES

Scientific paper
UDC: 669.055-408

THE INFLUENCE OF MG CONTENT AND IMPURITIES IN AA5083 ALLOY ON THE PROPERTIES OF FLOW FORMED TUBES

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Received 11.10.2013
Accepted 06.11.2013

Abstract

Microstructure and mechanical properties of flow formed thin-walled tubes of AA5083 alloy from two metallurgical heats are presented. The influence of the chemical composition and applied reduction on the surface features and residual macro stresses were also studied. The residual macro stresses were estimated by ring method. The heat with higher content of alloying elements and impurities (Mg, Mn, Fe, Si) had higher strength of preforms as well as flow formed tubes. These tubes exhibit three times higher residual stresses, lower spinnability, and the large amount of the surface defects (microcracks). This behaviour is attributed to the inhomogeneous material flow during deformation and presence of impurities.
Keywords: AA5083, Chemical Composition, Tube, Flow Forming, Residual Stress, Mechanical Properties

Introduction

Flow forming or tube spinning is one of the most effective processes for manufacturing thin-walled seamless tubes. Cylindrical preforms rotate with a mandrel, while one or more rollers compress against the preform and move axially from one end of the preform to the other (Figure 1) [1]. In this process the metal is displaced axially along a mandrel, while the internal diameter remains constant. In this way, the wall thickness is reduced as material is encouraged to flow mainly in the axial direction, increasing the length of the workpiece. Depending on the direction of axial flow during the process, there are two basically different methods, forward and backward tube spinning. For forward forming the material flow in the same direction as traversing rollers, so the material's the undeformed part is driven ahead of the rollers.

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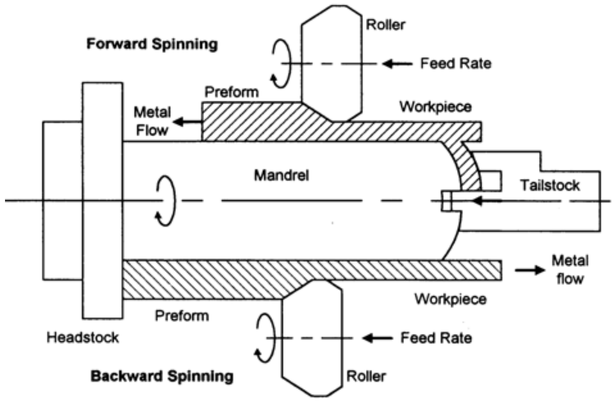


Figure 1. Schematics of forward and backward flow forming (tube spinning) [1].

This method is typically suitable for making high precision thin walled cylinders, such as rocket motor cases, hydraulic cylinders, high-pressure vessels and launcher tubes [2].

For backward forming the blank is pushed onto the mandrel and is held against the headstock and the axial thrust of the rollers pressed the preform against the mandrel. During flow forming, spun material flows under the roller in the opposite direction of the roller towards the unsupported end of the mandrel. Backward flow forming is especially suitable for long parts [3].

The main advantages of the flow forming technology for producing tubes are: low price of tubes, good surface quality, specially inside surface (R_a<0,63 μm), high accuracy (dimensional tolerances) thin wall with high strength can be obtain, and good surface roughness [3, 4]. The disadvantages of this technology are: high price of the modern (CNC) machines and low capacity. Therefore, flow forming is used for forming automotive, airspace and rockets parts.

Spinnability is defined as the maximum reduction in wall thickness that can withstand before either buckling or failure mode. It depends on material properties (microstructure and mechanical properties), as well as spinning process parameters (roller corner radius, roller angle, roller feed rate and mandrel revolution).

Spinnability can be divided into two categories depending upon the way to define the failure or fracture [1]. Macrospinnability is usually determined by two methods: first is based on step by step reduction of wall thickness (stepwise), and the second on the one-path spinning, where the wall thickness of the tube is gradually reduced from t_0 to t_f, where the tube failed [3]. Microspinnability is evaluated by optical, scanning or transmission electron microscope (OM, SEM, TEM, respectively). Using these technics some defects on the inside and outside tubes surface are observed, allowing the influence of microstructural features on the formation of the microcracks and there coalescence into macro or visible cracks to be evaluated.

