

## Firefighter Ladders Made of AA6063 Alloy Exposed to Elevated Temperatures and its Influence onto Mechanical Properties

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The firefighting ladders belong to essential tools used by members of the Fire Rescue Service of the Czech Republic. In the past, wooden ladders were used although their applicability and duration were strongly limited. Formerly used wooden ladders were then replaced with steel-made. However, the weight of such ladders caused big problems during the firefighting and therefore an aluminium ladders made of AA 6063 alloy are nowadays used. The ladders are however susceptible to thermal effects during firefighting and may reduce its mechanical properties. The present paper reports the microstructural change of two different ladders both made of AA 6063 alloy when annealed at different temperatures and duration. Both the ladders showed almost similar behaviour reaching the highest decrease in their TYS and UTS when exposed to a temperature of 400 °C reducing its initial TYS of 229 MPa for ladder no.1 and 237 MPa for ladder no.2 down to 71 MPa and 81 MPa, respectively.

**Keywords:** Microstructure, mechanical properties, annealing, firefighter ladders.

### 1 Introduction

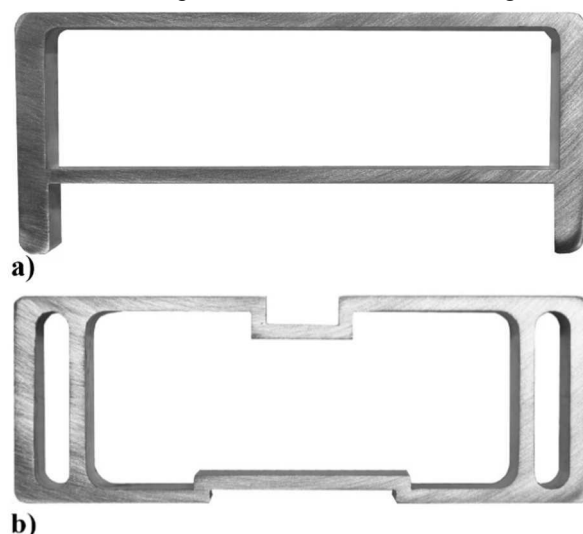
So far, the aluminium alloys are more often used in applications that were in past devoted mainly to steel-based materials. This is allowed by a good combination offering sufficient strengths while reducing the overall weight since the aluminium-based alloys are in general characterized by a relatively low density [1-7]. The group of Al alloys commonly described as AA6xxx belongs to the materials most widely utilized for production of a wide branch of products, mainly by hot-extrusion, which also includes firefighter ladders. They are usually used for different profiles in the construction industry, in aerospace [8-10] and automotive industry (chassis frame in Volvo, Jeep and BMW 5-series, body panels) [2, 11, 12] as well as it is suitable for the production of different decorative objects due to relatively easy anodization. The alloys are low-alloyed with Mg and Si in total amounts of only a few tenths of a percent. The low content of alloying elements increases the strength and hardness due to the formation of  $Mg_2Si$  precipitates and simultaneously increase the welding capability of these alloys [8, 13].

The alloys in this group are usually prepared by melting and quick casting that suppress the undesirable segregation of alloying elements. Consequentially, a homogenization annealing is implemented to reduce any undesirable microsegregation within the ingot. The prepared alloy is then preheated and hot extruded through the working tool with a shape of a future product. Prepared profiles are then thermally treated which consist of solution annealing consequential rapid water quenching and slow artificial ageing to increase the mechanical properties due to precipitation of  $Mg_2Si$  particles within the  $\alpha$ -Al grain interior. Since the process of thermal treatment tends to yield the maxima in properties, the change in temperature as well in a duration of the process may significantly influence the resulting properties. Considering the typical application of firefighter ladders, subsequential exposure to elevated temperatures might completely change the properties of such crucial equipment leading

to potentially life-threatening situations. Therefore, present work describes the influence of elevated temperatures onto the microstructure and mechanical properties of two firefighter ladders both made of AA6063 alloy.

