Melt spun aluminium alloys for moulding optics

G. Gubbels[1], L. Tegelaers[2], R. Senden[1]
[1]RSP Technology, Metaalpark 2, Delfzijl, The Netherlands
[2]Oerlikon Balzers, Schurhovenveld 4050, Sint-Truiden, Belgium

ABSTRACT

Melt spinning is a rapid quenching process that makes it possible to create materials with a very fine microstructure. Due to this very fine microstructure the melt spinning process is an enabler for diamond turning optics and moulds without the need of post-polishing. Using diamond turning of melt spun aluminium one can achieve ≤2 nm Rq surface roughness. Application areas are imaging and projection optics, mirrors, moulds for contact lenses and spectacles.

One of the alloys that RSP produces is RSA-905. This alloy has a solid track record as a better and cheaper concept in the application of moulds for optical components such as contact lenses. The RSA-905 is a dispersion hardened amorphous-like alloy that keeps its properties when exposed to elevated temperatures (up to 380°C). This gives the material unique features for optics moulding applications. RSA-905 moulds are cheaper and better than traditional mould concepts such as copper or brass with or without NiP plating. In addition logistics can be simplified significantly: from typical weeks-months into days-week. Lifetime is typically in the range of 100.000 – 200.000 shots.

For high volume production typically ranging from several 100.000 – several 1.000.000 shots, NiP plated steel moulds are typically used. By using an appropriate optical coating concept RSA-905 can be upgraded to a competitive alternative to steel in terms of price, performance and logistics. This paper presents some recent developments for improved mould performance of such concept. Hardness, wear resistance and adhesion are topics of interest and they can be applied by special coatings such as diamond-like carbon (DLC) and chromium nitride (CrN). These coatings make the aluminium alloy suitable for moulding mass production of small as well as larger optics, such as spectacle lenses.

Keywords: Optical moulds; diamond turning; melt spun aluminium; aluminium moulds; injection moulding; polymers

1. Introduction

Polymer injection moulding is used for production of small sized optical elements, such as micro-lenses used in smart phones and contact lenses, but also for larger sized optics, like spectacle lenses and even car-body panels. In these processes a polymer is molten and repeatedly injected into a cavity mould. After the polymer has been injected into the mould with pressure, the mould is cooled. As soon as the product is cold enough the mould is opened and the product released. This process is repeated until the number of parts has been made or when the mould has worn too much to meet the final dimensions/properties of the part. For increased production yield it is important to minimize cycle time, decrease production steps and increase the mould tool life. Cycle times can be shortened by a better cooling of the mould. Materials with a high thermal diffusivity are preferably used. Better than steel moulds are copper and aluminium alloys. Reduction of production steps can be achieved by a more efficient production technique of the moulds. Increase of tool life can be performed by an optimization of the mould material in combination with an optimum coating.

A special class of moulding is optics moulding. In this case low surface roughness is required. Conventional solutions use a base material with a deposited nickel phosphor (NiP) plating. Base material is a steel alloy that has to be ground prior to plating application, or copper that can be (diamond) turned. The NiP plating can subsequently be diamond turned and if necessary polished[1]. Problem of the conventional processing route is too long lead times before a mould can be used.

Melt spinning technology has led to the development of a special alloy called RSA-905 that is dispersion strengthened making it more suitable as an aluminium base material than conventional aluminium grades. Furthermore it can be used as a replacement of NiP plating. This paper describes two possible processing routes: 1) bare RSA-905 and 2) RSA-905 with a wear resistant coating.

2. Melt spinning technology

Melt spinning is a rapid solidification technique for producing alloys with the highest cooling rates possible, up to 10^6 K/s, providing ultra-fine and homogeneous microstructures. Figure **1** shows the different processing steps of the rapid solidification processing. Firstly, the alloy needs to be prepared using melting and different alloying elements. Next, the melt flows through a small nozzle onto a rotating copper wheel, creating a rapidly solidified ribbon. This ribbon is chopped to flakes and collected in a vessel. These flakes are degassed and subjected to hot isostatic pressure (HIP) processing to create a consolidated material. Principally, billet sizes of 1 m diameter can be prepared and these are available for large mirror optics. If necessary or required, the billets can be extruded or forged to different dimensions.