Surface quality mainly depends on process parameters, preform dimension and material properties [5]. If these parameters are not adjusted, deformation is non-uniform and except the large roughness, wave-like, fish scale or crack type quality problem can occur [3, 6]. Some of these defects can decrease spinnability. The other problem also can occur, like burring and tearing, diametral growth and permature fracture.

The influence of chemical composition and microstructure of two AA5083 alloys on the mechanical properties and residual macro stresses of flow formed thin-wall tubes are examined in this paper.

Experimental work

Material

Extruded rods, 90 mm diameter, of AA5083 aluminum alloy from two metallurgical heats (A and B), were used in this study. The chemical composition of the rods is analysed by XRF and given in the Table 1.

Table 1. The chemical composition of AA5083 alloy, mass (%).

Heat	Mg	Mn	Si	Fe	Cu	Ti	Al
Heat A	4.5	0.22	0.22	0.24	0.04	0.014	Bal.
Heat B	5.19	0.34	0.34	0.35	0.04	0.024	Bal.

Preform design

The preforms were hot forged cups, annealed at 370°C/90 min (heat A), and 415°C/90 min (heat B), machining to final dimension: outer diameter D=98.0 mm, inner d=84.7 mm, wall thickness t=6.65 mm (Figure 2).

Flow forming

Flow forming was carried out on a Kieserling AS24.61 CNC spinning machine with two rollers. Process parameters during flow forming were: axial roller feed rate f=110 mm/min, mandrel speed n=110 rev/min, (feed rate 1 mm/rev). The flow forming of preforms of the heat A was conducted in two passes: first pass to 4,00 mm wall thickness, (r=40 %), and second to final thickness of 1.6 mm (r=60 %). Total reduction of wall thickness was r=76 %. The preform and flow formed tube of the heat A are shown in Figure 2.

The flow forming of preforms of the heat B were performed in two or four passes. Process parameters during flow forming in two passes were the same as during flow forming of the heat A. During flow forming in four passes reduction of 35 % and 40 % were applied with intermediate annealing at 415°C/70 min after each pass. The other process parameters were the same as heat A. The gap between mandrel and inner diameter of the preform was 0.10 mm and 0.25 mm for preform of the heat A and B, respectively.

Methods

Mechanical properties included tensile tests and Brinell hardness measurement (HB2.5/62.5/30″). Tensile tests were carried out at room temperature on a “Zwick” testing machine, using small ASTM tension specimen with a 25 mm gauge length.

Macro residual stresses were determined by 20 mm high rings which were cut from the tubes. The outer diameter, as well as thickness were measured at four points before and after cutting of the ring. For calculation the residual stresses the equation (1) was used [7]:

$$\sigma = \frac{E\alpha\delta(3D_{av} + 2\delta)}{3D_{av}^{2} \cdot D} \cdot \Delta D \qquad (1)$$

Where:
E -modulus of elasticity, [MPa],
α -coefficient, $\alpha = \frac{1}{1-\mu^2}$, μ-Poissons coefficient,
D_{av} - average diameter of the ring, [mm],
D - outer diameter of the ring, [mm],
ΔD - the difference D_{out} after and D_{out} before cutting, [mm],
δ - ring wall thickness, [mm].

Figure 2. Preform and flow formed tube of AA5083 alloy.

The microstructure evolution of AA5083 alloy, surface features of flow formed tubes was examined using stereo and optical microscope, as well as SEM (JEOL JSM 6610LV). Preparation of the metalografic specimens included traditional grinding and polishing techniques up to 1 μm diamond paste, electrolytic polishing (in perchloric acid) and etching in Barker's solution.