### 2 Experimental

Two types of firefighter ladders (further denoted as ladder no.1 and no.2) were supplied to perform the tests to evaluate the exposure to elevated temperatures onto mechanical properties. The ladder no.1 already experienced real conditions during his 8-year service at a fire brigade. This ladder was equipped with latches that were attached to the ladder side rails by three rivets on each side. On the other hand, the ladder no.2 was a brand new piece of equipment that has not been used in action. Considering the main differences in both the ladders, ladder no.2 had latches attached to the side rails by welds. This was the main difference in both the ladders that might be used to distinguish them. Another difference was in the ladder profiles which are shown in Fig. 1.



**Fig. 1** The profile of both ladder side rails used for investigations: a) ladder no.1; b) ladder no.2.

As is evident, the ladder no.1 had a much simpler profile consisting of only one chamber forming the majority of the ladder. In comparison, the profile of ladder no.2 was much more complex consisting of three chambers including one in the centre and two smaller on both sides of the rails. Both the ladders were made of Al 6063 alloy which chemical composition (in wt.%) determined by Glow discharge optical emission

spectroscopy (GDOES, Horriba Jobin Yvon Profiler 3) is shown in Tab. 1. One can see, that the content of Mg was in the case of ladder no.1 even lower than that is prescribed in the technical description for the AA6063 alloy. The rest of the elements did not exceed the prescribed limits. Although this results, repeated measurement on different place corrected the results toward to prescribed compositions.

**Tab. 1** The chemical composition of both firefighter ladders used for investigations (in wt.%) compared to the nominal composition of the AA6063 alloy

Sample	Element [in wt.%]					
	Al	Mg	Si	Fe	Mn	Ti
Ladder no.1	bal.	0.42	0.37	0.2	0.05	0.02
Ladder no.2	bal.	0.47	0.37	0.2	0.04	0.02
Nominal composition of AA6063	bal.	0.45 - 0.9	0.2 - 0.6	max 0.35	max 0.1	max 0.1

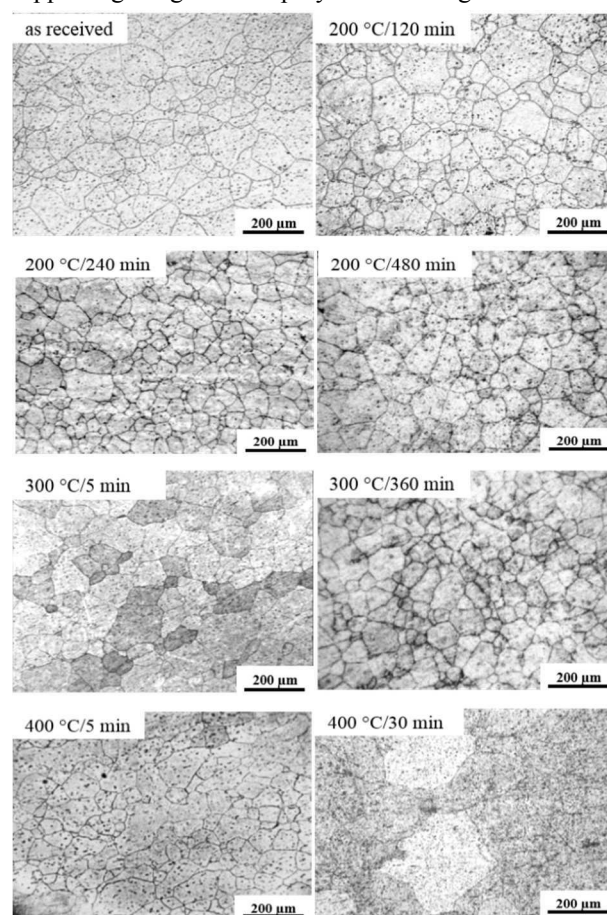
The rails were cut to obtain samples which were used either to investigate the microstructure as well to evaluate the influence of annealing which was done in temperatures ranging from 150 to 400 °C onto mechanical properties. The samples were exposed to these temperatures for several minutes to several hours as the temperature of annealing decreased from 400 °C towards to 150 °C. Annealed samples were examined for hardness change (accordingly to ČSN EN ISO 6506-1) using Brinell hardness measuring device with steel ball 2.5 mm in diameter and load of 62.5 kg. The same samples were also investigated for microstructural changes during annealing by light microscopy (LM, Olympus PME-3) and scanning electron microscopy (SEM, Tescan VEGA 3-LMU, 20 kV, SE+BSE detectors) equipped with an energy dispersion spectrometer (EDS, Oxford Instruments, 20 mm<sup>2</sup>). For this purpose, cross-sections were prepared by subsequential grinding on SiC papers marked as P120-P4000 and polished with diamond paste. The samples were subsequently etched in Keller's reagent (2.5 ml HNO<sub>3</sub>, 1.5 ml HCl, 1 ml HF, 96 ml H<sub>2</sub>O) and then in Weck's reagent (4 g of KMnO<sub>4</sub>, 1 g of NaOH, 100 ml H<sub>2</sub>O). Time the samples spent immersed in each reagent was as short as possible and did not exceed in total 5s. The dog-bone shaped samples prepared for tensile tests at laboratory temperature were cut from the side rails of each ladder. Their dimension fulfilled the prescribed parameters accordingly to ČSN EN ISO 6892-1. For this purpose, a universal testing machine was used with a strain speed of 0.001 s<sup>-1</sup>.

