SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220125

Towards an Objective Classification of Extruded Aluminum Surfaces – A Literature Review and Case Study

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Abstract. Large costs and lead-time losses are created by returned aluminum products - to a great extent unnecessarily. Much of the metal product complaints are due to visual surface defects. Today, the aluminum industry relies on several non-standardized classification systems for surface quality assessments which provides far too much scope for subjective and non-repeatable surface estimations. To challenge this situation, a common toolbox to describe and define surface quality in a more objective way needs to be developed. A first step towards such standardization is to speak the same language, thus this study is based on a state-of-the-art survey covering terminology and descriptions of surface defects in literature, and a round-robin assessment collecting terms used by employees at seven companies within the aluminum industry. The literature study showed that most attempts to catalog and categorized various types of defects on commercial aluminum extrusions are based on the origin of defects and how to prevent and/or reduce them, thus the vocabulary is production-oriented and most terms are not useful from the customers' nor the designers' point of view when coming to describe desired surface effect, i.e. perceived surface quality. The round-robin assessment confirmed the large variation of terminology used, and that defects were judged differently also within the same company due to experience and field of work. A common vocabulary is suggested to be based on the relationships between used expressions; from general terms at stages linked to consumers, designers and sale, tracing towards more technical terms the closer the stage where the origin of the defect can be found. This structure, in combination with e.g. manufacturing cost, is expected to guide customers towards more sustainable surface quality choices that, together with more consistent surface assessments along the production chain, is expected to strongly reduce unnecessary scrapping.

Keywords. Aluminum, Surface defects, Perceived quality, Kansei Engineering

1. Introduction

Today's strive for resource efficiency in a life cycle perspective in parallel with ever-increasing demands on shorter lead times, lessened waste and reduced costs push development and research forwards. Besides, the quality issue, where surface finish plays a major role, is crucial to perceived product quality. Costumers' first impressions judge the overall product quality, and too many complaints lead large costs and in the long term it might spill over to company trust. The value chain of extruded aluminum parts includes

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several stages where suppliers as well as subcontractors, customers and end-users make demands on surfaces produced. Each interface between those stages consists of one producer and one client that must agree on the specification and acceptable surface quality of the delivered product. Available today are a number of non-standardized classification systems for surface quality based on various combinations of and designations for surface defects, assessed by visual inspections either in-line or in a light cabinet at a defined distance to determine the severity of any detected surface deviations (see e.g. [1][2]). These similar classification systems – they differ between different industries, between suppliers and customers (many companies use their own internal classification system), between outdoor or indoor surfaces, and between various aesthetic requirements to mention some few examples – cause communication problems between customer and producer at all stages in a supply chain. The systems usually lack useful information like where the part shall be placed in regard to the eye of the customers or if any detected defect can be masked by next-coming surface treatment. All parties in the value chain would be facilitated by being able to discuss expected and actual production outcomes and further, it would be easier to e.g. compare results between batches or simulate paint quality by knowing the surface of the substrate before the paint process. Thus, general guidelines for a measurable and tolerance-based classification of visual requirements on extruded aluminum surfaces are highly needed. A first step towards such standardization is to agree on common nomenclature for surface quality assessments, thus this work includes on a state-of-the-art survey covering terminology and descriptions of surface defects in literature, and a round-robin assessment collecting terms used by employees at seven companies within the aluminum industry.

2. Literature study

Expressed surface quality is to be described by designers and then, communicated and translated into technical specifications to secure that the design intention is met, i.e. to reach customer satisfaction. The latter is not an easy task, humans perceive surfaces differently due to various reasons such as the condition of the eye, training and sensation. Further, environmental factors play a role (such as lightening and surrounding materials) as well as placement of the product (like distance and angle). To be able to implement a study where human factors, such as perceived quality, is a key question, the method of Kansei Engineering was applied.