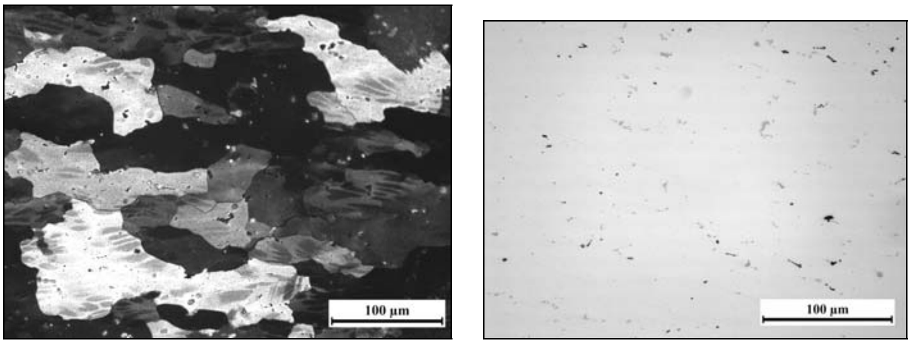
Results and discussion

Microstructure

Figures 3 and 4 illustrate the microstructures of the preforms from two metallurgical heats, processed trough hot forging and annealing. The microstructure is characterized by recrystallized coarse grains with homogenous distribution of the second phase particles in both A and B heat. However, the density of the second phase particles in heat B is much higher compared to heat A. It is attributed to the chemical composition. The higher content of alloying elements in heat B compared to heat A leads to greater amount of Mg, Mn, Si and Fe based second phase particles.

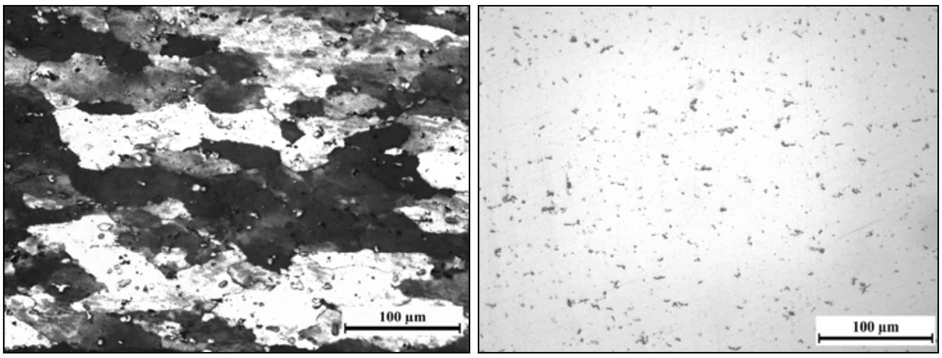
Mechanical properties

Results of mechanical testing annealed preforms are given in Table 2. The higher mechanical properties of the heat B is attributed to high content of Mg, Mn, Si and Fe. Magnesium has a strong solid solution strengthening effect on aluminum alloys, as well as manganese [8-10].



a) *b)*

Figure 3. OM. Microstructure of preform (heat A): a) grain structure, b) particle structure.



a) *b)*

Figure 4. OM. Microstructure of preform (heat B): a) grain structure, b) particle structure.

The higher content of Si and Fe also leads to greater amount of Si and Fe based second phase particles, what is confirmed by metallographic examination (Figures 3b and 4b). Therefore, strength can be attributed to strong strengthening effect of Mg and Mn, as well as particle strengthening.

Mechanical properties of the flow formed tubes after first and second (forth) pass are given in Table 3. The results obtained from these tests show that the flow forming has significant effect on the mechanical properties. The increase of the reduction leads to increase of hardness and UTS, while elongation decreases. The difference in the mechanical properties of the initial (annealed) condition between heat A and B is attained after flow forming tube in two passes. The specimens from heat B have some higher mechanical properties compared to heat A, what is expected due to higher mechanical properties in initial state (Table 2).

The tubes from the heat B, which formed in four passes and intermediate annealing, had lower hardness and strength and higher elongation compared to tubes formed in two passes, because the final reduction was 40%. The final reduction during forming tubes in two passes was 76 %.

