Investigation of structure and properties of the welded joint obtained by friction stir welding of 1580 alloy hot-rolled sheets

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The weldability of hot-rolled sheets of alloy 1580 by friction stir welding was investigated. The test blanks were cut from 6.0 mm thick sheets, which were produced under industrial conditions by hot rolling of large-size ingots with dimensions of 300×1445×2200 mm at the “SGP Kvarto 2800” mill. Cards of 210×297 mm size were cut from the sheets and then roasted under two regimes: at 300 °C for three hours and at 350 °C for three hours. The work solved the problems of determining the mechanical properties of welded samples by tensile tests, investigating the structure of the weld by metallographic and electron microscopic methods, assessing the quality of the weld by radiographic analysis and technological tests for static bending. It has been established that the use of the friction stir welding method for joining 1580 alloy sheets allows to obtain high quality of the welded seam. Mechanical tests have shown that the strength of welded joints obtained by the FSW method is almost at the level of the base metal strength and does not depend on the localization of the fracture point. The samples after welding withstood bending tests without cracks along the entire length of the weld, both by bending at an angle of 150° with a mandrel, and after continued testing by static bending in a vise to parallelism of the sides.

Key words: friction stir welding, aluminum alloys, scandium, welded seam, mechanical properties, static bending, *X*-ray analysis, macrostructure.

DOI: 10.17580/nfm.2024.02.11

Introduction

The process of friction stir welding (FSW) is based on the use of heat generated by friction between the workpieces to be joined and the rotating tool (pin) of the welding machine. This energy transforms the metal of the workpieces into a plastic state, and the subsequent mixing of the bordering volumes of the two workpieces ensures the formation of a strong joint between them. This type of welding is widespread, especially for aluminum alloys that have a relatively low melting point [1–4]. Deformable alloys of the Al – Mg system (magnalia) are characterized by the combination of high weldability with corrosion resistance. Therefore, magnalias are extremely demanded in shipbuilding, railroad transportation, for the manufacture of chemical industry tanks, as well as in other industries that use structures that can be welded and at the same time successfully resist the harmful effects of aggressive media. Classical magnalias became the basis for the creation of a group of alloys (01570, 1580, etc.) to which rare earth metals (REMs) are added. It was shown in [5–7] that the best effect of small REM additives is observed when scandium is introduced into magnalium, which provides hardening of these alloys due to inhibition of migration of small-angle boundaries in the deformed and then in the roasted structure of alloys by dispersed particles of Al_3Sc phase with the size from less than 10 nm. The high efficiency of joint alloying of magnalium with scandium and zirconium is also noted. In [1] it is stated that in sheets made of 01570 alloy containing (wt.) 0.2% Sc and 0.1% Zr, the conventional yield strength is 300-320 MPa, which is almost two times higher than this index for 1560 alloy with the same content of Mg, but without Sc and Zr. Due to the high cost of scandium, the greatest interest for consumers is 1580 alloy, in which the content of this element is minimal and ranges from 0.05 to 0.14% (wt.). The structure and mechanical properties of 1580 alloy are already studied well enough [8, 9], the evaluation of its manufacturability at sheet forging is described in [10], and the characterization of the structure and properties of the weld seam at fusion welding are given in [11]. In works [12–25] the properties of aluminum alloys at FSW were investigated. However, the structure and properties of welded joints obtained by FSW of industrial, in particular, hot-rolled sheets from alloy 1580, have not been studied in detail so far, although such sheet semi-finished products for the manufacture of welded construction parts are widely demanded by industry.

Therefore, the ***purpose of the work*** was to study the structure and properties of the welded joint obtained by FSW method of 1580 alloy hot-rolled sheets. For this purpose, the following tasks were solved in the work:

– investigation of the structure and quality assessment of the welded joint;

– study of properties of samples obtained by the FSW method.

Materials and methods

Test blanks were cut from 6-mm-thick sheets of 1580 alloy obtained under industrial conditions by hot rolling of large-size ingots with dimensions of 300×1445×2200 mm at the "SGP Kvarto 2800" mill. Cards of 210×297 mm were cut from the sheets and roasted under two regimes: at 300 °C, for three hours and at 350 °C, for three hours, respectively, regimes M1 and M2. The chemical composition of the sheets is given in **Table 1**.

