THE EVOLUTION OF MECHANICAL PROPERTIES AND MICROSTRUCTURE IN EARLY STAGES OF NATURAL AGEING ON 2024 PLATES

Ioan SAVA[1], Gheorghe DOBRA[1], Cristian STANESCU[1], Marin PETRE[1]
[1]ALRO 116 Pitesti Street, Slatina 230104, Romania

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Abstract

The evolution of plasticity of heat treatable alloys in W temper is important for an efficient stress releasing by stretching or compression (Tx51 and Tx52 tempers) but also for some special hardening operations that combine cold working and ageing practices. For the alloys that have a significant natural ageing, the environment temperature has an important influence. In order to evaluate the influence of this temperature, the mechanical properties and the microstructure were investigated at various temperatures between -10 and + 80 °C and ageing time between 0 and 80 h on plates in alloy EN AW 2024, using standard tensile tests, electronic microscopy and X Ray diffraction.
The results demonstrate that from many standpoints (mechanical properties, plasticity, electrical conductivity, microstructure etc.) the ageing transformations end before the limit of 96 hours that is considered as standard.

Introduction

Immediately after solution heat treatment, the alloys are soft and plastic, suitable for plastic deformations. For the alloys that have significant natural ageing at room temperature, this temper is unstable. Usually it is called "fresh quench" and designated W_t, where "t" is the ageing time at room temperature (i.e. $W_{1/2h}$). It is generally accepted that the alloys considered to spontaneously age at room temperature are mainly the alloys belonging to 2xxx series of alloys and the ageing is finished in 96 hours. Despite this common understanding, in industrial practice of manufacturing 2xxx alloys flat rolled products, the evolution of plasticity during the natural ageing process is many times lower in early stages of ageing while the mechanical properties reach the standard provisions much early than 96 hours. Plasticity of metal in W temper is important for an efficient stress releasing by stretching or compression (Tx51 and Tx52 tempers) but also for some special hardening operations that combine cold working and ageing practices [1]. The dynamic of transformation is well described by a Sigma type curve, as in the Figure 1.

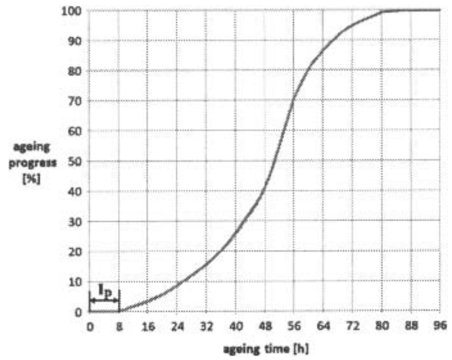

Figure 1: Ageing progress on 2024 alloy.

The time that precedes the beginning of transformation, (I_p in the Figure 1) is usually called "incubation period". During this stage, the nucleation of the new phases is dynamically controlled by germination mechanisms, which significantly depend on the available energy and consequently depends on the environment temperature [2]. A temperature lower limit may be defined that fully blocks the ageing transformation and preserves the fresh quench temper for a longer time.
In ALRO, for fine tuning of the technologies and for process optimization, we evaluated the W temper for 2xxx and 7xxx alloys in current production. The scope of investigations was to define the evolution of mechanical, physical and technological properties as well as the transformation of the internal structure. This information can be used to set a time window for stress releasing and cold deformation processes. In this paper, results for one of the common alloys, (2024) are presented.

Experiments and Results

The objects of experiments were hot rolled plates with thickness of 30 mm obtained from 500x1650x3500 mm cast slabs. The slabs were homogenized in industrial facilities, scalped 15 mm each side, preheated at 420 °C and hot rolled. The chemical composition is according to the Table I.

Table I. Actual Chemical Composition

EN AW – 2024					
Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**
0.1	0.13	4.57	0.65	1.53	0.014
Zn	**Ni**	**Ti**	**Ga**	**V**	**Al**
0.15	0.004	0.02	0.011	0.018	REM.