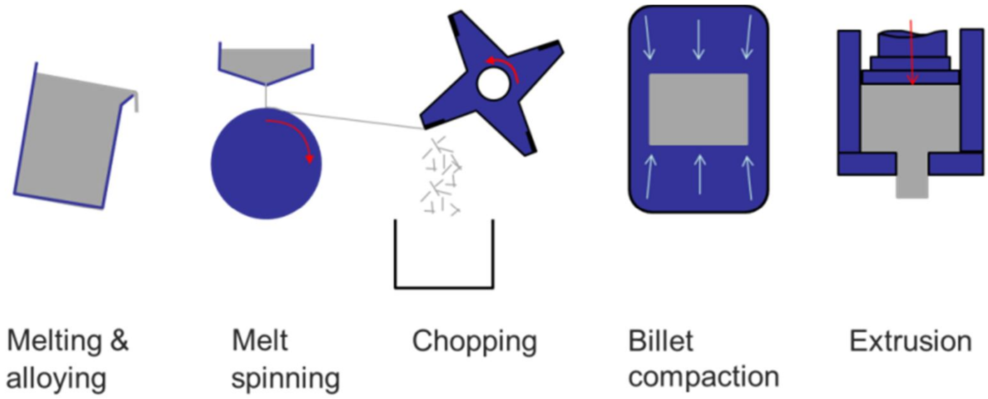


Figure 1. Processing steps in the rapid solidification processing.

Melt spinning makes it possible to achieve a very fine microstructure. For optical applications the Rapidly Solidified Aluminum (RSA) alloys RSA-6061 and RSA-905 are most commonly used[2]. In contrast to conventional aluminum, these RSA's can be diamond turned to very low surface roughness values (Rq< 2 nm) without the need of post-polishing. For larger mirrors, post-polishing is generally required to achieve the final shape accuracies and sufficiently low surface roughness values. For polishing operations, The RSA aluminum alloys benefit from the very homogeneous microstructure, which enables increased polishing rates and super-polished surfaces [3].

3. Melt spun aluminium as mould material

3.1. Mould materials

Many mould materials are known, but only little are used for optical moulding applications. The most used material is steel in combination with a nickel phosphor (NiP) plating. The NiP plating has an amorphous structure, making it ideal for diamond turning it to low surface roughness values.

Some moulding companies use copper based alloys. Copper alloys have very good thermal properties, but are more difficult to machine to low surface roughness values and are often used in combination with a NiP plating, because it tends to react chemically with polymers.
Table 1 shows a summary of the thermo-mechanical properties of some commonly used optical mould materials. Conventional aluminium mould materials like AA-7075 suffer from a low maximum operation temperature, typically limited to 150°C, making even polymer processing difficult. Polymers with higher T_g temperature are therefore requiring steel or copper moulds with NiP materials. Also, the AA-7075 alloys suffer from pull-outs during diamond turning, leading to less tool life of the moulds in production. Applying hard coatings on these aluminium grades is also difficult, since maximum adhesion of these coatings is typically achieved at deposition temperatures around 200°C, leading to deterioration of the mechanical properties of the conventional alloys. Since RSA-905 is a dispersion strengthened alloy

and has no precipitation hardening like the conventional alloys, it maintains its unique properties until the dispersoids start to grow and start forming new phases. This is happening at temperatures above 400°C, setting the upper temperature for the RSA-905 on 380°C. This puts it close to the maximum operating temperature of the amorphous NiP plating that starts crystallizing at a temperature of 400°C[4]. This makes it possible to mould polycarbonate lenses using aluminium alloys. Polycarbonate is typically injected at 310°C.

NiP platings are typically applied with a thickness of 100-200 µm for moulding. Therefore it influences mostly the mechanical, near-surface properties like scratch resistance, while thermal properties will mostly be influenced by the main body material. The hardness of the NiP is high compared to the other materials.

Table 1: Overview of thermo-mechanical properties of some optical moulding materials.