Table 1
Chemical composition of industrial sheets of 1580 alloy

Elements, % (wt.)										
Si	Mn	Mg	Cr	Zr	Sc	Fe	Cu	Zn	Ti	Others each/sum
0.08	0.56	5.00	0.15	0.11	0.10	0.20	0.03	0.15	0.02	0.01 / 0.02

Table 2
Welding tool design parameters and welding modes of 1580 alloy sheets

Shoulder / tip diameters, mm	16.0 / 6.0
Tip length, mm	5.7
Tip profile	Left-side helical groove
Welding speed, mm/min	250 ± 20
Welding tool rotation speed, rpm	450 ± 30
Welding tool axis tilt angle, deg.	2
Axial thrust, kN	20 ± 0.2

Table 3
Mechanical properties of 1580 alloy sheets in the roasted state under M1 and M2 regimes

Regime	Mechanical properties		
	σ_t, MPa	$\sigma_{0.2}$, MPa	δ%
M1	$405^{\pm5}$	$295^{\pm5}$	$16^{\pm1}$
M2	$385^{\pm5}$	$250^{\pm5}$	$18^{\pm2}$

The cards required for welding were cut from blanks of 100x295 mm, then their end edges were cut, and the surfaces of the edges to be welded and adjacent areas with a width of at least 40 mm on both sides were cleaned with wire metal brushes and degreased with acetone. The cards were assembled for welding by pressing the edges to be welded closely along the entire length of the joint.

The FSW process was performed on the USTP-T13F20 unit, and the configuration of welding tools and welding modes were selected according to the recommendations given in [1] for FSW of aluminum-magnesium alloys with thickness from 4 to 6 mm. The design parameters of welding tools and welding modes are presented in **Table 2.**

Welding was performed in one run in automatic mode with continuous recording of such basic welding parameters as current coordinate, axial thrust, welding speed and rotation speed of the welding tool. The welded seam at FSW was located across the rolling direction.

Assessment of weldability and quality of sheets included: radiographic inspection, examination of macrostructure in the cross-section of the welded seam, static tensile and static bending tests of welded samples.

Radiographic control was carried out according to GOST 7512–82, 20426–82 and ISO 17636-2-2017 using: ERESCO 65 MF3 *X*-ray apparatus, computer radiography system based on Duerr NDT HD-CR 35 scanner with X-Visor software, HD-IP Plus storage plates of 250×100 mm size, wire indicators of image quality (sensitivity standards according to GOST 7512–82) and duplex type image quality indicator according to ISO 19232-5. Illumination of the plates was carried out in one single exposure.

Bending tests were performed in accordance with GOST 6996–66 (ISO 4136-89, ISO 5173-81, ISO 5177-81) on two samples of each card. The first sample included the beginning, the second – the end of the welded seam, and the root of the weld was located in the tensile zone. The tests were performed at room temperature on a P-5 testing machine with a 10 mm diameter mandrel until a bending angle of 150° was reached, and then continued with static bending tests in a vise until the sides were parallel, unless a crack had previously appeared. In the first type of test, the rate of increasing load on the sample was 3 mm/min.

Tensile tests were conducted according to GOST 1497–84 on the LFM 400 kN machine, and the welded seam was located in the center of the working part of the sample.

The structure of the welded seam was studied using a Stemi 2000C stereomicroscope, an Axio Observer.A1m microscope and EVO 50 and KYKY-EM8100 electron microscopes.

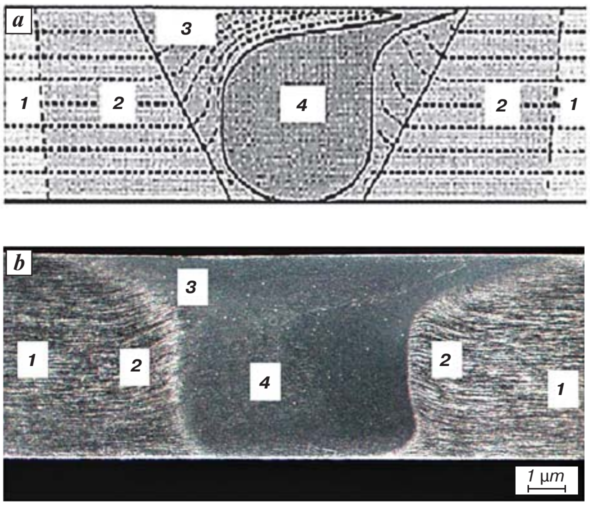
Results and discussion

Before welding, tensile tests of mechanical properties were carried out, the results of which showed (**Table 3**) that increasing the roasting temperature lead to a decrease in the strength of the sheets, but almost without a decrease in ductility.

The macrostructure of the welded seam after FSW had a typical picture, where, according to [1], the base metal zone (1), the zone of thermal influence (2), the zone of thermomechanical influence (3) and the weld core (4) are distinguished. **Fig. 1*, a*** shows the scheme of these zones and, accordingly, their location on the macrostructure of the welded seam of the studied sample (**Fig. 1, *b***).