After hot rolling, specimens for mechanical tests were machined. The specimens were solution heat treated at 475 °C (alloy 7050) and 495 (alloy 2024) in a laboratory furnace (Nabertherm and Memmert). Quenching was done by immersion in cold water (20 °C). The specimens were kept at various temperature, between -10 and + 80 °C and tested (using a Zwick tensile test machine) after specific times, as presented in the Table II. Samples from the same material were investigated using X-Ray diffraction and scanning electronic microscope Philips ESEM XL 30 TMP with EDAX analyzer.

Table II. Experimental Program and Results

Ageing Temperature [°C]	Ageing Time [h]	Rm [MPa]	Rp_{02} [MPa]	$Rp_{3.5}$ [MPa]	Elongation [%]	Hardness [HBW]	Work to Break [Nmm]
-10	1	397	187	266	30.5	103	410,000
0	1	389	189	273	20.0	92	258,000
20	1	412	206	291	28.0	102	401,000
50	1	442	260	341	12.0	118	166,000
80	1	463	275	357	24.5	118	403,000
-10	2	378	177	255	27.5	98	353,000
0	2	393	185	264	28.0	97	377,000
20	2	415	217	298	13.0	103	167,000
50	2	451	263	345	24.0	118	387,000
80	2	454	267	350	24.5	118	394,000
-10	5	365	183	249	18.0	95	208,000
0	5	403	196	276	28.5	102	395,000
20	5	404	232	301	13.0	112	175,000
50	5	454	267	351	23.5	122	373,000
80	5	460	280	357	24.0	116	394,000
-10	10	393	180	263	28.5	102	383,000
0	10	410	210	285	20.0	102	350,000
20	10	441	254	335	23.0	120	361,000
50	10	456	266	351	2.0	123	210,000
80	10	463	285	361	24.0	121	395,000
-10	40	388	195	280	18.5	96	230,000
0	40	420	229	285	20.0	101	400,000
20	40	457	269	352	23.5	122	377,000
50	40	458	287	351	4.5	124	300,000
80	40	459	282	361	22.0	127	356,000
-10	80	412	209	291	29.5	104	422,000
0	80	440	240	326	29.0	112	441,000
20	80	455	271	353	23.5	123	378,000
50	80	459	275	359	23.0	125	373,000
80	80	460	283	361	10.0	128	300,000
20	0	396	220	288	30.5	102	407,000

With the obtained results, statistical models were defined for mechanical properties. We established regression equations by the least square method [3] and the associated coefficient of determination, R^2.

Ultimate Tensile Strength

$$Rm = 391.2957 + 1.5097T + 0.9199t - 0.0058Tt - 0.0087T^2 - 0.0052t^2 \quad (1)$$

Coefficient of determination, $R^2 = 0.90$
Global Maxima Rm = 467 MPa, for T = 70.36 °C, t = 49.21 h

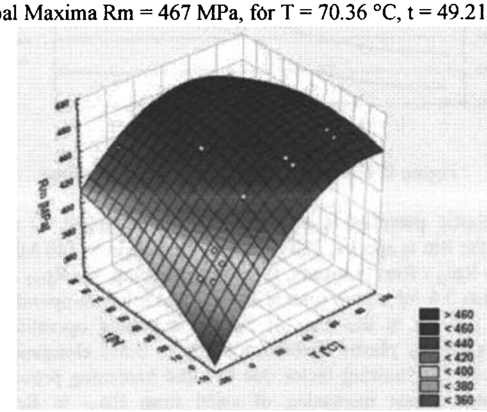

Figure 2: Ultimate Tensile Strength.