	RSA-905	Copper alloy	Steel + NiP	NiP plating	AA-7075
Principal elements	Al, Ni, Fe, Cu	Cu, Ni, Si, Cr	Cr Mo Steel		Cu, Mg, Zn
Density (g/cm^3)	2,95	8,72	7,8		2,85
Mechanical properties					
Young modulus (GPa)	90	131	205		70
YS (MPa)	480	510	895		525
UTS (MPa)	600	662	1020		565
Elongation (%)	6	13	20		10
Brinell Hardness (HB)	180	210	301	480	160
Thermal properties					
CTE (µm/m/K)	19	17,5	12,1	13	24,7
Conductivity (W/m/k)	115	208	29		160
Heat capacity (J/kg/K)	849	381	460		844
Diffusivity (mm^2/s)	46	63	8		67
Volumetric thermal stability (m^{2}K/s)	2,4	3,6	0,7		2,7
Max. operating temperature (°C)	380	482	400	400	125
Surface characteristics					
Diamond turnable	Good	Medium (large crystals)	Steel bad NiP good	Good	Medium (large crystals; pull-outs)
Surface roughness Sq (nm)	2	5-10	2	2	5-10

3.2. RSA-905 as mould material

RSA-905 can be directly used as a mould material without the use of a NiP plating. Figure 2 shows the production steps needed before moulding for different RSA-905 solutions compared to steel with a NiP plated layer. It becomes clear that the use of RSA-905 requires only blank production and diamond turning before moulding can start. Comparing this to the production of a steel blank and plating work, it will improve lead time by weeks and it has no risk of delaminating plating layers.

It is known from Kusner et al[5] that better thermal properties lead to better thermal management of the mould tools. It is stated that an increased thermal diffusion will lead to less warpage. Also, for optical moulding of polymers internal stresses will lead to birefringence, which is unwanted for lenses. The volumetric thermal stability defined as the diffusivity/expeansion coefficient, indicates the volumetric stability for non-homogeneous temperature distributions in the mold. It can be readily seen that steel has a very low thermal stability and that the aluminium alloys behave much better in that respect. Using the high thermal diffusivity of the RSA-905 will yield a homogeneous temperature profile and the prevention of hot spots in the mould. Based on the results of Kusner et al[5] it can therefore be expected that the RSA-905 can yield cycle time reductions of 20-30% compared to steel moulds.

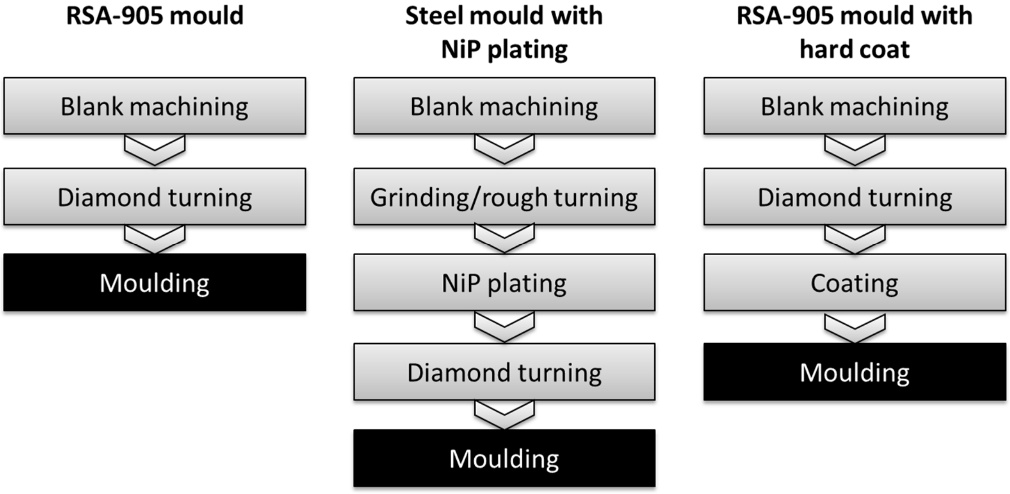


Figure 2: Processing steps of RSA-905 mould with and without hard coat, compared to steel mould with NiP plating.

