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ON THE Al-Mg ALLOY SHEETS FOR AUTOMOTIVE APPLICATION: PROBLEMS AND SOLUTIONS

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ABSTRACT

Aluminium alloys suitable for automotive application were reviewed briefly as well as the reasons for the future wider application of Al-Mg type alloys. Basic problems related to the limited consumption of Al-Mg type alloy sheets in automotive applications as the appearance of stretcher-strain markings and paint baking - induced softening considered. Also, the current knowledge on the promising approaches to overcome those problems was estimated.

Key words: Al-Mg alloys, automotive application

1. INTRODUCTION AND GENERAL CONSIDERATIONS

Considerable efforts devoted to replacing steel with aluminum alloys in manufacturing auto bodies [1-4] because the promising weight saving, ensuring fuel consumption and pollution reduction, or even improvement of certain safety and driving performances [4]. The aluminium alloys also have some advantages such as a high corrosion resistance [1, 5] or good weld ability [1]. Since 1920, after the first aluminium based alloy sheets introduced into car body construction (Rolls-Royce and Pomeroy) [2], the attempts to introduce aluminium alloys to the construction of car bodies were changeable. Now days, when the requirement for environment protection and energy saving are very strict, the interest for weight saving in all kinds of transport vehicles is significant more than ever in the past.

In the use of Al alloys for car bodies, initially the predominant role was given to 2036-T4, copper based alloy and the 5182-O, magnesium based alloy by most car producers both in America and Europe [1, 6]. Using these alloys the required rigidity of car bodies was achieved by mounting 20%-40% thicker Al sheets in respect to the usual mild steel sheets. The 2036 alloy is heat – treatable (hardenable by aging) and it was used for outer body parts, while 5182 sheets due to their particular surface relief developed during Lüdering (due dynamic strain aging) were rather suitable for inner body elements. The 5182 alloy is non-heat-treatable, and hardenable by the Mg solute as well as by deformation. The two alloys have a quite different response during curing the painted car bodies. So, during paint baking the 2036 alloy at around 180°C considerable strengthening effects can be achieved due the precipitation hardening. At the same conditions the strength of Al-Mg alloys in a similar extent decrease after a 5-7% pre-deformation. Further, it was recognized that the combination of these two alloys is unfavorable as far as recycling is concerned, due to the relatively high copper content in 2036 alloy. Searching for the alloy more compatible in recycling with 5000 type, the AlMgSi alloys (6000-heat-tretable series) were chosen. The basic response of 5000 and 6000 alloy sheets in paint baking is shown in Fig.1. It is obvious that after annealing at 200°C/30' the heat-treatable 6009 alloy considerably hardened (the precipitation sequence is quite complicating [7]), while the 5182 one in a similar extent softens. The most frequently used alloys today and their chemical compositions are listed in Table 1. Summary of the main characteristics and applications for the aluminium alloys used in car body constructions are given in Table 2. Some recent analyses [8] shown up a recommendation that the further automotive application of aluminium should be focused to the development of low cost, non-heat-treatable aluminium alloy body sheets. Namely, it was estimated that there is potential for at least 10% lower costs for the non-heat-treatable alloys compared to the heat-treatable types. Such a considerations make attractive the further research and improvement of the highly alloyed and high strength Al-Mg sheets. So, the objective of this work is comprehensive consideration of the basic deformation behavior of Al-Mg alloy sheets, current applicability restrictions and possible solutions for overcoming them.

Table 1. Compositions of some aluminium alloys used for automotive panel applications (wt.%) [9]

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
5182-O	0.20	0.35	0.15	0.2-0.5	4.0-5.0	0.10	0.25	0.10
5754-O	0.40	0.40	0.10	0.50	2.6-3.6	0.3	0.2	0.15
5030-T4	0.25	0.40	0.50	0.20	3.5-5.0	0.2	0.1	0.10
2036-T4	0.50	0.50	2.2-3.0	0.1-0.4	0.3-0.6	0.10	0.25	0.15
6009-T4	0.6-1.0	0.50	0.15-0.60	0.2-0.8	0.4-0.8	0.10	0.25	0.10
6010-T4	0.8-1.2	0.50	0.15-0.60	0.2-0.8	0.6-1.0	0.10	0.25	0.1
6016-T4 (Ac-120)	1.0-1.5	0.5	0.2	0.2	0.25-0.6	0.1	0.2	0.15