Yield Tensile Strengths

$$Rp_{02} = 191.0490 + 1.9532T + 1.3214t - 0.0050Tt - 0.0120T^2 - 0.0098t^2 \quad (2)$$

Coefficient of determination, $R^2 = 0.95$
Global Maxima Rp_{02} = 293 MPa, for T = 71.12 °C, t = 49.28 h

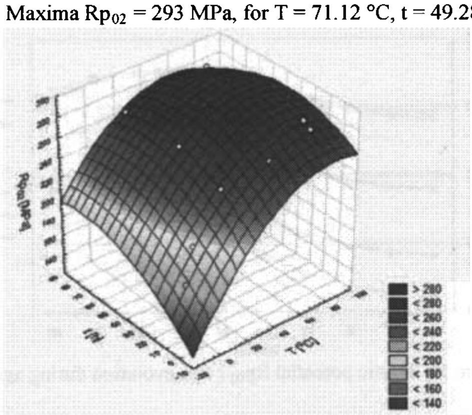

Figure 3: Yield Tensile Strength (0.2% offset).

$$Rp_{3.5} = 269.8475 + 2.0070T + 1.0233t - 0.0062Tt - 0.0121T^2 - 0.0053t^2 \quad (3)$$

Coefficient of determination, $R^2 = 0.94$
Global Maxima $Rp_{3.5}$ = 367 MPa, for T = 68.46 °C, t = 56.50 h

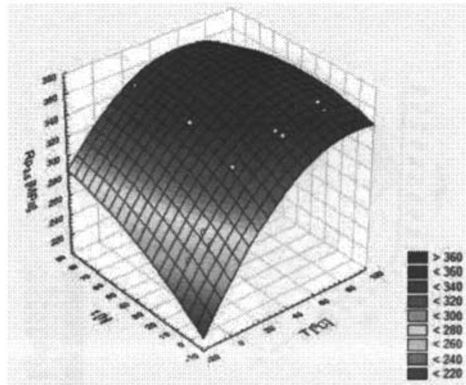

Figure 4: Yield Tensile Strength (3.5% offset).

In order to evaluate the plastic potential during ageing, the ratio Yield Strength / Ultimate Strength was evaluated. Based on the previous experience, this ratio describes very well the stretching behavior. As the maximum stretching of heat treated plates (T651 temper) is of 3.5%, two offsets were considered for Yield Strength: 0.2%, beginning of stretching and 3.5% end of stretching.

Plastic Potential Rp_{02} / Rm

$$Rp_{02}/Rm = 0.4890 + 0.0028T + 0.0019t - 5.4552e\text{-}06Tt - 1.8641e\text{-}05T^2 - 1.5921e\text{-}05t^2 \quad (4)$$

Coefficient of determination, $R^2 = 0.92$
Global Maxima Rp_{02}/Rm = 0.6301 MPa, for T = 68.08 °C, t = 48.01 h

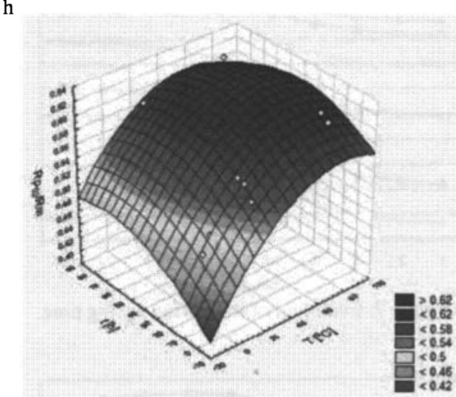

Figure 5: Plastic Potential Rp_{02} / Rm.