2.1. Definition of perceived quality from an engineering perspective

In the method of Kansei Engineering, perceived quality is to be considered as a multi-dimensional reality, normally a result from a designer's intention with the foundation in e.g. philosophy, marketing science, engineering and/or manufacturing. The definition varies over the professions and background and can be seen differently by the different research schools, therefore it is important to be agreed on the definition within a domain and context. E.g. one philosophy means that perceived quality could be seen as 'perception of the customer' and oppose it to the 'objective' quality, while another means that perceived quality is defined as a subjective customer's judgment regarding overall product excellence. [3] sees these definitions partial since it does not consider the engineering aspect in the equation of perceived quality, however only focus on the customer experience. This could adventure the dialogue regarding quantification of quality control. From the engineering point of view, the perceived quality domain is a place where the product meaning, sensorial properties and its performance, interconnect with human experience. Such an experience is driven by the relationship between product quality and its context.

Perceived quality could also be seen as a result of the total appearance of the artifact/gestalt, obtained through sensorial stimuli. From an engineering point of view, sensorial stimuli, could be referred to soft metrology, while physical measurements could be referred as hard metrology. Soft Metrology can be defined as “the set of techniques and models that allow the objective quantification of certain properties of perception, in the domain of all five senses” and address a broad range of measurement, outside of the traditional field of physical metrology [4]:

- Psychometric measurement or perceived feeling (colour, taste, odour, touch);
- Qualitative measurements (perceived quality, satisfaction, comfort, usability);
- Econometrics and market research (image, stock exchange notation);
- Sociometry (audience and opinion),
- Measurements related to the human sciences (biometrics, typology, behaviour and intelligence).

The ideal would be to perform physical measurement using sensors applied to a subject placed in a test situation and the establishment of useful measurement scales correlating human responses and physical metrology, i.e. combining traditional physical “hard metrology” (geometry-, colour-, gloss-, taste-, smell-, noise- and tactile properties) to enable increased understanding of the influence of physical product properties on human responses, see figure 1. By combining soft- and hard metrology in an interconnecting methodology, the traditional philosophy of perceived quality could be challenged and driven towards a more engineering perspective, with the intention to secure a more robust production regarding perceived quality of the total appearance [5].

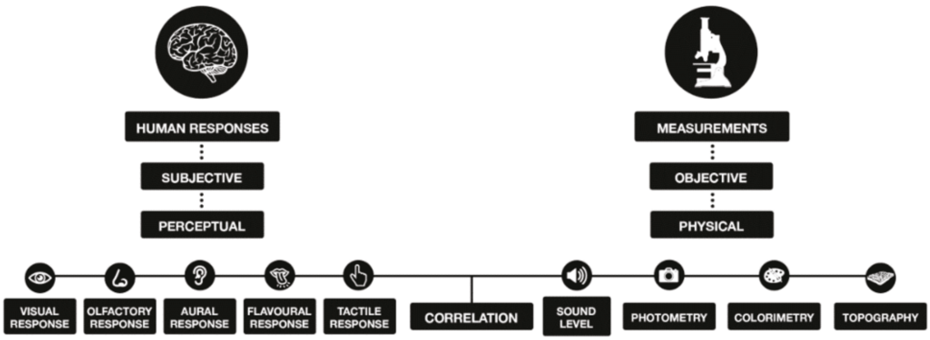


Figure 1. Soft metrology, correlating objective physical measurements to human subjective perceptions [5].

2.2. Hard metrology

To define the overall surface quality, master samples as comparison objects or roughness parameters used as target- or max/min-values on drawings are used. Terms and definitions of surface texture parameters (as well as e.g. feature parameters like Lpvh - local peak/pit height, and Spd – density of peaks) are to be found in ISO 25178-2 [6], which corresponds to the standard for profile methods ISO 4287 [7] where the commonly used Ra-parameter is included. Parameters based on (2D)profile methods can in some cases be misleading and should be used by caution; surface topography variation despite similar roughness values [8].