3.2.1. Diamond turning of RSA-905

Although it is often stated that NiP platings can be diamond turned to 1 nm surface roughness, the effort to reach this is only of interest to the high-end equipment builders. For general visual applications, like ophthalmics, surface roughness values below 4 nm are generally sufficient. Common surface roughness values for NiP plated optical moulds are Sq ≈ 3 nm. For conventional aluminium and copper alloys surface roughness values of Sq 5-10 nm can be achieved. The RSA-905 can be easily diamond turned to optical quality. The amorphous NiP plating is known to copy the diamond tool geometry perfectly into the surface structure, therefore often leading to diffraction effects. Post-polishing can be applied to remove the diffraction effect. Polishing may increase the costs up to 30% [6]. In contrast to the NiP the nano-crystalline microstructure of the RSA-905 leads to less/no diffraction effects of the diamond turned surface, see Figure 3. Post-polishing is therefore not necessary for the RSA-905.

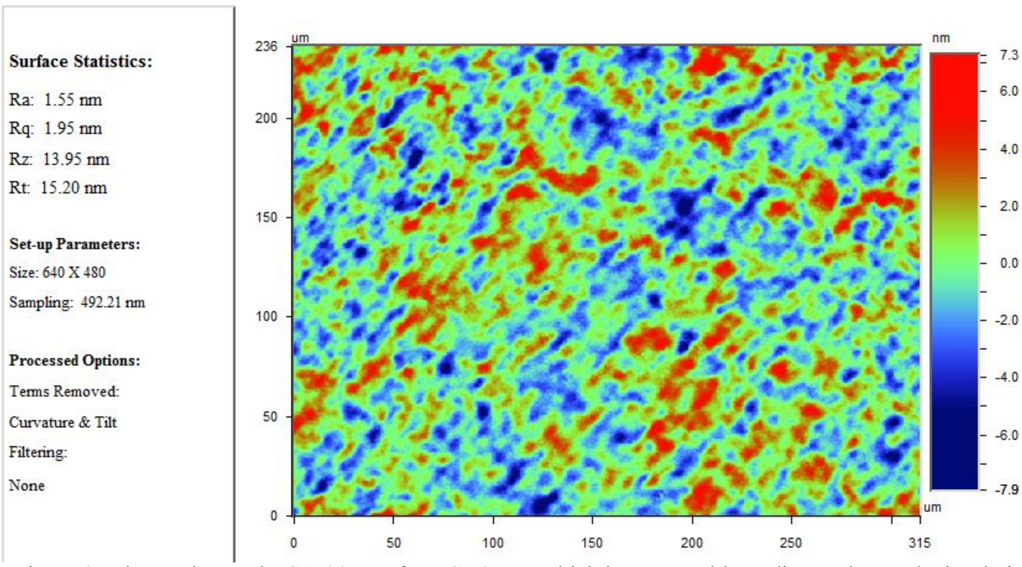


Figure 3: Diamond turned RSA-905 surface. Sq 2 nm, which is comparable to diamond turned NiP plating.

3.3. Tool life comparison

Typically steel with NiP coatings are used for large series moulding (several millions). Copper with NiP coatings are used for small series, up to a several thousands. The difficulty of copper alloys is too much tool wear leading to bad surface finish and surface shape accuracy. A NiP plating is therefore required leading to longer lead times. An injection moulding test has been performed using a copper alloy mould with and without a NiP plating and a similar RSA-905 mould without NiP plating. In the moulding test polycarbonate lenses were moulded with a mould temperature of 115°C, and mould temperature 300°C. Four mould inserts for biconvex lenses with a diameter of approximately 12 mm were used. Figure 4 shows the amount of shots that could be made using the different moulds. It becomes directly clear that the RSA-905 has a significantly longer tool life than the copper tools. The copper based mould suffers from corrosion by the polymer. From this figure it becomes clear that neither the hardness of the NiP or the good thermal properties of the copper alloy contribute to tool life in the moulding process: the RSA-905 outperforms the copper based alloys. It may be clear from this figure that the RSA-905 can be a suitable material as an easy to use replacement material for copper moulds and in some cases for the more difficult to manufacture steel moulds with NiP platings.