Plastic Potential $Rp_{3.5}$ / Rm

$$Rp_{3.5}/Rm = 0.6897 + 0.0022T + 0.0009t - 5.5082e\text{-}06Tt - 1.4589e\text{-}05T^2 - 3.6644e\text{-}06t^2 \quad (5)$$

Coefficient of determination, $R^2 = 0.90$
Global Maxima $Rp_{3.5}$/Rm = 0.7913 MPa, for T = 60.84 °C, t = 77.07 h

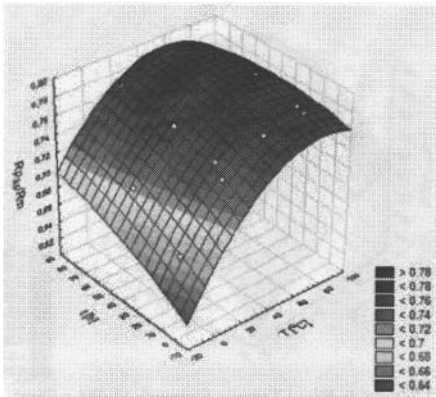

Figure 6: Plastic Potential $Rp_{3.5}$ / Rm.

Discussions

Mechanical Properties

According to most of the standards provisions, the natural ageing of the 2024 alloy is supposed to end in 96 h at room temperature. Actually, if we consider the target Rm = 420 MPa the ageing should be considered ended after 2 h at 20 °C. At lower temperature (– 10 °C), the target Rm is reached after 80 h but at high temperature the target Rm is reached in less than 1 h. It is obviously that the environment temperature has a big influence over the ageing results both on Ultimate Tensile Strength and Yield Tensile Strength.

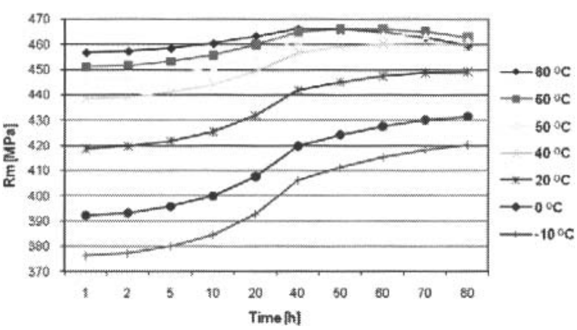

Figure 7: Evolution of Rm during ageing time.

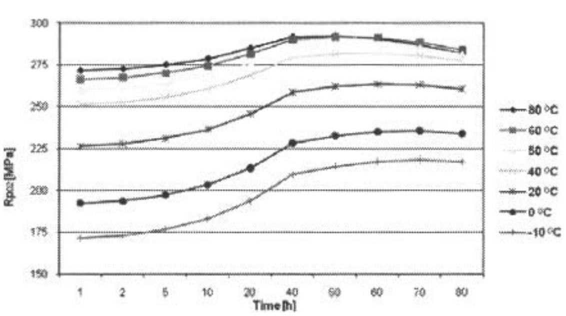

Figure 8: Evolution of Rp_{02} during ageing time.

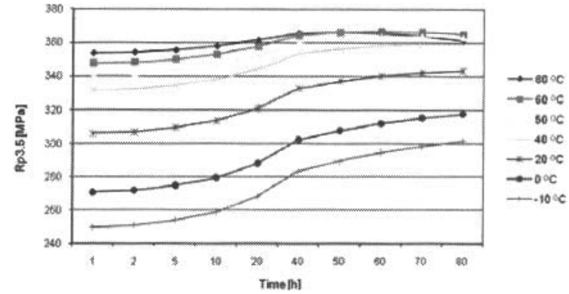

Figure 9: Evolution of $Rp_{3.5}$ during ageing time.

The plastic potential is maximum in full annealed, O temper, when the Rm is approx. 220 MPa and Rp_{02} approx. 140 MPa, that means Rp_{02} / Rm is approx. 0.6. During ageing, the Rp_{02} / Rm is less than 0.6 for a long time at normal and lower temperatures(20 °C). Even in the case of simple stretching operation, that involves lower plastic deformation (up to 3.5% elongation) the plasticity is a limiting factor due to rapid hardening process that generates a fast increasing of yield from Rp_{02} to $Rp_{3.5}$. In industrial environment, when the temperature usually varies between 15 °C or even less during winter and 40 °C or even over during the summer, the 2024 plates behavior during plastic deformation is significant. Accepting a Rp02 / Rm factor of 0.6, similar to O temper, at 40 °C temperature, plasticity is kept within this limit only 20 h after quenching, while during the winter, at 20 °C temperature, plasticity is kept bellow this limit for more than 80 h.

