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Gallig-Free Dry Net Shaping of Titanium and Titanium Alloy Eye-Glass Frame Parts toward Green Manufacturing

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Abstract. Massively carbon supersaturated (MCSed) tool steel dies were prepared for dry, galling free forging, microtexturing and fine-blanking of titanium and titanium alloy eye-glass frame parts. Titanium temples were forged in dry and galling-free to investigate the role of MCS treatment to reduce surface roughing of temples. They were also micro-textured to discuss the superiority of MCS to product quality. Dry, galling-free fine-blanking was utilized to describe the life-time extension of MCSed tool steel dies. Various eye-glass frame parts were forged in dry to state the statistic evaluation on the galling-free manufacturing features. The intermediate chemical treatments as well as barreling and polishing steps were saved to reduce the amount of wastes from manufacturing factories of titanium and titanium alloy eye-glass frames toward zero emission.

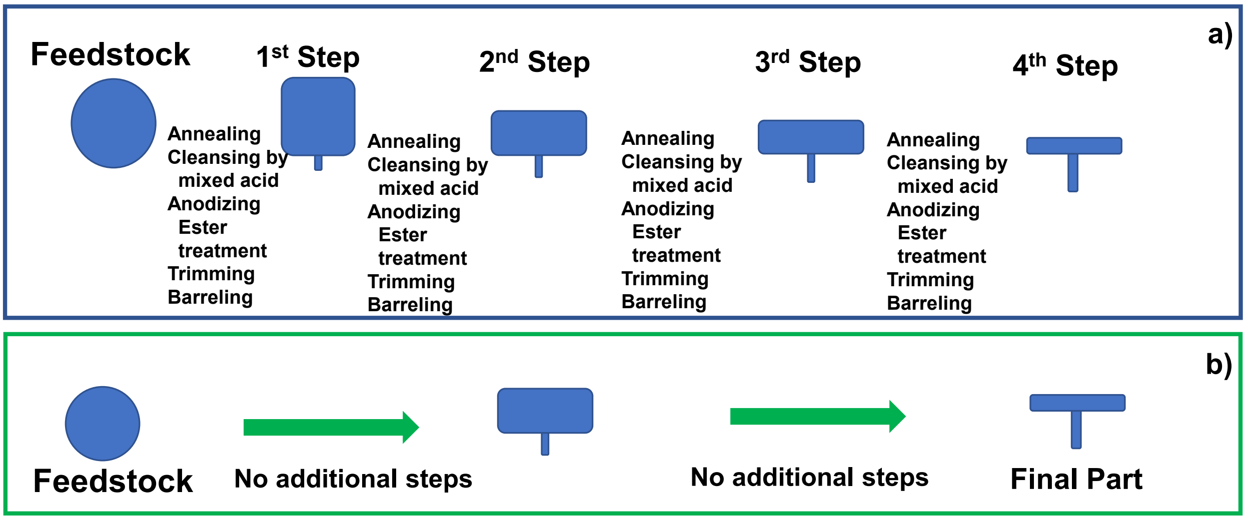

Fig. 1. Comparison of the dry manufacturing procedures for pin-formation with and without use of MCS treatment. a) Without MCS-treatment, and b) with MCS-treatment.

Introduction

The galling or adhesive wear has been identified as one of the most essential issues in metal forming [1-2]. Especially, severe galling was studied in dry sliding friction tests on various coated test-pieces against titanium balls [3]. In dry upsetting of titanium bars, the debris particles splashed in the air together with much adhesion of titanium fragments [4]. No improvements took place in deep drawing of titanium sheets even using the ceramic dies [5]. Hence, the manufacturing procedure in dry required multi-steps to fabricate the eye-glass frame parts from titanium bar feedstock [6]. A typical multi-step procedure was illustrated in Fig. 1a. In additional to multi-step forging processes, the intermediate treatments of anodizing, chemical treatments, barreling and polishing steps were needed to continue the forging procedure without severe galling. In particular, nitric acid (HNO_3) and hydrogen fluoride (HF) solutions were utilized to remove the used titanium oxide films on the forged titanium work material surfaces in every intermediate step.