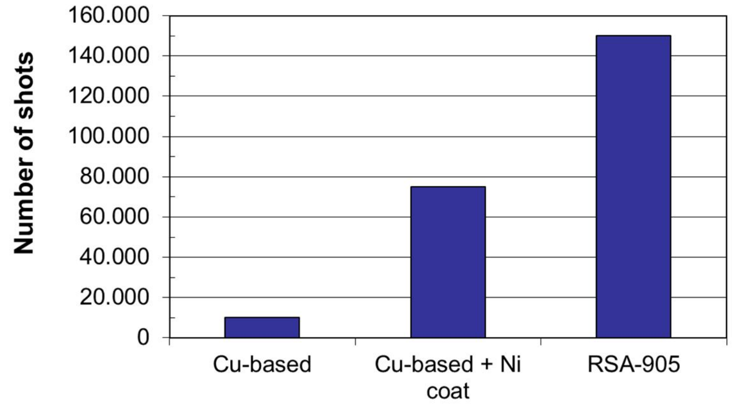


Figure 4: Comparison of tool life of RSA-905 with unplated and plated copper.

3.4. Cost and lead time comparison

Two investigations were made for a cost comparison of RSA-905 with steel based moulds with a NiP plating. Figure 5 shows the results of two customers, where the bench mark of steel with NiP plating mould was set to 100%. Customer 1 investigated the costs and lead time for moulds for small sized optics (intraocular lenses), while customer 2 investigated the results for large size optics (spectacle blank sized optics).

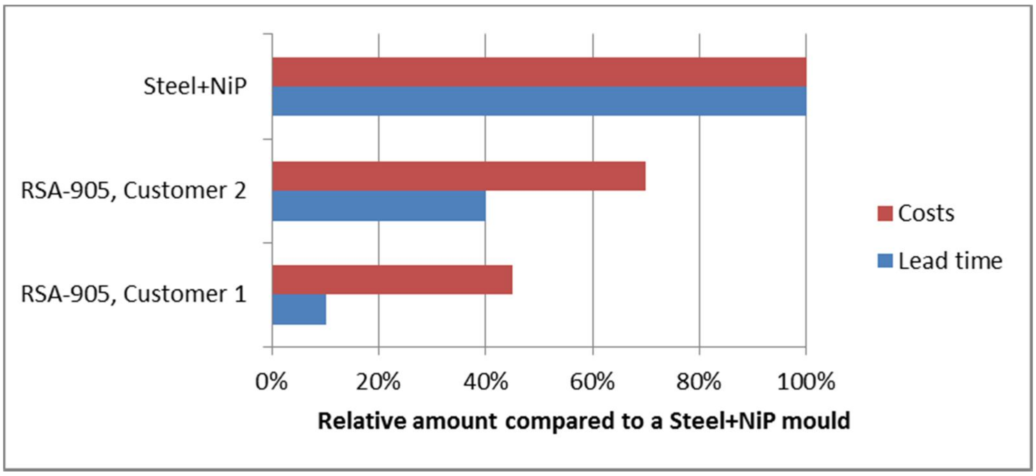


Figure 5: Comparison of lead time and costs when using RSA-905 alloy for moulds as compared to steel moulds with a NiP plating.

4. Mould coatings

Section 3 described the results for bare RSA-905 aluminium material for moulding applications. Figure 4 showed the achievable amount of shots achievable with this material as compared to Cu and Cu+NiP moulds. In order to increase the tool life of the material to more shots and be competitive to steel moulds with NiP plating, it would be necessary to apply a hard, wear resistant coating. This coating needs to comply to:

- High hardness
- Scratch resistance
- Good adhesion to the base material
- Maintaining the superior optical surface quality.

Looking at Figure 2 it can be seen that using RSA-905 with a wear resistant coating still has less production steps than application of steel moulds with NiP plating.

Two coatings were chosen to be applied to the RSA-905 for research purposes:

- Balinit D, and
- Balinit DLC star.

Typical application temperature for these kind of coatings is >200°C. Application of these coatings to conventional aluminium alloys is difficult, because of their low mechanical stability at these temperatures and increased aging effects. The RSA-905 that has dispersion hardening instead of precipitation hardening does not suffer from these thermal problems as long as the temperature remains below it thermal stability limit of 380°C.

4.1.1. Balinit D

Balinit D is a coating with excellent wear, corrosion and oxidation resistance. It is used extensively in plastic injection moulding. Oerlikon recommends this coating because of its good releasing properties of plastics from the mould.