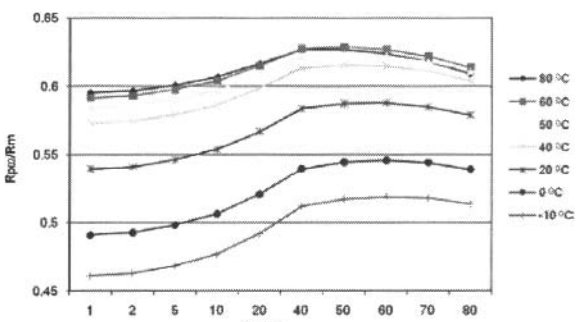

Figure 50: Plastic potential Rp_{02} / Rm evolution during ageing.

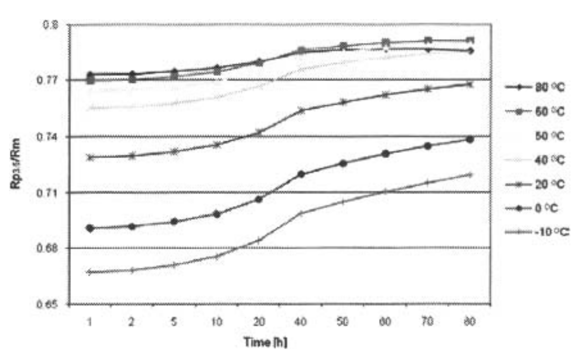

Figure 61: Plastic potential $Rp_{3.5}$ / Rm evolution during ageing.

For a specific time after quenching, the highest plasticity is for lower temperature, as in the Figure 12.

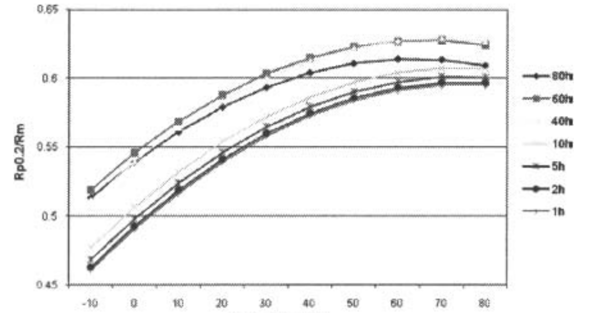

Figure 72: Plastic potential at various temperatures.

<u>Internal structure</u>

In order to evaluate the ageing progress, microscopic investigation were performed at 20 °C before and after solution heat treatment. The purpose of investigation was to identify structure changes immediate after quenching and in early stages of ageing.

In non-heat treated metal, the main phases are solid solution and soluble and non-soluble compounds. Generally there are not major changes in early stages of ageing in optic microstructure of metal. The changes consist mainly of nucleation and growth of small size particles such as Guinier - Preston zones and coherent intermetallic phases [4]. The soluble intermetallic compounds are based on Cu, Mg, Mg_2Si and Mn while insoluble compounds are based on Fe and Si [5, 6].

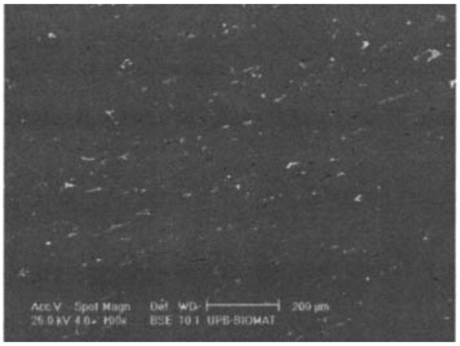

Figure 8: Non-heat treated metal, at magnification 100 x.