Another approach is to use a more design-oriented approach to describe surface quality or rather *disturbances* that might ruin perceived surface quality, i.e. to used Gestalt factors. *Gestalt* can be defined as "an arrangement of parts which appears and functions as a whole that is more than the sum of its parts.", i.e. form, colour and material structure influence one another – a form deviation might be perceived as more distinct, more disturbing, if the colour is changed [9]. Gestalt *factors* are concepts that express various ways to create a whole, a gestalt, out of several parts. Examples of gestalt factors are shown in figure 2. This could be linked to metal surface quality in terms of the frequency and distribution of defects (proximity), discoloration or local gloss variations (similarity), and defects across the direction of extrusion or local/punctual marks (good, by means of significant, curves). This means e.g. that even though a surface is measured to be too rough compared to the drawing, it could still be ok in the customers' point of view – if, and only if, actual gestalt factors are fulfilled, e.g. the product has a homogeneous surface structure and is separated from different looking parts.

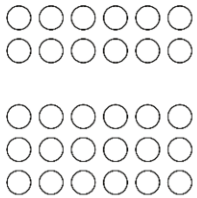
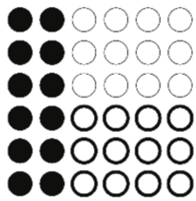
The proximity factor "the closer it is, the clearer the gestalt"	**The similarity factor** "principle of common properties"	**The good curve** "common determining factor"
		

Figure 2. Example of three gestalt factors that link to defect perception, adapted from [9] [10].

2.3. Definition of the concept defect

ISO 9000 defines a ***defect*** as a '*nonconformity*[1] *related to an intended or specified use*' [11], i.e. '*non-fulfilment of a requirement*[1]'. ISO 8785 uses the term *imperfection*[2] instead of surface defect due to the legal aspect of the term defect [12]. 2019 a new standard, ISO 25178-73 [13], was published, which redefines defect as '*part of the measurement standard's geometrical feature*[3] *(non-ideal surface) on which the geometrical shape and geometrical dimensions deviate from those on the nominal feature*[4] *(ideal surface) EITHER by an amount greater than some agreed or stated maximum value, OR, in the absence of any such agreed or maximum value, by an amount greater than what is typical or characteristic of the processes used in manufacturing the measurement standard*'. This means that any stated value of the material measure deviating from the expected one is to be considered as undesirable, i.e. as a defect. Note that small marks due to the nature of chosen manufacturing process are *not* included in the concept defect since they are unavoidable and so expected, and that such defects are 'considered to be a portion of the physical surface…'. So, *when* does a nonconformity become a defect?! Well, when it is not approved by a customer, i.e. undesired results. [14] point this out – the definition of quality is "fitness for use" or "user satisfaction". In production that is when a nonconformity on a detail or product cannot be masked and/or repaired by any next-coming process steps. In other words, a surface feature is a ***design effect*** if it is intended to be there (wanted), and a ***defect*** when not (unwanted).

The older, but still valid, standard ISO 8785, describes 31 specific types of surface imperfections (related to the cause of the imperfections) divided into four categories: recessions, raisings, combined, area & appearance imperfections (all visualised by simple sketches). Several parameters defining length, width etc. of surface imperfections are also defined. The new standard, ISO 25178-73 dealing with surface defects on material measures, has another approach. It defines terms for ten possible responses to geometrical defects: outward/inward/neutral/negative, effective/ineffective, cosmetic, visible/invisible, and gestalt defects. These should then be used by each industry to define their own defects more precisely. Stains and discolorations are discussed in Annex A. Parameters for defect characteristics are not included here, but corresponding parameters can e.g. be found in part 2 for Feature attributes [6].