### 3 Results and discussion

#### 3.1 Microstructure

The LM micrographs of both the as-received ladders made of AA6063 alloy (see Fig. 2 and Fig. 3), which chemical composition determined by GDOES is shown in Tab. 1, showed a presence of large polyhedral  $\alpha$ -Al grains and small phases which were homogeneously distributed in the  $\alpha$ -Al grains interior. Based on the data available in scientific publications, the present phases shall be composed of Mg<sub>2</sub>Si precipitates and of rod-shaped Al(FeMn)Si. The present large polyhedral  $\alpha$ -Al grains

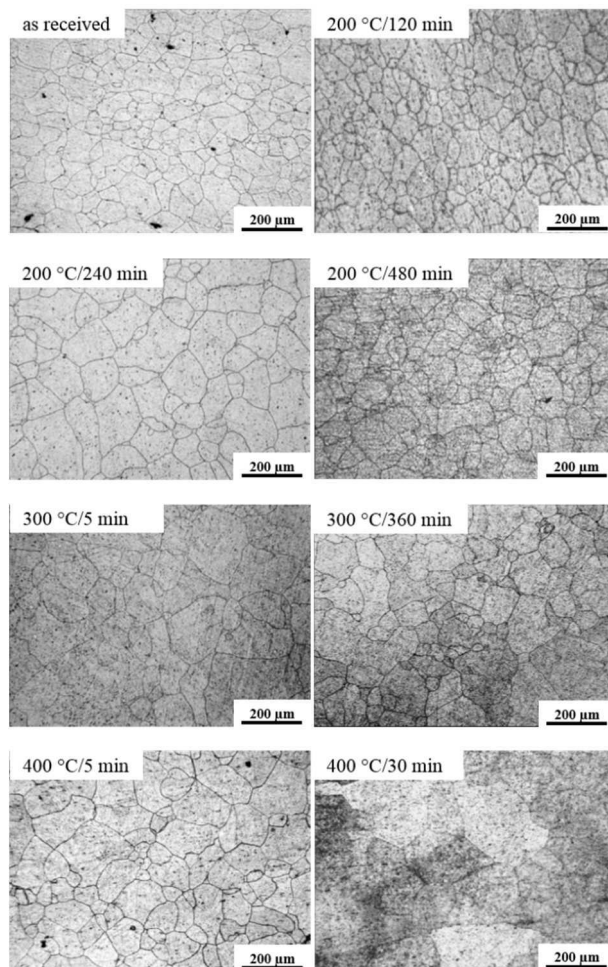
suggested fully recrystallized microstructure of the side rails in both the ladders. Thus, since we do not know the exact thermal treatment, the microstructural observations provided evident indications that temperature was high enough to eliminate the texture caused by extrusion supporting the growth of polyhedral  $\alpha$ -Al grains.