The massive carbon supersaturation (MCS) treatment to tool steel dies, was proposed to make dry, galling-free forging of titanium and titanium alloy feedstock [7]. MCSed SKD11 and ADC56 dies were utilized not only for upsetting the titanium bars in high reduction of thickness [8, 9] but also for fine-blanking the titanium plates to gears with high accuracy [8, 10]. The original forging steps in the pin formation in Fig. 1a were nearly halved, and, most of intermediate steps were saved by using the MCSed ACD56, as illustrated in Fig. 1b. In addition of this reduction in the number of steps, the energy consumption in forging was saved by 20-30% because of significant reduction in the applied load. This suggests that MCS treatment has a role in reduction of environmental burden in the life cycle assessment (LCA) [11].

In the present paper, tool steel dies are MCSed using the plasma carburizing method. The single-shot forging and fine-blanking processes with the use of MCSed ACD56 dies, are performed to describe the galling-free shaping of pure titanium feedstock by in situ formed carbon tribofilm on the contact surface and to demonstrate the role of MCS treatment in high qualification of forged and blanked products. Various titanium eye-glass frame parts are forged to statistically describe the superiority to MCS treatment of dies toward green manufacturing. In particular, no surface roughing by MCSed die directly results in high qualification of products; fine microtexturing by MCSed die is preferable to design-oriented decoration of eye-glass frames.

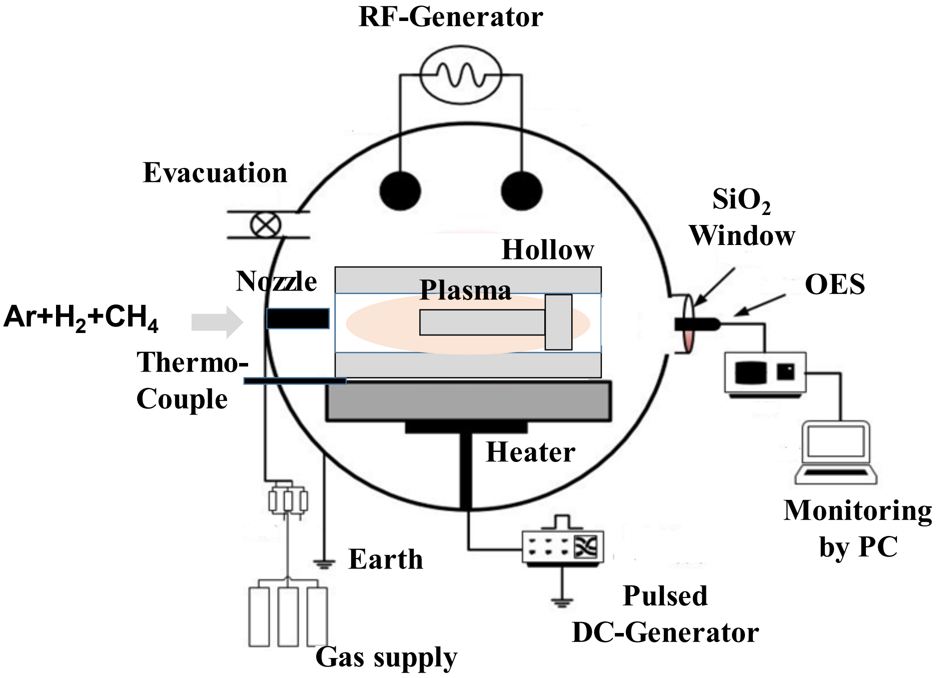

Fig. 2. Plasma immersion carburizing system for MCS treatment of tool steel dies.

Methods and Materials

The plasma processing conditions for MCS treatment were explained to prepare for MCSed dies. A single-shot forging process with the use of MCSed ACD56 dies was stated for net-shaping of various titanium eye-glass frame parts. Fine-blanking and microtexturing processes were also described to find the superiority to MCS treatment for galling-free manufacturing.