Coating material:	CrN
Micro hardness:	1750 HV 0.05
Friction coefficient:	0.5
Max. service temp.:	700°C
Coating colour:	Silver gray

The Balinit D coatings have proven successfully for processing thermoplastics, (e.g. PE, PP, PS, PA, PC, PMMA and PU) and thermosets, making them ideal for optical coatings.

4.1.2. Balinit DLC Star

Balinit DLC star is a modified diamond-like-carbon coating with enhanced load bearing capacity. A hard, tough metal based layer (chromium nitride) provides adequate surface hardness and support (load bearing capacity) for the superposed, tribologically effective carbon coating. Simultaneously, the compact chromium nitride layer enhances the fatigue and corrosion resistance of the components.

Coating material:	CrN + a-C:H
Micro hardness:	>2000 HV 0.05
Friction coefficient:	0.1-0.2
Max. service temp.:	350°C
Coating colour:	Black

4.2. Assessment of optical coatings on RSA-905

To investigate the applicability of optical mould coatings four plano workpieces (Ø80) were diamond turned to an optical quality. Figure 6(a) shows the diamond turned surface of the RSA-905 workpiece. The four workpieces had an average surface roughness of 4.8 nm Sq before coating. Two workpieces were coated with Balinit D (CrN) and the other two with Balinit DLC Star. Due to some error, the CrN were brushed prior to coating, increasing the surface roughness to approximately 10 nm (value estimated from surface roughness of the coated surface roughness).

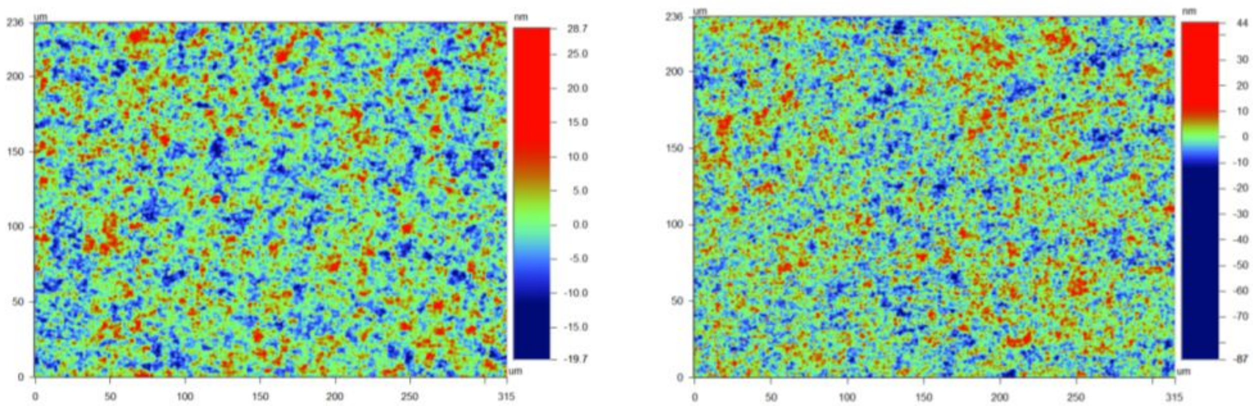
After coating the samples were measured for surface roughness and adhesion properties. Figure 6(b) shows the coated Balinit DLC Star surface. The surface roughness of this sample was 4.8 nm, showing that no significant increase in surface roughness occurred and that optical quality of the mould surface is maintained. Unfortunately the CrN surface could not be evaluated before and after the coating, since the brushing was accidentally applied. Still, the brushed surface had a surface roughness of 11 nm Sq after coating. Since brushing makes surface dull/milky white, it is currently assumed that the brushing led to an initial surface roughness of approximately 10 nm Sq, indicating that no surface deterioration occurred during the coating process.

Table 2 shows the results of the coating tests on the RSA-905. As a first assessment the coating adhesion was judged using the VDI 3198 standard, in which an indentation is made. The appearance of the indent is a measure for the adhesion properties. Using a Rockwell A hardness tester (because of the aluminium) the Balinit D (CrN) was classified as good adhering to the RSA-905, while the Balinit DLC Star was classified as excellently adhering to the RSA-905.

Table 2: Coating assessment for optical moulding applications with RSA-905.