**Fig. 2** LM micrographs of the ladder no.1 after heat treatment.

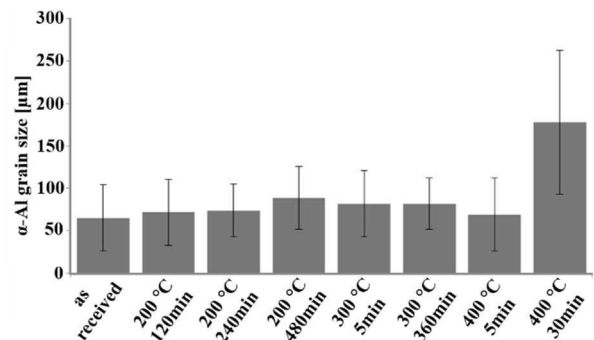
Both the ladders showed microstructural coarsening as the temperature and duration of annealing increases. When exposed to temperatures of 200 °C, the microstructural coarsening was the slowest and both the ladders remained almost the same  $\alpha$ -Al grain size even

when exposed up to 240 min. However, the microstructure coarsened when the time of annealing at 200 °C was prolonged up to 480 min showing a presence of larger  $\alpha$ -Al grains approximately 70  $\mu\text{m}$  in diameter. Exposure to a higher temperature of 300 °C resulted in a size increase of  $\alpha$ -Al grains growing up to 80  $\mu\text{m}$  in diameter already after 5 min exposure and then retained the same size even when exposed for the total duration of 360 min. The annealing at the highest temperature of 400 °C resulted in the highest increase in  $\alpha$ -Al grain sizes that were newly approximately 170  $\mu\text{m}$  in size after 30 min of exposure. Simultaneously,  $\text{Mg}_2\text{Si}$  precipitates, as well as the  $\text{Al}(\text{FeMn})\text{Si}$  phases coarsened as the time or temperature of annealing increased up to higher values. Both the ladders showed the same behaviour and thus, the results for the ladder no.2 are not shown.



**Fig. 3** LM micrographs of the ladder no.2 after heat treatment.

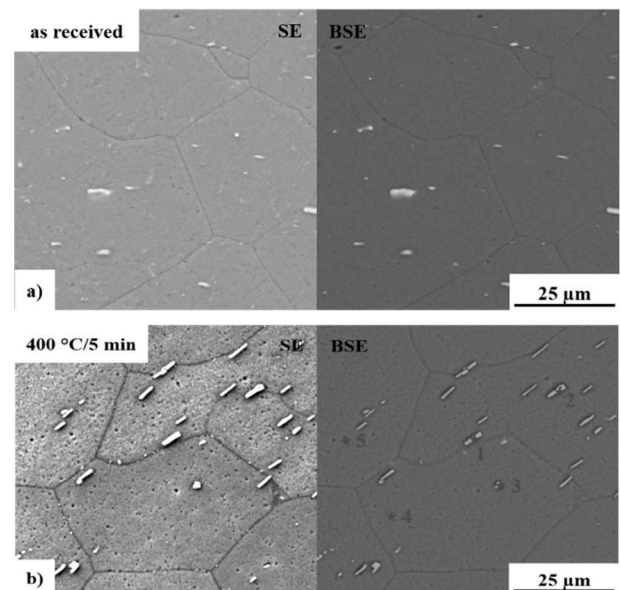
One can see, that the  $\alpha$ -Al grain growth, considering the standard deviation displayed as error bar, was lower in the case of samples annealed up to 300 °C. However, both the ladders significantly changed  $\alpha$ -Al grain sizes when exposed to 400 °C at least for 30 minutes. From this point of view, temperatures above 400 °C are significantly dangerous since the exposure to such temperatures quickly changes the microstructure-related properties like tensile yield strength (TYS) and ultimate tensile strength (UTS) of both the ladders.



**Fig. 4** Grain size development (in  $\mu\text{m}$ ) in the ladder no.1 during annealing at temperatures ranging from 200 °C to 400 °C and a different time.