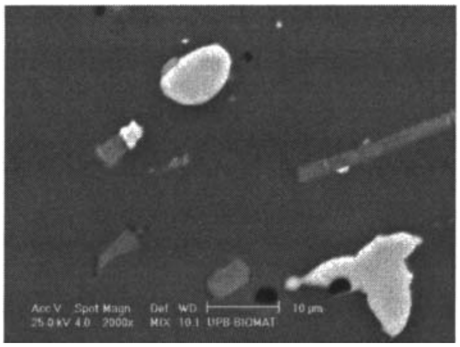

Figure 9: Non-heat treated metal, at magnification 2000 x.

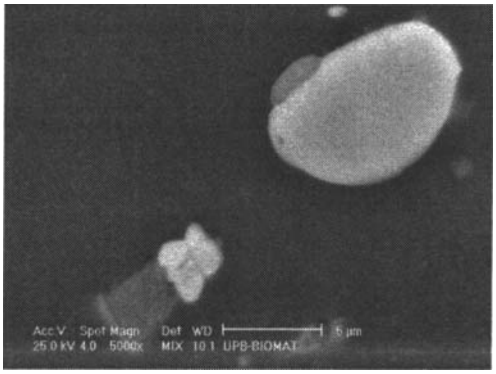

Figure 105: Non-heat treated metal, at magnification 5000 x.

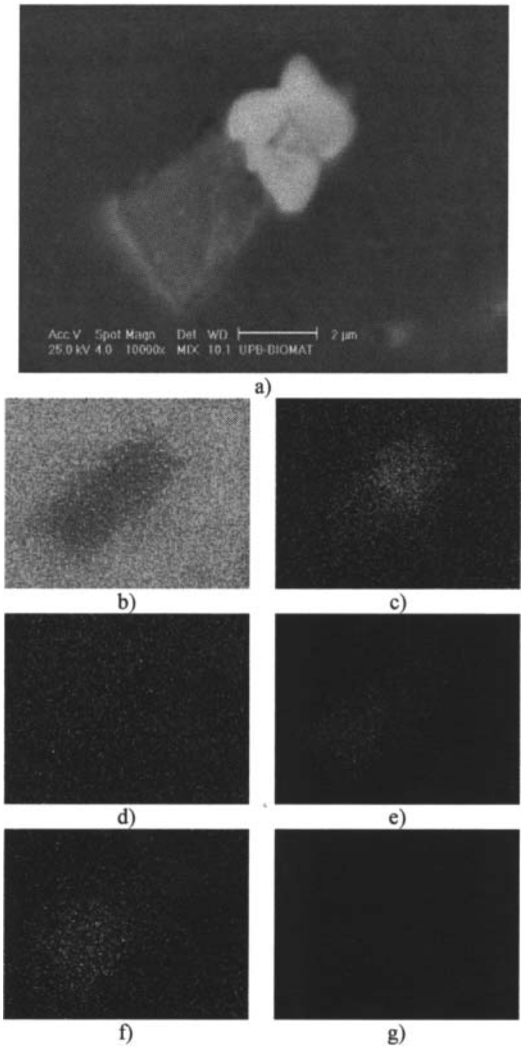

Figure 16: Non-heat treated metal and multi-element mapping: a) Optic image; b) Al; c) Cu; d) Mg; e) Fe; f) Mn; g) Si.