MCS-treatment

The plasma carburizing immersion system was utilized for MCS treatment of tool steel dies. As illustrated in Fig. 2, the die was plasma carburized in the hollow cathode to intensify the carbon ion and CH-radical densities. The holding temperature was 573 K to be free from thermal distortion. After heating and presputtering for 1.8ks via the DC (Direct Current) plasma under the bias voltage of -500 V, the dies were carburized for 16 ks under the RF (Radio-Frequency) voltage by 250 V and the bias by -500 V respectively before cooling in the nitrogen atmosphere down to RT (Room

Temperature). After cleansing and polishing, this die was directly utilized in the following forging, fine-blanking and microtexturing processes. A knuckle-joint stamper (AIDA160; AIDA, Co., Ltd.; Kanagawa, Japan) was utilized in these processes with the maximum load of 1200 kN. The applied load was monitored in each forging strokes. Under the constant stroke, velocity and duration, the applied energy was proportional to load.

Forging process

Titanium feedstock was upset and net-shaped by MCSed ACD56 dies. In-situ carbon tribofilm formation is proved after continuously upsetting in 30 shots. Temples are dry-forged with and without MCS to describe the role of MCS to suppress the surface roughness in forging. SEM (Scanning Electron Microscopy) – EDS (Electron Dispersive x-ray Spectroscopy) is utilized for microstructural analysis on the die surface.

Fine blanking

Shearing the titanium plates and forged parts, becomes an essential step in fabrication of eye-glass frame parts. Titanium plates with the thickness of 5.0 mm were continuously punched out to describe the effect of MCS on the burnished surface area ratio. This fine blanking is utilized to demonstrate the die-life extension by MCS treatment.

Microtexturing

Various designs of eye-glass titanium frames are allowable in decorating microtextures on the titanium temples. An acetate temple was a typical new material design instead of a traditional plastic one. This temple material is made from natural cellulose so that no environmental burdens are generated even in disposal. In most of designs, this acetate temple is strengthened by a titanium plate as shown in Fig. 3. This plate is often microtextured for decoration of light-colored or transparent acetate temples.

Fig. 3. Microtexturing to titanium temple surfaces for decoration of eye-glass frames.

Results and Discussion

A single shot upsetting process was employed to describe the galling-free performance when using the MCSed ACD56 dies. A fine-blanking process was performed to demonstrate the tool life extension by MCS treatment. A microtexturing process was done to state the role of MCS in high qualification of forged eye-glass frame. Various eye-glass frame parts were forged for statistical survey on the superiority to productive technology toward zero-emission. In common, the pure titanium in the industrial grade II was utilized as a feedstock in every forging and forming step.

Single-shot forging process

Pure titanium bar with the diameter of 5.0 mm was continuously upset using the MCSed ACD56 dies in the reduction of thickness (r) by 50% up to 30 shots. Figure 4 compares the first and 30th upset works. When N = 1, the work surface is covered by the white debris particles while no debris particles are seen when N = 30. Without MCS treatment, the debris particles gradually deposited onto the die and work surfaces; the whole surfaces were covered by debris particles when N = 20 [4]. This galling-free upsetting behavior in Fig. 4 is completely opposite to the conventional upsetting process without MCS. In addition, the shear-localization, which was observed in the normal upsetting of titanium bar at r = 50%, never took place when using the MCSed die. That is, the titanium bars are upset with homogeneous work hardening without plastic localization.

Fig. 4. Comparison of MCSed ACD56 die surfaces at N =1 and N = 30.

This unique forging behavior to MCS treatment comes from the in situ formation of amorphous carbon tribofilm during upsetting. SEM-EDS (JEOL; Tokyo, Japan) was used to make microstructure analysis on the MCSed die surface after upsetting up to N = 30.