On the other hand, the precipitate growth and the change in their dislocation-interaction mechanism degrade the properties of ladders made of AA6063 alloy even at much lower temperatures.

More detailed SEM micrographs (Fig. 5) revealed the presence of both the phases, namely of the  $\text{Al}(\text{FeMn})\text{Si}$  phase, which actual chemical composition vary due to the background effect. On the other hand, the presence of  $\text{Mg}_2\text{Si}$  phases was highly controversial since it tends to dissolve during etching leaving small dimples in the  $\alpha$ -Al grain interior.



**Fig. 5** The SEM micrographs of the ladder no.1: a) in as received state; b) after 5 min annealing at 400 °C with marked points of SEM+EDS analysis which results are shown in Tab. 2

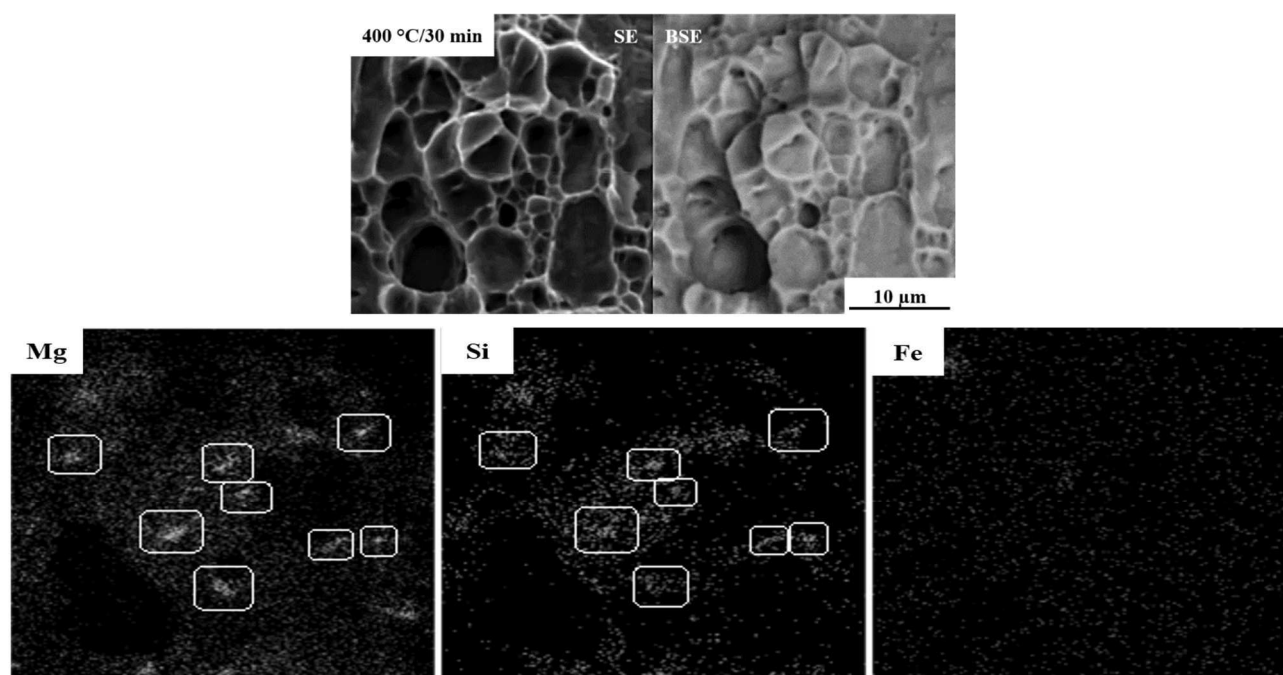
The results of SEM+EDS point analysis of present phases (see Fig. 5b) in the ladder no.1 which has been annealed at 400 °C for 5 min are shown in Tab. 2. The analysis of bright rod-shaped particles confirmed the increased concentration of Fe (up to 5.3 at.%) and Si (up to 3.9 at.%) although the influence of surrounding area highly affected the results. Regarding the common data available in the literature, these phases were identified as  $\text{Al}(\text{FeMn})\text{Si}$ . Presence of  $\text{Mg}_2\text{Si}$  precipitates has not been observed since they dissolved during two-step etching.