Analysis of the macrostructure of the welded seam showed that the area of the core *4* is stretched in the direction of rotation of the welding tool and repeats the outline of its working part trajectory. On the top right, relative to the core, according to the terminology of work [4], there is a zone of "overlap", and on the top left there is a zone of "withdrawal". In the core itself, the result of intensive mixing of the material of the two workpieces is observed, which led to the formation of an ultrafine-grained equiaxed structure. The grain size in this zone is approximately by an order of magnitude less than in the region of the base metal. On both sides of the core there are thermal influence zones *2*, which are not affected by the welding tool and in which the heredity in the form of fibrous partially recrystallized structure obtained by rolling and subsequent roasting is preserved. **Fig. 1**, ***c*** shows the transition section of core zone *4* to thermal influence zone *2*.

Fig. 2 shows the elemental composition of base metal and weld zone excess phase inclusions obtained by micro-*X*-ray spectral analysis (EDS) using an energy dispersive spectrometer.



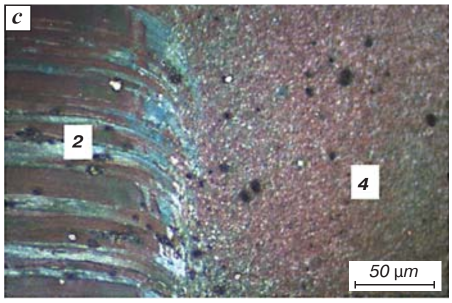
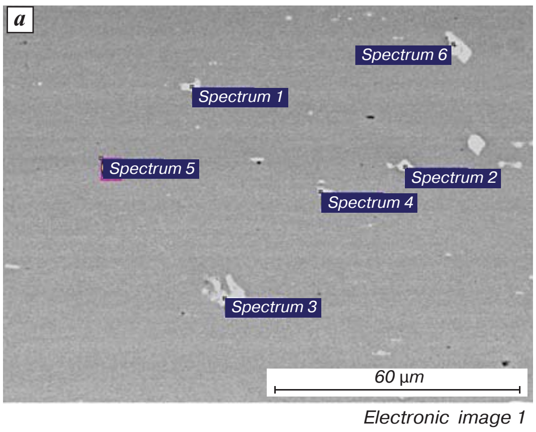
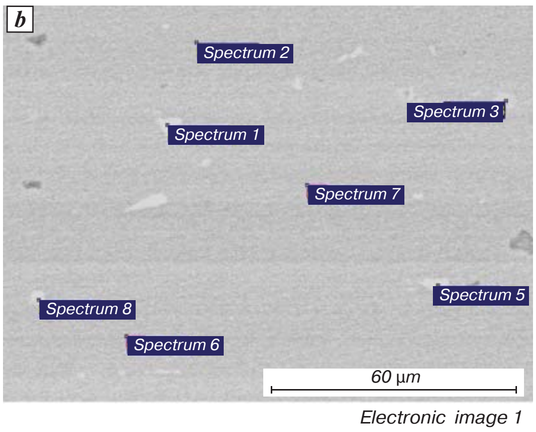


Fig. 1. Scheme (*a*), macrostructure (*b*) and border of transition between zones 2 and 4 (*c*) of the welded seam obtained by FSW method of 1580 alloy sheets:
1 – zone of the base metal, *2* – zone of thermal influence, *3* – zone of thermo-mechanical influence, *4* – weld core



Wt. %

Spectrump	Mg	Al	Si	Mn	Fe
Spectrum 1	5.49	75.90	0.00	6.05	12.56
Spectrum 2	2.55	72.06	4.22	8.47	12.70
Spectrum 3	2.32	72.07	2.88	7.83	14.89
Spectrum 4	7.05	89.82	0.00	1.10	2.03
Spectrum 5	5.59	94.41	0.00	0.00	0.00
Spectrum 6	2.25	77.42	0.00	8.01	12.32



Wt. %

Spectrum	Mg	Al	Si	Mn	Fe
Spectrum 1	0.00	72.50	0.00	16.28	11.22
Spectrum 2	5.29	94.71	0.00	0.00	0.00
Spectrum 3	11.12	78.42	0.00	10.46	0.00
Spectrum 5	0.00	69.87	0.00	10.53	19.60
Spectrum 6	6.09	93.91	0.00	0.00	0.00
Spectrum 7	4.43	95.57	0.00	0.00	0.00
Spectrum 8	0.00	70.38	5.70	11.95	11.97

Fig 2. Electronic image and EDS results of the base metal (*a*) and weld seam (*b*) zones of 1580 alloy workpiece after STP welding

The studies showed that the excess phases in the base metal zones and in the welded seam contain the elements Al, Mg, Mn, Fe, Si, which corresponds to the phases normally present in the structure of 1580 alloy [9]. In addition, when analyzing the macrostructure of the welded seam, no internal defects in the weld were detected in it.