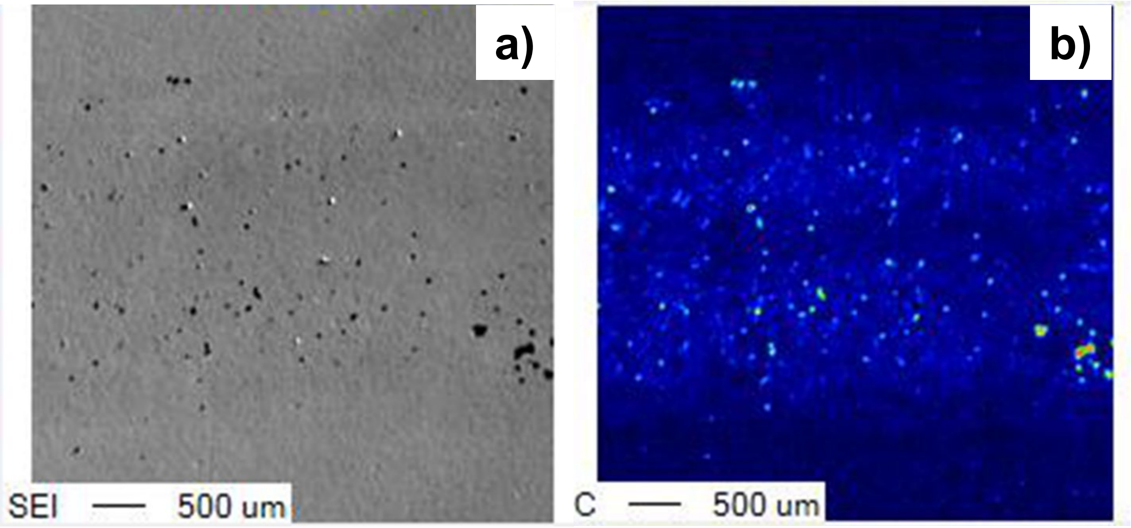

Fig. 5. SEM-EDS analysis on the MCSed ACD56 die surface at N = 30. a) SEM image on the MCSed die surface at the center, and, b) carbon mapping on the same area.

As shown in Fig. 5a, the contact area of titanium work is traced in dark at the center of die surface. This area is just corresponding to a carbon map in Fig. 5b. Especially, the back dots in Fig. 5a consist of carbon dots in Fig. 5b. Thie proves that carbon solutes are isolated from MCSed dies to in situ form a carbon film only on the contact surface of MCSed die to titanium work. Let us state the effect of MCS treatment on the product surface quality.

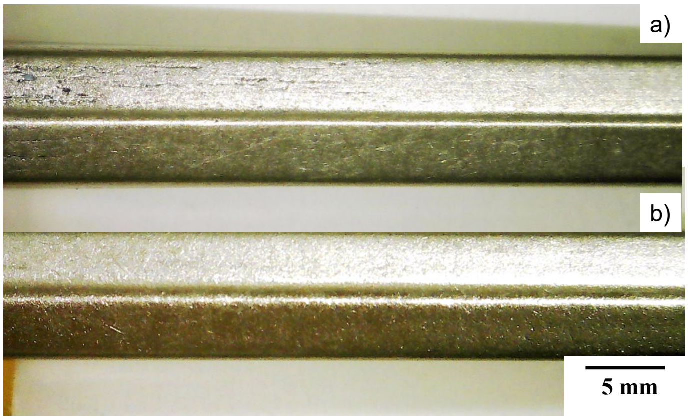

Fig. 6. Comparison of the forged eye-glass temples with and without MCS treatment. a) Without MCS treatment, and b) with MCS treatment.

Residual adhesives from titanium work onto the die surface, often deteriorate the surface roughness in dry forging of temples. Figure 6 compares the forged temple surfaces with and without MCS treatments. As seen in Fig. 6a, the die surface roughness by galling is imprinted onto the product surface as scratches and flaws. Additional barreling, polishing and cleansing processes are keenly needed to remove these defects; the cost-performance is deteriorated in manufacturing. When using the MCSed dies, no galling took place so that no flaws were left on the MCSed die surface. As depicted in Fig. 6b, the temple surface is never roughed so that no additional steps are necessary in this dry forging.