Table 2. Mechanical properties of the annealed performs.

Heat	UTS (MPa)	A_5 (%)	Z (%)	HB
Heat A	247	35	51	64
Heat B	297	32	44	74

Table 3. Mechanical properties of the flow tubes.

Heat	First pass (r=40 %)			Second pass (r=60 %)*		
	UTS (MPa)	A_5 (%)	HV5	UTS (MPa)	A_5 (%)	HV5
A	345	16	110	401	11.9	125
B	388	8.8	120	433	10.5	135
B**				378	13.2	120

* Total reduction of wall thickness was 76 %

** Flow formed in four passes

The results of determination of macro residual stress in tubes of both heat A and heat B (formed in four passes) are given in the Table 4. The rings after cutting are presented in the Figures 5 and 6.

Table 4. Resudual stress in flow formed tubes, σ [MPa].

Heat A -C6	1	26.5
	2	35.9
Heat A -C61	1	38.1
	2	35.0
Heat B - 70	1	119.3
	2	113.5
Heat B -130	1	121.8
	2	100.2

The results indicate that residual stresses in tubes of the heat B formed in four passes are almost three times higher compared to tubes of the heat A. It is obvious that tubes of the heat B** (see Table 3) have lower UTS and higher elongation and that cannot cause significant increases in tensile residual stresses. It is supposed that high residual stresses in the tubes of the heat B** are caused by significant radial flow due to large gap between mandrel and and inner diameter of the preform. The gaps were 0.10 mm and 0.25 mm for preform of the heat A and B, respectively. The radial flow influences on increased ovality and decreased the wall thickness.

Figure 5. Tube rings (Heat A).

Figure 6. Tube rings (Heat B).

Surface quality

The surface quality after first and second pass of flow forming was observed by SEM. Typical appearance of the surface are shown in Figures 7 to 10. Roller marks produced on the tube surface after spinning are more pronounced on the B specimens. Therefore, the surface finish of B specimens is rougher than that of A specimens, after both first and second passes. The microcracks are visible on the outside surfaces, in both axial and circumferential direction (heat B). At higher magnification, the appearance of the outside surfaces is shown in Figure 10. These microcracks (deformation tongues) can eventually extend to form cracks. These surface defects degrade the surface finish and reduce the spinnability of the AA5083 alloy. It was previously reported that these deformation tongues and microcracks have little effects on the static tensile properties and hydraulic test, but they can initiate the fatigue cracks under dynamic loading and sever corrosion environment for thin-walled long tubes [1].

In some cases during flow forming in two passes (heat B) the cracks occurred in radial and axial direction (Figure 11). It is supposed that significant radial flow causes coalescence of the microcracks in primary radial crack. Due to plastic instability in the tube wall, the radial crack achieves the critical length and propagates in the axial direction, which is the main strain direction. Experiment has shown that AA5083 alloy of the heat B can be deformed up to 40 % reduction without micro and macro cracks, and than has to be annealed before next pass. Therefore, preforms of the heat B, wall thickness of 6.65 mm flow formed in four passes with intermediate annealing (415°C/75 min) up to wall thickness of 1.5 mm.

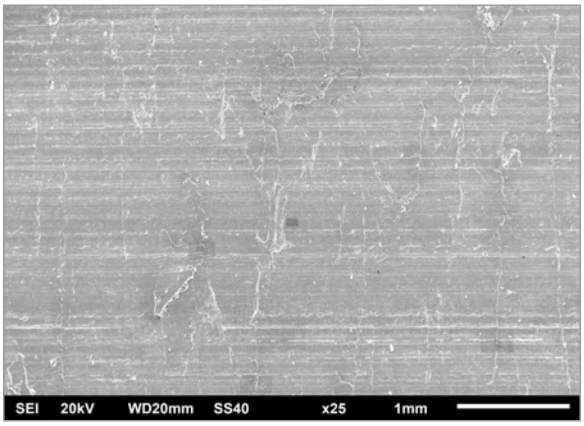


Figure 7. SEM. The surface of the flow formed tube after second pass (Heat A).