**Tab. 2** The results of the SEM+EDS point analysis of phases marked in Fig. 5

Point no.	Element concentration [at.%]				
	Mg	Al	Si	Mn	Fe
1	0.4	89.7	3.9	0.7	5.3
2	0.6	94.0	1.8	0.9	2.6
3	0.5	97.6	0.8	0.7	0.4
4	0.6	98.4	0.7	0.4	0.0
5	0.4	97.9	0.8	0.6	0.2

The  $Mg_2Si$  precipitates were observed on the fracture surface of the ladder no.1 sample that was annealed at 400 °C for 30 min. These precipitates with an average dimension of approximately 5  $\mu m$  were located at the tip of the present micro-dimples as is shown in Fig. 6. Since

the dimples were also small in their diameter, the EDS analysis was highly time-consuming. Thus, the investigations of present  $Mg_2Si$  precipitates was done using transmission electron microscopy (not shown).



**Fig. 6** The SEM micrographs and SEM+EDS element distribution maps of the ladder no.1 fracture surface that has been annealed at 400 °C for 30 min. (white rectangles point at places with possible occurrence of  $Mg_2Si$  phases)

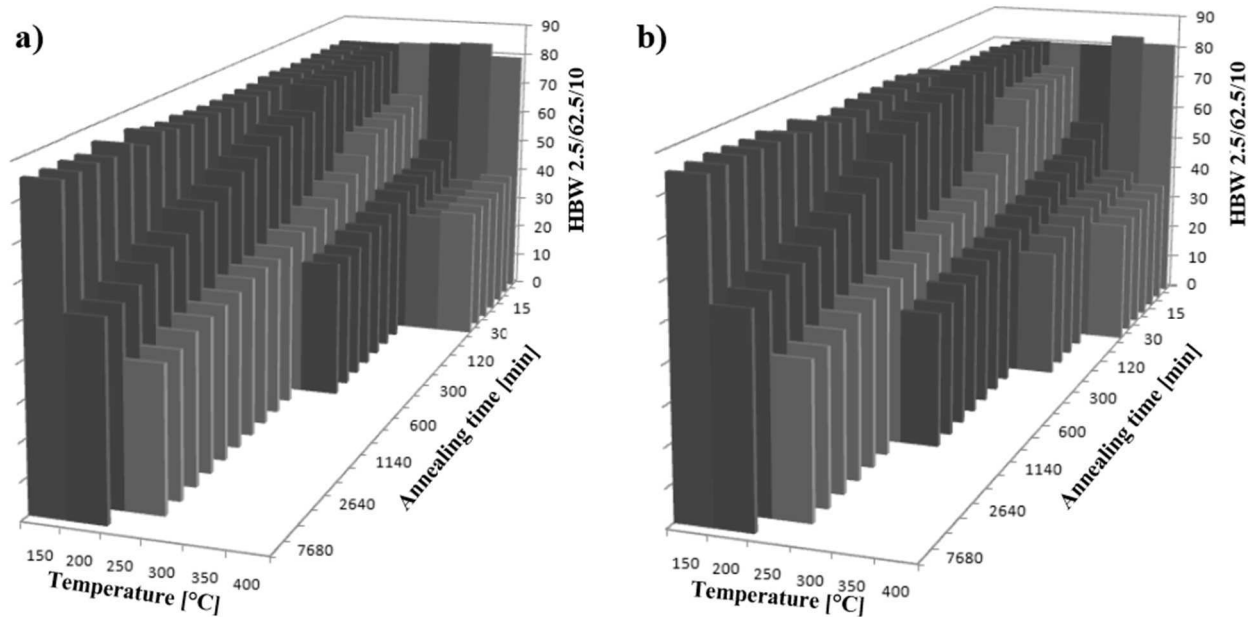
### 3.2 Mechanical properties change during annealing

Both the ladders were investigated for mechanical properties change during annealing. For this purpose, the Brinell hardness change was the first indication of the microstructural changes during annealing. Based on the results of hardness measurements (see Fig. 7), the samples were consequentially investigated for microstructure and tensile tested. The hardness measurements were done until the sample did not change their hardness during at least 3 consequential time periods. From this point of view, it is clearly visible, that the ladders annealed at a temperature of 150 °C were tested for the longest period reaching up to 7680 min while the samples annealed at 400 °C were tested only up to 30 min already reducing their hardness by more than 50%.