Fine-blanking process

A fine blanking step is always necessary to pick up the forged product from its skeleton and to decorate the temples by pierced holes or bands. Two issues must be solved in this die technology; suppression of severe galling to attain nearly full-burnished surfaces, and, die-life extension even in dry fine blanking.

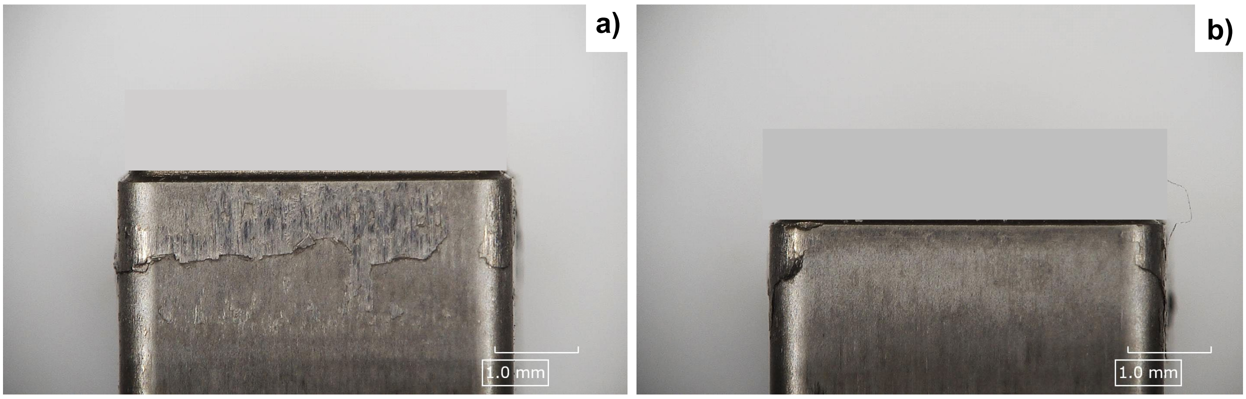

Fig. 7. Comparison of ACD56 punches for fine-blanking of titanium plates with and without MCS treatment, a) ACD56 punch without MCS treatment at N = 1000, and b) ACD56 punch with MCS treatment at N = 10,000.

Figure 7 compares the ACD56 punch surfaces after the selected number of shots with and without MCS treatment. Without MCS, severe galling took place to form the debris films on the whole head and side surfaces of tool steel punches, so that further fine blanking is terminated at N = 1000 by this blockage to clearance. On the other hand, no galling was observed even at N = 10, 000, which is ten times more than the situation observed in Fig. 7a. This direct comparison in Fig. 7 proves that MCS treatment provides a way to make galling-free fine blanking continuously without deterioration of die surface.