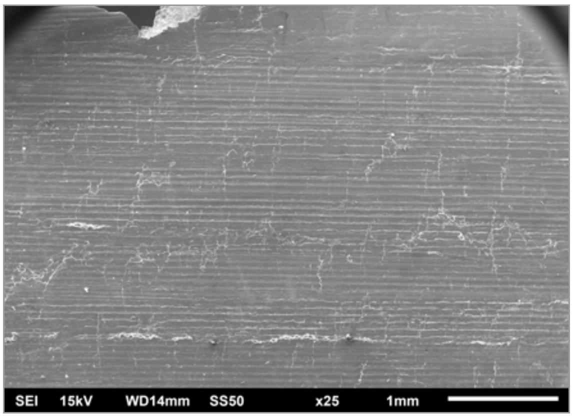


Figure 8. SEM. The surface of the flow formed tube after second (final) pass (Heat B).

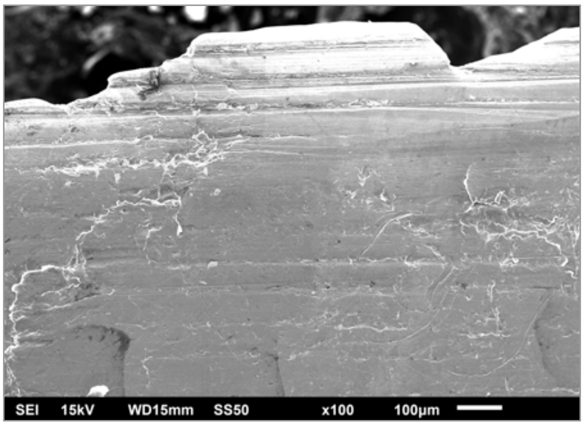


Figure 9. SEM. The surface of the flow formed tube in the vicinity of the fracture (Heat B).

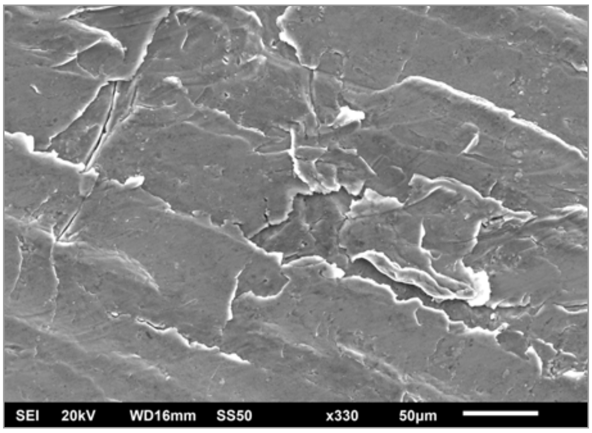


Figure 10. SEM. Detail from the Figures 8 at higher magnification.

Figure 11. Flow formed tube with radial and axial cracks problem.

Conclusion

Metallographic analysis revealed that heat with higher content of the alloying elements and impurities has higher content of the second phase particles. This resulted in higher mechanical properties of the preform and more intensive deformation strengthening during flow forming.

The large amount of the surface defects (microcracks) was observed on the flow formed tubes of heats with higher content of the alloying elements and impurities. This behaviour was attributed to the inhomogeneous material flow during deformation.

Larger gap between mandrel and inner diameter of the preform had the negative effect on the surface quality and micro and macro cracks appearance, as well as level of tensile residual stresses. The larger gap increased the radial flow of the material and decreases spinnability.

Intensive deformation strengthening due to higher density of the second phase particles, trace impurities and surface microcraks also reduced the spinnability of AA5083 alloy.

Acknowledgment

Experimental work was carried out in cooperation with „Sloboda“ Company Čačak and „Orao“ a.d. Bijeljina. The authors are indebted to Ministry of Education and Science for financial support through Project TR-34018.

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