Table 2. Aluminium car body sheet alloys [10]

Alloy	Advantages	Disadvantages	Examples
Al-Mg AA5xxx	- high formability - good corrosion resistance - medium to high strength	- Lüders lines, "A" and "B" - SCC sensitive after exposure to temp. ~ 100°C - softening after annealing	AA5754, AA5182 for inner body parts
Al-Mg-Cu AA5xxx	- as above but also additional age hardening	- as above, but only "B" Lüders lines	AA5030, AA5032 for outer body parts in Japan
Al-Mg-Si AA6xxx	- high formability - good corrosion resistance - strengthening by aging	-	AA6016, AA6022 standard alloy for outer body parts
Al-Mg-Si-Cu AA6xxx	- as above but higher strength	- as above but decreased corrosion resistance	AA6009, AA6111 outer/inner body
Al-Cu-Mg-Si AA2xxx	- high formability - strengthening by aging	- decreased corrosion resistance	AA2008, AA2036 only used in USA

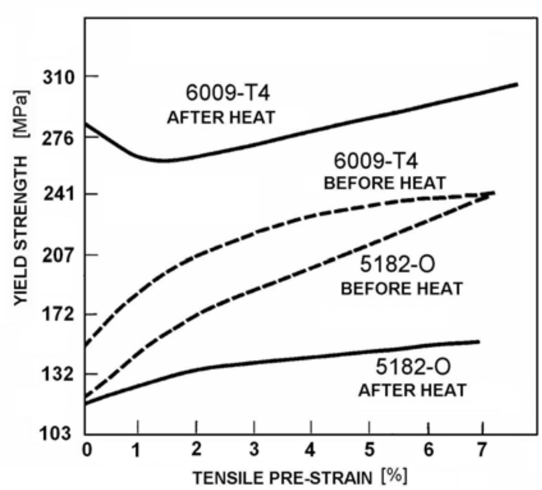


Fig. 1. Effect of stretching and aging (30' at 204°C) on yield strength of 5182-O and 6009-T4 alloy sheets [6].

2. Al-Mg ALLOY SHEETS FOR AUTOMOTIVE APPLICATION

The Al-Mg alloys have a favorable formability, as due solution hardening they can achieve high strength and high strain hardening ability, which enable a stable behavior in the complex forming operation, reducing the further material flow in the locally strained regions [11,12]. Such behavior is improved in alloys with higher Mg content. Besides the favorable forming behavior, the present solute atoms can induce some harmful surface appearance of produced auto body parts.

Surface appearance. In Al-Mg alloys the dislocation reactions with solute Mg atoms, i.e. the dynamic strain aging (DSA), is the main source of unstable plastic flow during the uniaxial tension test. This unstable flow in alloys with more than 2% magnesium [7] appeared as a yield point elongation, know as a Lüders elongation. This inhomogeneous deformation occurs within the first few percent of straining when the stress is constant. After that – at higher strains, the DSA is manifested as a discontinuous or serrated yielding. Flow curves for a highly alloyed AlMg6.5Mn alloy sheet, after different treatment and strain rates are shown in Fig.2. The Lüders elongation plateaus and serrations or discontinuous yielding ranges are very clear. Both Lüdering and serrated yielding during uniaxial stretching cause the appearance of specific surface relief known as "A" ("flamboyant") and "B" ("parallel bands") type surface markings, respectively. Those markings and the appropriate parts of the flow curves are sown in Fig.3. The "A" stretcher markings are the most harmful as the appropriate roughness valleys developed within the first percent of straining can be more than 100 μm deep [14]. The roughness created by "B" marking never exceeds 10 μm [15]. So, the "A" type stretcher markings are the main problem which reduces the application of a higher strength (highly alloyed) Al-Mg sheets only to the production of inner panels in car bodies