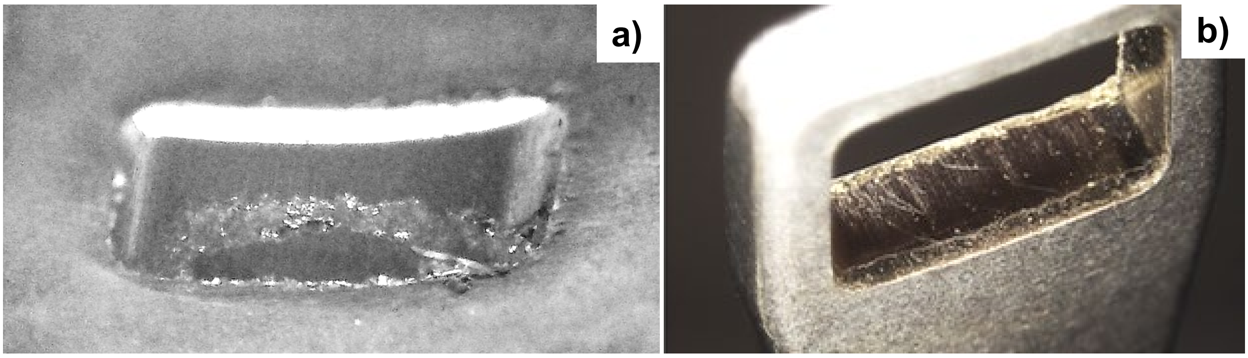

Fig. 8. Comparison of the fine-blanked titanium skeleton by ADC56 tool steel die with and without MCS. a) A skeleton fine-blanked at N = 1000 without MCS, and, b) a skeleton fine-blanked at N = 10,000 with MCS.

Suppression of galling behavior by MCS reflects on the sheared surface quality after fine blanking. Figure 8 compares the fine-blanked skeletons with and without MCS. In fine blanking without MCS, the secondary sheared area was observed in Fig. 8a at N = 1000. This proves that fractured surface area is inevitably formed without MCS. When using the MCSed ACD56 die, the sheared surface is preserved to be nearly full-burnished even until N = 10, 000. This comparison assures that MCS also provides a solution to improve the fine-blanked product quality and to extend the tool life at the same time even in dry fine blanking.

Microtexturing process

Fine microtextures are often required for design decoration of the eye-glass frames, as introduced in Fig. 3. In order to promote the customer interests in products, fine microtextures must be deeply cut into the titanium temple inserts by dry forging with higher aspect ratio of the microtexture depth to its width.

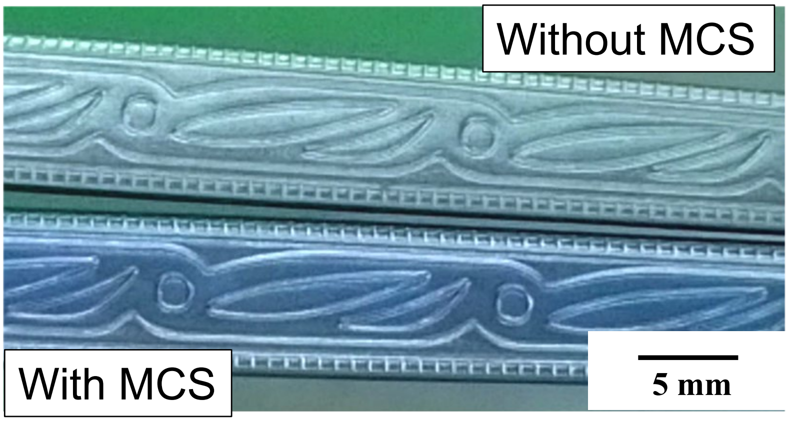

Fig. 9. Comparison of the microtextured titanium temple surfaces with and without MCS treatment.

Figure 9 compares the dry-forged titanium inserts with and without use of MCSed die. Without MCS, the aspect ratio of microtextures is small to be colored in light blue. Using the MCSed die in forging, this aspect ratio is enhanced enough to be colored in dark blue. This difference in the quality of microtextures into the titanium inserts influences on the total quality of eye-glass frame.

Statistical study in dry forging of various eye-glass frame parts

This MCS has been applied to forging and forming of various eye-glass frame parts in two factories. Seven titanium parts and three rectangular frames were forged in dry to make statistical study on the yield of products, as listed in Table 1. The parts from A to C and rectangular frame-A were fabricated at the main factory in Japan. While other parts and rectangular frames were yielded at the Malaysian branch. Using MCSed dies, each part was yielded by a single cold dry forging operation till the number of products listed in Table 1. In case of Part-A, 500 armors were yielded by a single forging without any stops due to cleansing and polishing operations.

Table 1. A statistical study on the dry, cold and galling-free forging operations to yield various titanium eye-glass frames and parts in two factories.