Surface roughness before coating	Sq 4.8 nm	
	Accidentally brushed, new roughness ≈ 10 nm Sq	Not brushed
Coating type	Balinit D (CrN)	Balinit DLC Star
Layer thickness	5.1 µm	2.4 µm
Surface roughness after coating	Sq 11.7 nm	Sq 4.8 nm
Adhesion classification (VDI 3198 std, with HRA, instead of HRC)	HF 3 ("Good")	HF 1 ("Excellent")

Figure 7 shows the coated workpieces as photographed. All show reflective properties, although the brushed CrN coating shows a bit dull. The DLC coated surfaces looks darker by its black appearance as compared to the uncoated RSA-905 surface.



(a) (b)

Figure 6: (a) RSA-905 surface microstructure before coating (Sq 4.6 nm), and (b) RSA-905 surface structure after coating with Balinit DLC Star (Sq 4.8 nm).

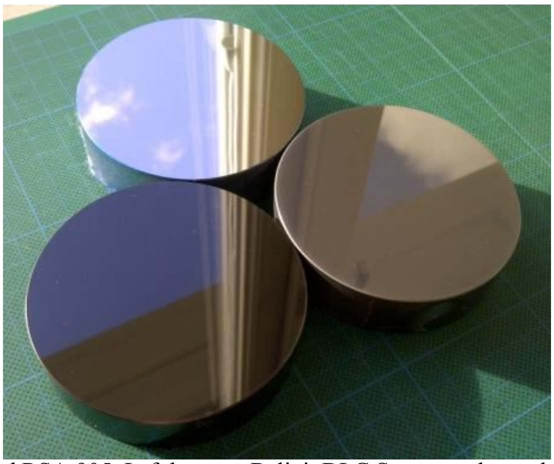


Figure 7: Top left: diamond turned RSA-905. Left bottom: Balinit DLC Star coated sample. Right: Balinit D coated sample.

5. Summary and conclusions

RSA-905 is a dispersion hardened alloy offering unique features for optics moulding applications compared to traditional mould concepts as well as conventional aluminium alloys.

RSA-905 moulds show proven advantages above traditional mould concepts:

- Cheaper: cost reduction in the range of 25 – 60%
- Better: good thermo-mechanical properties, excellent thermal stability at elevated temperatures (up to 380°C) in combination with a perfect diamond turnability
- Improved logistics: since no additional platings are necessary: lead time improves from typical weeks-months into days-week

Life of uncoated RSA-905 moulds typically ranges from 100.000 till 200.000 shots. For high volume production typically ranging from several 100.000 – several 1.000.000 shots, the RSA-905 can be coated with Balinit coatings that have a proven track record for moulding applications. An excellent adhesion of the Balinit coatings can be reached as the superior thermal stability of the alloy, allows high temperature processing during coating. It has been shown that the optical surface finish of the diamond turned RSA-905 is maintained during coating.

As a follow up field tests of the plated version will be carried out for mass production applications in order to determine mould life in more detail.

6. Acknowledgments

The authors acknowledge TNO in the Netherlands for performing surface roughness measurements.

7. References

[1] L. Mertus and A. Symmons, "Implications of diamond-turned versus diamond-ground mold fabrication techniques", Proc. SPIE 8489, (2012), DOI 10.1117/12.927771

[2] Guido Gubbels, Bart van Venrooy and Roger Senden, "Rapidly solidified aluminium for optical applications", Proc. SPIE 7018 (2008), DOI 10.1117/12.788766

[3] Rik ter Horst; Menno de Haan; Guido Gubbels; Roger Senden; Bart van Venrooy; André Hoogstrate, "Diamond turning and polishing tests on new RSP aluminum alloys", Proc. SPIE 8450, (2012), DOI 10.1117/12.926406

[4] Lou Mertus and Alan Symmons, "Implications of diamond-turned versus diamond-ground mold fabrication techniques", Proc. SPIE 8489, (2012), DOI 10.1117/12.927771

[5] R.E. Kusner, J.C. Kuli, D.B. Veitch, "A copper-nickel-silicon-chromium alloy for mold tooling", MoldMaking Technology Magazine, (1/2007)

[6] Uddeholm, "Uddeholm tool steel for moulds", Technical note, edition 10, Sept. 2012