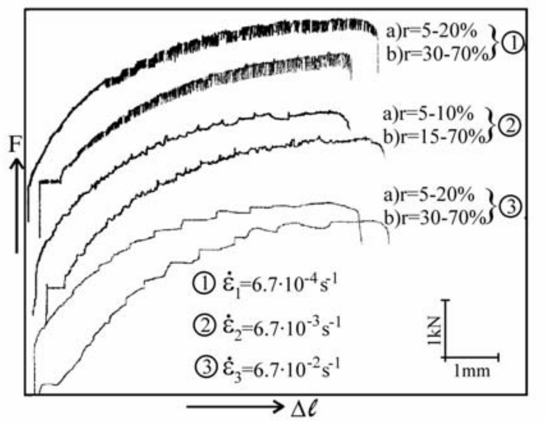


Fig. 2. Load extension curves for the AlMg6.5Mn sheets at different strain rates and working conditions. [13]

During biaxial stretching the surface appearance seems to change dependently on the degree of biaxiality. Namely, after stretching blanks of different widths across the hemispherical punch in a hydraulic press a net of parallel bands can be seen at the surface of the nearly uniaxially stretched samples which are “B” type (Fig. 4.a) without any traces of “A” type. The surface banding completely disappeared in the case of equibiaxially stretched sample (Fig.4.b). It is important to note that in the samples even nearly uniaxially stretched over the punch, the very harmful “A” type (“flamboyant” type) surface markings could not be observed. The latest result (Fig.4) indicates that the surface appearance can be influenced in a great deal by changing the stress state, and that the harmful stretcher lines disappear in equibiaxial stretching. At this stage of the knowledge it is not clear how the stress state influence the DSA, inhibiting the appearance of the surface relief development under equibiaxial stretching. The meaning of the considered surface relief effects are clearly shown in Fig.5 at the photographs of real fender produced from AlMg4.5Mn0, 5 sheets, for the "ZASTAVA" car. The stretcher-strain lines developed are not uniform over the whole fender, but it seems dependent on the imposed stress state (the biaxiality varying over the fender during the pressing operation).

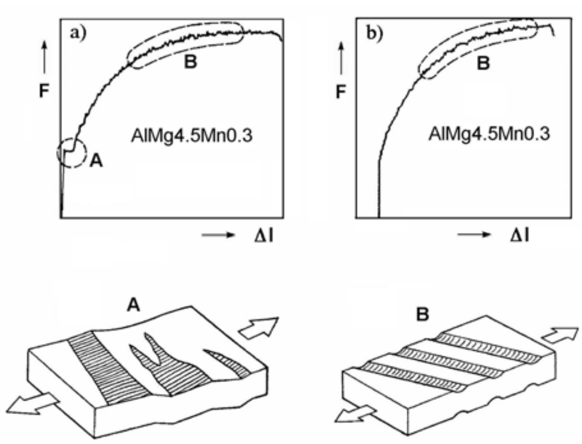
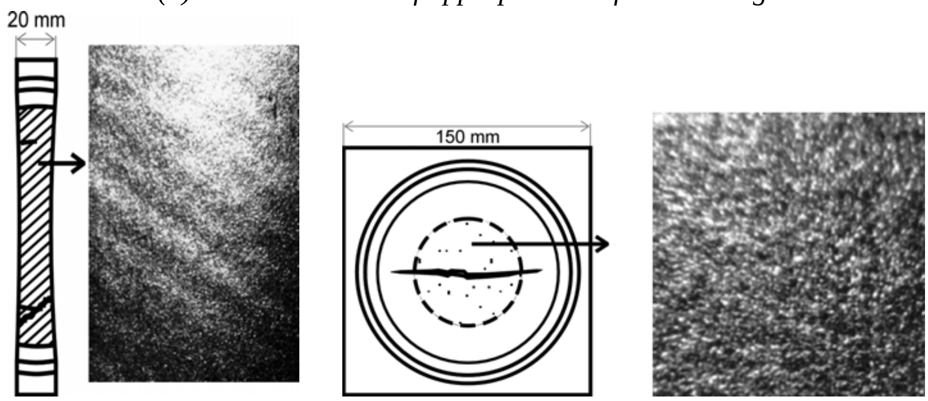


Fig. 3. Uniaxial stress-strain curves with Lüders elongation (a) or only with serrated yielding straining range (b) and the sketches of appropriate surface markings.



a) b)

Fig. 4. Photographs and sketches for the samples stretched over hemispherical punch in near uniaxial (a) and equibiaxial tension (b) [16].

Considering the problem how to suppress the Lüders elongation it is worth of note that applying some specific thermo-mechanical treatments as a combination of low cold rolling reductions and annealing (Fig.2), the Lüders elongation was completely suppressed. The grain size distributions for the applied working conditions are given in Table 3.