Eye-Glass Frame Parts	Part Name	Number of Products
Part-A	Armor	500
Part-B	Bridge	300
Part-C	Armor	70
Rectangular frame-A	Temple + bar	2000
Part-D	Tempe + temple tip	11,000
Part-D	Temple + joint	18,000
Part-E	Temple + temple tip	5,000
Part-F	Temple + temple tip	7,000
Part-G	Temple + joint	12,000
Rectangular frame-B	Temple	5,000
Rectangular frame-C	Temple	5,000

Without MCS, every eye-glass frame part was fabricated in the multi-step procedure including the intermediate steps of the barreling, polishing and chemical treatments. For an example, in case of rectangular frame-A, three to five steps were needed to minimize the adhesion of debris fragments onto the die surface.

The total number of products for each part item in Table 1, was yielded in less forging steps without any intermediate steps including the barreling, polishing and chemical treatment when using the MCS treatment. Let us compare the number of steps to fabricate the Parts-D/-E/-F and -G as well as the rectangular frames-B and -C in Table 1. Without MCS, 27 steps were needed in total, including the forging steps, the barreling, polishing and chemical treatments. When using MCS, this number of steps was reduced to 11 forging steps only. The whole intermediate treatments were completely saved to reduce the related energy and resource consumption.

As discussed before, the number of forging steps in production procedure for each item is also reduced nearly by 50%. In case of Part-D/-E/-F ad -G, the friction coefficient is reduced during each forging operation by MCS so that the applied load is also reduced by 30% in forging temples. That is, the total forging time was nearly halved or less, and, the energy consumption for single forging operation is reduced by 30 % when using MCSed dies.

In the following, let us quantitatively evaluate on the saving impact of intermediate steps by MCS. As depicted in Fig. 1a, a series of intermediate operations consists of five tasks: heat treatment for annealing, mixed acid cleansing, barreling, anodizing and Estor coating. Among five tasks, the impact to production time in the annealing, the anodizing and chemical cleansing tasks saved by MCS, is evaluated from the statistical data in Table 1.

In the heat treatment, each forged eye-glass frame was subjected to annealing lot-by-lot in operation. In average, 110 minutes were needed for each treatment of a single lot. The total time for treatment of 60 lots were wasted for heat treatment of parts and frames in Table 1 per a month. Then, the wasted production time reached 4,752 ks = 1320 hours per a year.

The anodizing process was indispensable to coat the protective oxide layer onto the titanium work after every forging operation without MCS. In average, 54 minutes were needed for each anodizing step of a single lot. The total time for treatment of 60 lots were wasted for this anodizing of parts and frames in Table 1. Then, the wasted production time reached 2, 333 ks = 648 hours per a year.

In the chemical treatment, a mixed acid solution, which consists of HF and HNO_3, was utilized to delete the titanium adhesives as well as titanium oxide debris. A working time by 2.5 days was needed to exchange the whole used solution with a new one. In each month, 9 exchanges were required to preserve this chemical treatment capacity per a month. Then, the wasted production time by anodizing step, reached 7, 778 ks = 2, 160 hours per a year.

Main three intermediate steps wasted in total 4, 128 hours, or, 172 days per a year. This significant loss is saved by using MCS to eliminate these intermediate steps from the production line of eyeglass frames and parts.

In the above three steps, no direct emission of wastes was generated in two factories with respect to the heat treatment and anodizing steps. However, the used HF and HNO_3 mixed acid solutions were directly emitted from factory sites to outside. Let us qualitatively estimate this waste action and evaluate on its impact as an environmental burden toward fully standardized LCA.