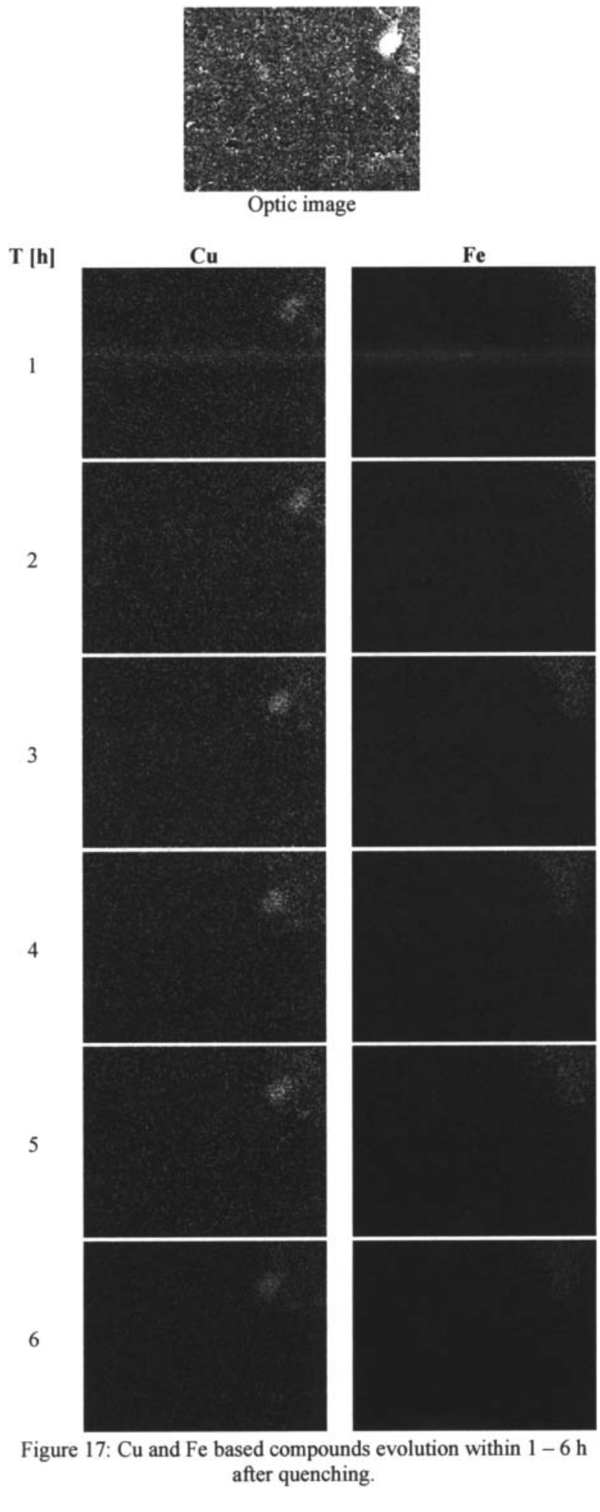

Figure 17: Cu and Fe based compounds evolution within 1 – 6 h after quenching.

The components were identified and followed up by multi – element mapping as in the example presented in Figure 16.

Even at intermediate magnification, 10,000 – 20,000 x, the evolution of hardening phases based on intermetallic soluble compounds is visible, while insoluble compounds have no significant evolution, as it can be easily observed in the Figure 17: the Cu rich field increases significant while the Fe rich field remains stable. Similar is the behavior for all soluble compounds (based on Cu, Mg, Mn, Si), that have a tendency to concentrate.

Conclusions

The ageing progress depends strongly on environment temperature. From mechanical properties stand point, the ageing reaches significant stage after 1 h after quenching in environment temperature of 50 °C, Rm = 440 MPa. When the environment temperature is -10 °C, this level is not reached after 80 h, when Rm = 410 MPa.

The plastic potential, expressed by the ratio Rp_{02} / Rm is much suitable for plastic deformation in early stages of ageing and is conserved for a longer time when the environment temperature is kept at lower values (0 to -10 °C).

Internal structure investigated by optic microscopy has no significant changings at medium magnifications, up to 10,000 X. Multi-element mapping techniques revealed a significant evolution of soluble intermetallic compounds even in short time after solution heat treatment, up to 6 hours, while the non-soluble compounds have no evolution.

The results were successfully applied in ALRO for planning of plastic deformation operations (stretching, forming, cold plastic deformation etc.) within a time window depending on environment temperature.

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