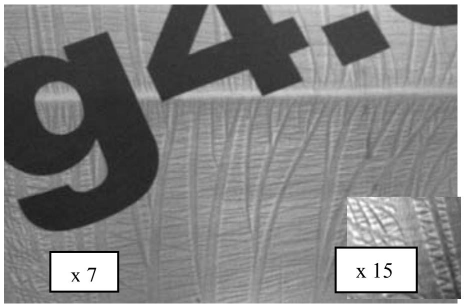


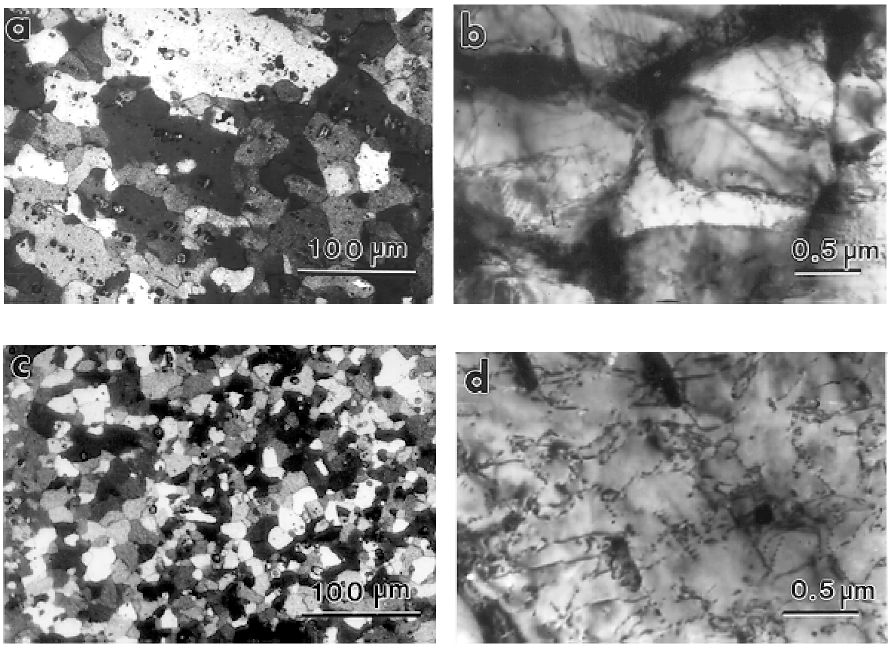
Fig. 5. Photographs of the surface appearance at the fender made of AA5182 alloy sheet. [17]

Table 3. Average grain diameters after different reductions and annealing at 320°C/3h. [13]

r (%)	d_{av} (μm)	r (%)	d_{av} (μm)
0	30.9	30	30.4
5	35.1	40	23.2
10	38.4	50	21.8
15	40.5	60	20.6
20	35.4	70	16.1

Micrographs revealing the structures for the samples with no yield point elongation – after 10% deformation and with pronounced yield point elongation after 60% deformation are shown in Fig.6. The grain structure after 10% imposed reduction and annealing (Fig.6a), is a result of additional grain growth in the basic structure retained from the as received-annealed condition. Also subgrains were generated by such a low deformation (Fig.6b). Besides the additional hardening brought by the presence of 1.0-1.5 μm sized subgrains [13] it was assumed that the higher dislocation density with weaker solute drag, as the Mg atmospheres become more dilute, is the main reason for vanishing the yield point elongation. It should be emphasized that grain sizes after those low reductions and annealing where ranged to 35÷40μm (Table 3), what is rather close to the grain sizes found in AA5754 alloy with Mg=2.6 - 3.6% when the Lüdering was suppressed [6]. On the other hand it is considerably finer than it was found for the AA5182 alloy with Mg=4 - 5%, when zero Lüders elongation was experienced after attaining the average grain diameter above 100μm [11]. Such a behavior is rather clear if it is taken into account that the Lüders elongation increases by increasing the Mg content [11]. This result, in respect to some other considerations [18] that the free slip distance during Lüdering is equal to the grain size, lead to the assumption that the subgrains doesn't restrict the free slip distance.