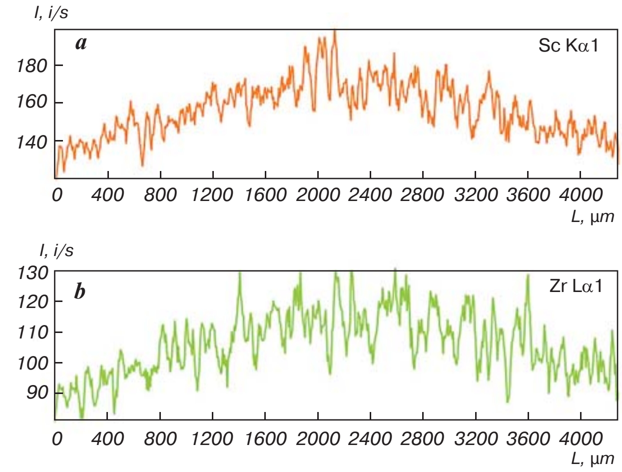
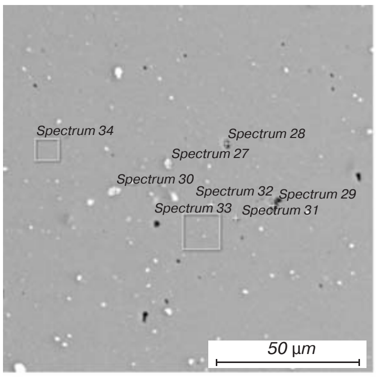


Fig. 3. EDS results of Sc (*a*) and Zr (*b*) distribution along the length of the core zone during friction stir welding of 1580 alloy

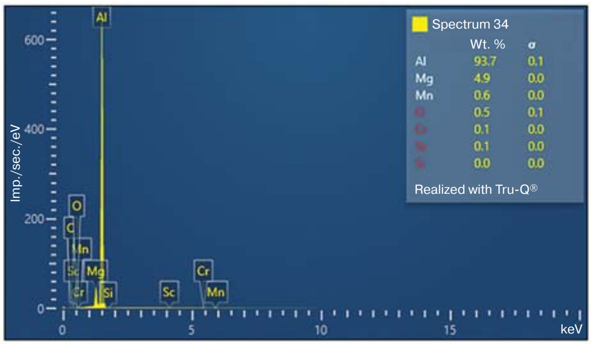
The distribution in the weld core zone of small Sc and Zr additives was performed using a KYKY-EM8100 microscope and an Oxford Instruments EDS energy dispersive spectrometer. A 4 mm long line running along the weld core was selected for analysis. The obtained distribution of elements is presented in **Fig. 3**. The maximum amount of scandium and zirconium was found in the center of the weld core, which is confirmed by the fact that the *X*-ray intensity (I), of these elements, defined as the ratio of the number of pulses (i) per second (s), measured along the length L of the central zone of the weld core was higher compared to the boundaries of the core zone.

The electronic image of the weld core area, showing the spectra of individual points and the elemental content of this zone, is shown in **Fig. 4, *a, b***. Spectra 31–34 correspond to the solid solution regions. It is shown that the content of Sc in the solid solution is in the range of 0.08–0.11%. The distribution maps of Sc and Zr in the center of the weld core indicate their uniform distribution in the studied area, **Fig. 4, *c, d***.

High quality of hot-rolled sheets welded seam was confirmed by radiographic control, which did not detect