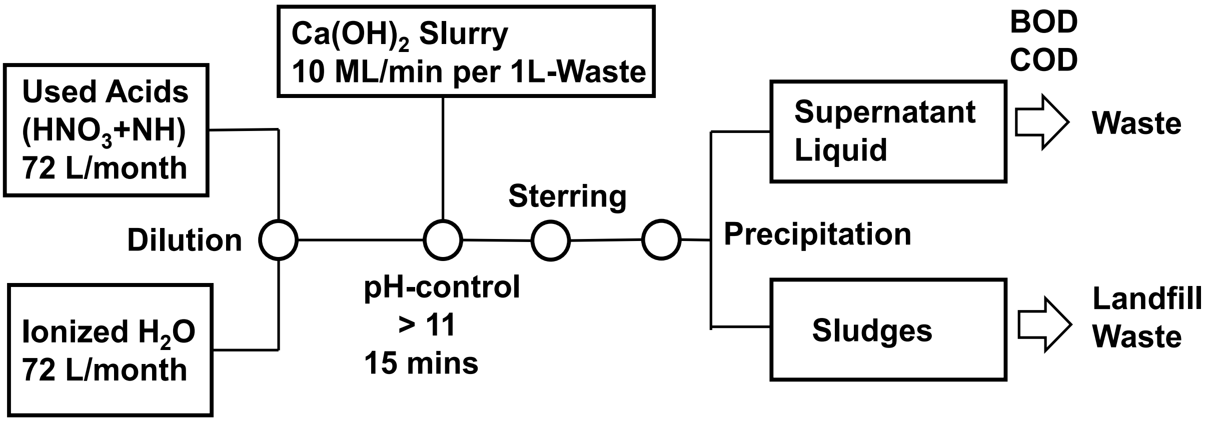

Fig. 10. Post-treatment routine of the used mixed-acid (HNO_3 + HF) solutions finally to sludges and supernatant liquid wastes.

The mixed acid waste solution was first diluted by ionized water by the ratio of 1L for waste to 10L for water in volume after regulated routine in [12]. This diluted solution was further mixed with 10% Ca $(OH)_2$ slurry by the ratio of 1L for diluted solute to 10 ML for slurry per a minute to increase the pH of waste solution above 11. The duration is 15 mins in this treatment. After precipitation treatment, the supernatant liquid was emitted as an industrial water under BOD (Bio-chemical Oxygen Demand) and COD (Chemical Oxygen Demand) control. The sludge must be disposed as a landfill waste.

As stated before, the mixed acid solution by 8 liters per a task was monthly exchanged with new one in 9 times. The solution contents were 2 litters for HF and 6 litters for HNO_3. Then, the monthly total waste reached 72 litters. This direct emission of used chemical solutions is evaluated in Fig. 10. In the dilution stage, the ionized water of 720 L was used before mixing and stirring with the slurry of 720 ML/min. Since the duration time of this treatment needs 15 mins, the total amount of slurry reaches to 10,800 ML. After precipitation treatment, this waste was divided to the solid sludge including the titanium – calcium oxide powders and the supernatant liquid with the volume of 10,800 ML.

The industrial water and chemical consumption calculation reveals that total ejection from dry cold forging operations is much saved by MCS treatment to reduce the environmental burden. Toward fully standardized LCA, the energy and feedstock consumption by single forging operation and the reduced number of steps in total manufacturing must be considered in addition to the water and chemical consumption estimates in the above.

Conclusion

A sustainable manufacturing requires for long life of tools, less emission of wastes, reduction of energy and time consumption, and, flexible production lines. Dry metal forming of titanium eyeglass frames and parts is employed to demonstrate that massive carbon supersaturation (MCS) treatment of dies is just adaptive to green manufacturing with satisfaction of four items in the above. The adhesive wear of titanium fragments and debris to die surfaces is reduced to prolong the die life with less maintenance costs. Intermediate steps including the barreling, cleansing, anodizing, heat treatment and polishing, are saved in manufacturing. The water and chemical consumption calculation proves that environmental burden is also reduced by MCS. Less number of forging steps and reduction of applied energy in forging demonstrate that amount of labors as well as waste of time are saved together with reduction of energy wastes.

This MCS has a possibility to change the production line in practice. At present, every eye-glass frame and related part is fabricated by a single-shot forging. Manual handling is needed to feed the work and to eject, pick-up and store the forged parts. Using the MCSed die system, this single-shot operation changed to transfer- or progressive-stamping system, where a lot of parts are automatically forged, ejected and stored with much less of labors and costs.

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