The general rule of the grain size effect on the appearance of the yield point elongation was established many years ago, estimating that at grain sizes above 50μm the Lüders lines are eliminated or enough suppressed [19]. This result unfortunately didn't bring a final solution, as a coarse grained structure is mostly unacceptable due the lover strength, lower biaxial ductility with the pronounced surface roughness. Also, in some cases is unacceptable the technologically demanding procedure to achieve such a range of coarse grains. Namely, the grain growth is inhibited in the presence of dispersoids formed in homogenization or hot rolling [12], specially in the presence of Mn bearing particles (Al_6Mn) [20] which are typical for most of Al-Mg type alloys.



Figs.6a to d. Optical micrographs of grain structure for samples deformed 10% (a) and 60% (c), and annealed at 320°C/3h, and TEM micrographs of the corresponding dislocation substructures showing: subgrains (b) and randomly distributed dislocations (d), respectively.[13]

Having in mind the basic demand to control the DSA, it was assumed that altering the temperature and strain rate in shaping operation is a good approach for prevention surface relief formation [21]. In other words serrated yielding occurs only within specific strain rate and temperature ranges. In Fig. 7. the regions marked C, A+B, and A are regions where different types of serrated yielding occur on the stress - strain curve. The regions marked zero are where no serrated yielding or Lüdering occur. This figure shows that at higher temperatures, higher strain rates can be achieved in the forming operations without formation Lüders bands.

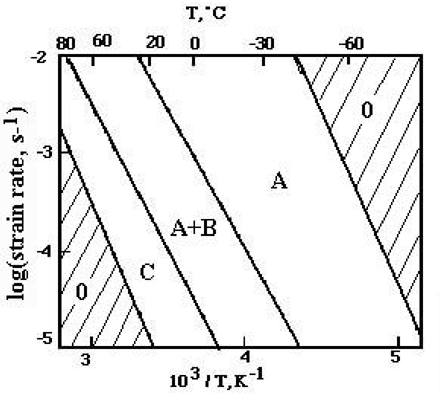


Fig. 7. Temperature and strain rate dependence of serrated yielding which results in Lüders band formation [21].

Softening. Important point in making car bodies is the paint baking sequence inducing softening of the parts made by Al-Mg sheets, what is the second unfavorable property for their automotive application. The softening effects are well documented [7, 11]. Fig.8 shows the softening responses in the AA5182 sheets. As was already mentioned the heat-treatable alloys were chosen because of their ability to overcome this problem by precipitation at baking temperatures, which are ranged to 160°-180°C, usually in 30'. However, due to introducing some new materials in car bodies and reasons of environment protection, when water-based automobile paints are expected to be introduced, the baking temperatures seems to be shifted to the range of lower temperatures as 140°C-170°C [22, 23]. On the other hand those temperatures appeared to be not sufficient for effective precipitation hardening of AA6000 type alloys.

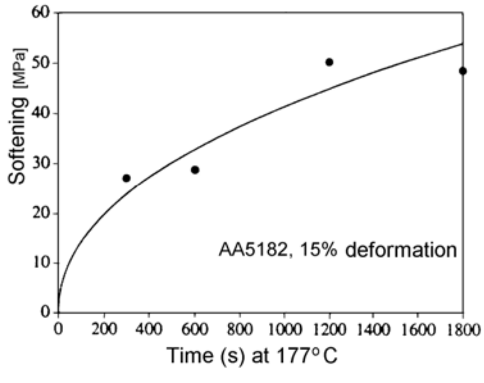


Fig. 8. Aging time influence on the yield stress decrease (softening) in AA5182 sheets [7].

The current efforts to overcome the softening problems in Al-Mg alloys resulted with the idea of adding a small amount of copper to the Al-Mg alloys, i.e. the development of Al-Mg-Cu type alloy, which could additionally harden by precipitation during paint-baking [24-29]. This alloy has a low Cu/Mg ratio: 0.14-0.29 in wt%. Basically the AA5182 alloy was additionally alloyed with 0.5% Cu, appearing as new alloy designated as AA5030 (the chemical composition is given in Table 1.). Such alloy should be pertinent for solution of both the necessary hardening effects at reduced baking temperatures and prevention of the softening effect typical for the classical Al-Mg alloys.