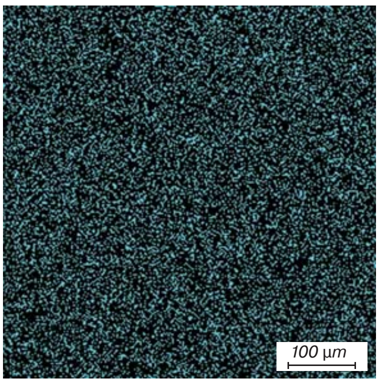


a

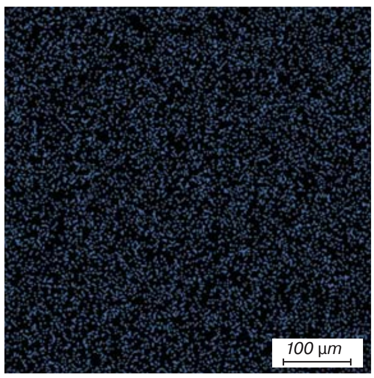


Spectrum	Mg	Al	Si	Sc	Cr	Mn	Fe	Zn
Spectrum 27	1.93	73.96	168	0.03	0.82	7.30	13.70	0.28
Spectrum 28	4.05	70.40	10.23			0.39		
Spectrum 29	28.68	39.05	17.77			0.17		
Spectrum 30	3.85	85.79	0.70	0.06	0.40	3.00	6.01	0.19
Spectrum 31	4.78	92.32	0.04	0.11	0.20	1.05	0.94	
Spectrum 32	4.87	93.29		0.08	0.14	0.53	0.18	0.22
Spectrum 33	4.90	93.53	0.04	0.10	0.13	0.55	0.13	
Spectrum 34	4.94	93.69		0.11	0.14			

b



c



d

Fig. 4. EDS results (*a*, *b*) and distribution maps of Sc (*c*) and Zr (*d*) in the core zone during friction stir welding of 1580 alloy, wt. %

Table 4
Tensile strength (σ_t), coefficient of strength (K^w) and fracture location of FSW-welded hot-rolled industrial sheets of 1580 alloy in M1 and M2 roasted condition, determined by tensile test

Regime	σ_t, MPa	Destruction site	K^w
M1	$410^{\pm 5}$	Base metal	1.0
M2	$385^{\pm 3}$	Base metal, welded seam, thermal influence zone	0.99

a

b

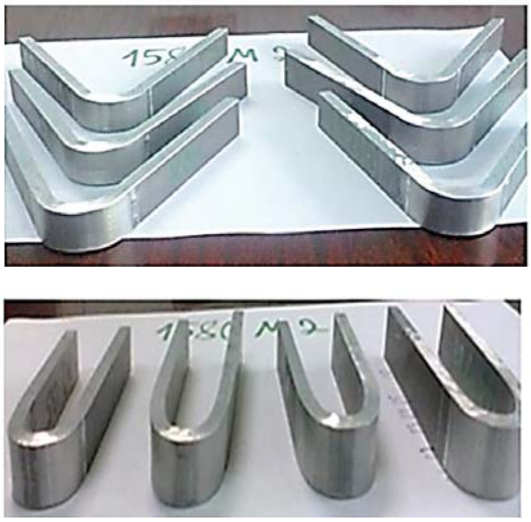


Fig. 5. Appearance of welded joint samples obtained by the FSW method from 1580 alloy sheets after static bending tests with a mandrel up to 150° (*a*) and after continued static bending tests in a vise to parallelism of the sides (*b*)

cracks, flaws, delaminations and other internal defects in welded samples.

The test results of mechanical properties of samples after FSW are presented in *Table 4*, where K^w is the strength coefficient of welded seam.

External inspection of the samples showed that in the M1 condition all samples failed along the base metal, and in the M2 condition they failed along the base metal, along the thermal influence zone and along the welded seam. At the same time, the strength of welded joints obtained by FSW of hot-rolled sheets is almost at the level of the base metal strength and does not depend on the localization of the fracture site, which is quantitatively confirmed by the values of the weld strength coefficient $K^w = 0.98–1.0$.

All samples withstood static bending tests with a mandrel at an angle of 150° without failure (**Fig. 5, *a***), as well as after continued static bending tests in a vise until the sides were parallel (**Fig. 5, *b***).

Inspection of the samples of both types also showed the absence of defects in the root zone of the seam.

Conclusion

The friction stir welding method was used to obtain welded joints of industrial hot-rolled sheets 6.0 mm thick of alloy 1580, roasted by two regimes: at 300 °C, for three hours and at 350 °C, for three hours. *X*-ray inspection of all samples and analysis of their macrostructure showed the absence of cracks, delaminations, non-flakes and other types of internal defects in welded samples, which indicates the high quality of weld formation in the process of welding by friction stir welding.

X-ray inspection of all samples and analysis of their macrostructure showed the absence of cracks, delaminations, discontinuity flaw and other types of internal defects in welded samples, which indicates the high quality of weld formation in the process of friction stir welding.

All samples withstood bending tests without cracking along the entire length of the weld, both by bending to an angle of 150° with a mandrel, and after continued testing by static bending in a vise to parallelism of the sides. Thus, hot-rolled industrial sheets of alloy 1580 can be used to produce friction stir welding joints.

The work was carried out by the laboratory of low-carbon metallurgy and power engineering within the framework of the state assignment of "Siberian Federal University" of the organization-participant of REC "Yenisei Siberia" within the framework of the national project "Science and Universities", project number FSRZ-2024-0004.

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