One can also see, that the ladder no.2 hardened during annealing at 150 °C suggesting further precipitation hardening. This behaviour corresponds to the state of the ladder, which was supplied completely new. In comparison,

the ladder no.1 already experienced 8 years of heavy workload which could either thermally influence the ladder itself while such long period might lead to spontaneous ageing. Therefore, the effect of hardening was in case of ladder no.2 almost negligible.

The thermal conductivity of the Al 6063 alloys is 218  $W \cdot K^{-1} \cdot m^{-1}$  (234  $W \cdot K^{-1} \cdot m^{-1}$  correspond for 99.5% Al) according to [1] and thus, evident exposure to elevated temperatures on a local scale may affect a larger piece of ladder even beyond the area which was in direct contact with clearly seen flames. More importantly, the highest danger is that the firemen are equipped with special gloves, coats and many other life-protecting gears which can withstand temperatures of approximately 200-300 °C without getting noticed by a person wearing them. Such a problem may increase the total duration the ladder was exposed to temperatures of 200 and higher which lowers the mechanical properties of a ladder and increases the risk of sudden life-threatening failure during an emergency situation.



**Fig. 7** The HBW change during annealing at temperatures ranging from 150 °C to 400 °C of the: a) ladder no.1; b) ladder no.2

The similar trend was also observed during tensile tests performed at laboratory temperatures. Both the ladders showed TYS and UTS in its as received state reaching 229 MPa (237 MPa for ladder no.2) and 250 MPa (268 MPa for ladder no.2), respectively. The annealing affected this values tremendously reducing both properties down when exposed (even for 5 min) to temperatures

reaching 400 °C. Considering the main purpose of fire-fighter ladders that should retain its structural properties, reduction of TYS down to 44 MPa seems to be a very serious life-threatening hazard. Both the ladders also reduced its TYS and UTS when exposed to relatively lower temperatures of 300 °C, although the reduction was lower.

Ladder	State	Tensile properties		
		TYS [MPa]	UTS [MPa]	Tensile strain [%]
no.1	as recieved	229	250	11.9
	200 °C/120 min	212	244	10.2
	200 °C/240 min	211	234	9.2
	200 °C/480 min	192	215	8.5
	300 °C/5 min	182	212	9.6
	300 °C/30 min	70	123	14.5
	400 °C/5 min	71	130	13.2
	400 °C/30 min	44	112	25.6
no.2	as recieved	237	268	10.3
	200 °C/120 min*	219	242	10.4
	300 °C/5 min	187	216	10.7
	300 °C/120 min*	75	131	12.3
	400 °C/5 min	81	137	11.6
	400 °C/120 min*	59	147	21.7

**Fig. 8** Results of the tensile stress-strain tests of both ladders corresponding to its state. \*data obtained from [14]

#### 4 Conclusion

Both the ladders were almost identical in their chemical composition although the processing route during its manufacturing was probably different. The microstructure of both the ladders was composed of

polyhedral  $\alpha$ -Al grains and of smaller particles corresponding to  $Mg_2Si$  precipitates and of rod-shaped  $Al(FeMn)Si$  phases. The  $\alpha$ -Al grains were fully recrystallized while the smaller phases were elongated in the extrusion direction. During the annealing, strong microstructural coarsening was observed and this

phenomenon further intensified as the annealing temperature increases. The results showed that both the ladders can withstand temperatures up to 200 °C even when exposed for several hours. During this exposure, the hardness and tensile properties are only slightly reduced showing still good results. On the other hand, exposure to temperatures of 300 °C even for 5 min influenced the mechanical properties of both ladders. Exposure to even higher temperatures drastically changes the properties and ladders showed a steep drop in their properties.

## Acknowledgement

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