The mechanical properties for the most often used Al alloys are given in Table 4. It should be noted that two 5030 alloys presented, first is the original Kobe produced one [9] and the second - experimental one developed and produced by IMPOL-SEVAL Rolling Mill in cooperation with the Faculty of Technology and Metallurgy of the Belgrade University. In table 4. the bake hardening is also shown up by listing the yield stress values after simulating baking conditions. In the case of IMPOL-SEVAL type 5030 alloy sheet the range of yield stresses and elongations are given, which have been achieved by applying a different thermo-mechanical treatments.

Table 4. Mechanical properties of some aluminium alloys used for automotive panel applications, including [9]

Alloy	R_{p02} *[MPa]*	R_{p02}* *[MPa]*	R_m *[MPa]*	e_t *[%]*
2036-T4	185	179	338	24
6009-T4	131	234	220	25
6010-T4	186	255	290	24
6016-T4 (Ac-120)	137	220	248	29
5182-O	130	-	276	26
5030-T4 Kobe	138	172	276	30
5030-T4 Impol-Seval**	125-140	155-170	280-287	21-26

R_{p02}* - yield stress after paint baking

** Under development and current laboratory testing

Stress corrosion cracking (SSC) susceptibility. The Al-Mg alloys containing more than 3% Mg become susceptible to SSC due the supersaturation of solid solution and increased tendency of Mg atoms to precipitate at grain boundaries as a highly anodic β-phase (Mg_5Al_8) [30-33]. The influence of the thermomechanical treatment on the SSC properties in AlMg6.8 type alloy, estimated by the elongation loss (El_{loss}=1-(El_{SCC}/ El_{air})x100%) in slow strain rate tension test in corrosive environment, is shown in Fig.9 [34]. The tested specimens were sensitized for 7 days at 100°C after the applied treatments. It is apparent that the low temeprature annealing is beneficial in respect the SSC, when discontinuous β-phase precipitates were experienced in a globular form throughout the grain structure [34]. In the deformed and fully annealed structures the β-phase was found precipitated along the planes of localized deformation and grain boundaries, respectively.

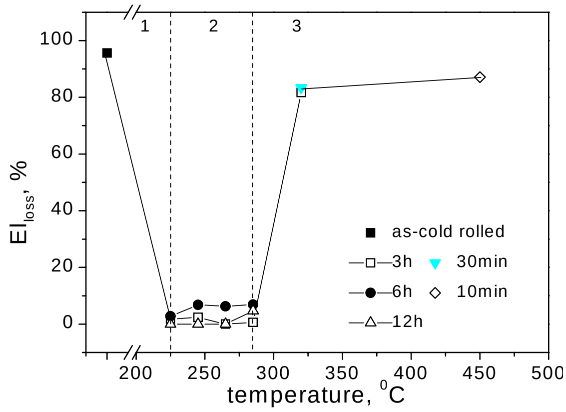


Fig. 9. The elongation percentage loss, El_{loss}, for the various specimens after sensitization. [34]

CONCLUSIONS

The Al-Mg type alloy sheets are cost-effective very promising material for automotive application. The most important obstacles for their wider applications are related to the bed surface appearance developing during the forming operations and to the softening effect coming into play in the paint baking sequence of car bodies.

The harmful surface appearance is closely related to dynamic strain aging (DSA) due the reactions of Mg atoms with mobile dislocations. So, the solution for suppressing the DSA is firstly defined as a particular temperature – strain rate conditions necessary for performing the forming operation when the serrated yielding vanishing. For avoiding the harmful "A" type stretcher strain markings (developing during the yield point elongation), the coarse grain size was found beneficial. This effect is limited, as the coarse grains can cause other problems in the forming operations. The specific – low reduction treatment of the annealed sheet material (characterized with higher density of mobile dislocations) seems to be promising in suppressing the yield point elongation. Finally, it was also noticed that the surface banding is stress state dependent and that it can disappear in equibiaxial stretching.

The softening effect as a natural consequence of the recovery process in the deformed parts during paint baking was prevented introducing a little amount of copper, which can produce an additional hardening effect compensating the mentioned recovery induced softening.

Both solutions for eliminating the surface relief are of limited meaning as their implementation is rather complicate for routine industrial practice. The new 5030 type alloy is the promising solution for overcoming both the undesired surface appearance as well as the softening problems.

The susceptibility to the appearance of SCC appeared to be completely suppressed after low temperature annealing.

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