2.4. Classification systems for aluminium extrusions' surface defects

The Aluminum Association [15] has compiled "visual quality attributes of aluminum extrusions", an alphabetic list of defined terms all visualised by pictures and with possible causes explained. Similar lists, but less comprehensive, can be found in e.g. [16-18] combining photos with sketches (see example in figure 3).

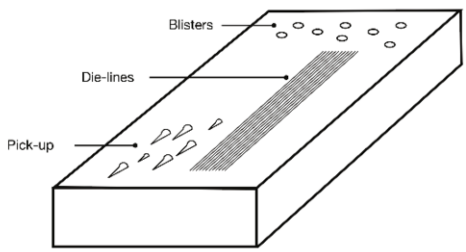


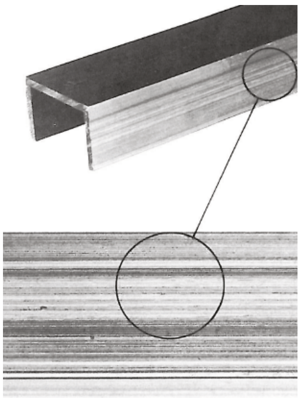
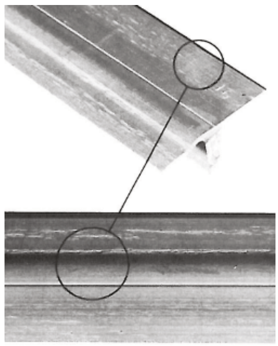
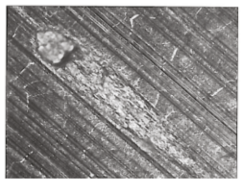
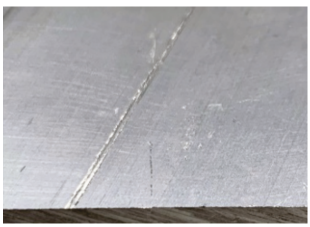
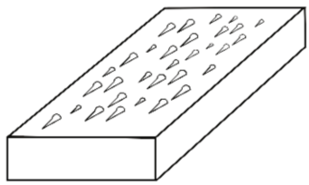
Figure 3. Visualization of various defects by a simple sketch.

Found scientific articles and other topic related sources tend to focus on one or few types of defects, how to detect them, their causes and how to avoid them. In common for all are the production focus, i.e. defects named and classified due to typical causes, and the lack of quantitative descriptors/measures of the defects which are often visualised by 'the worst case scenario'. Table 1 exemplify the variation and often indistinctness in how common defects, here die lines and pickups, are described and visualised in various sources – a reason (or consequence) to why many companies build up their own galleries of photos taken of defected samples collected over time and linked to their own business.

[17] clusters defects according to their origins in three general groups: metallurgical (such as hot spots), operational (inside the process window, such as die lines and back-end), and operational (outside the process window) defects. [19] and [20] present an attempt of various types of defects as they call flaws, in commercial aluminium extrusion, including their causes and how to prevent and/or reduce them. The defects are categorized into eight groups: metal-flow, surface, weld, metallurgical, temperature & speed, equipment & tooling, anodizing, and painting related. Further, they point out that "some of the defects…cannot be avoided due to the nature of the process and existing circumstances. ...they can either be prevented or mitigated.". Their goal was to propose

a cost model based on the probability of producing a defective part at each stage of the process (based on 10 years of data collection of defects resulting in complete rejection of extruded sections). [21] have, based on data collected at one company, proposed adequate indicators to be used to control the production process and to identify critical extrusion variables directly linked to extra waste and defects to be able to increase productivity. A list of observed nonconformities is presented in terms of type, total amount, accumulated value and percentage. They concluded that defects are commonly detected in the end of the production line and that it affects both deadlines and costs. In this case, blisters (cause & effect are presented in the form of a Pareto diagram) and scratches/damages were the most common defects mainly due to the lack of temperature control and maintenance.

Table 1. A collection of how the two defect types Dieline and Pickup are defined in different sources. Note that the pictures from source [15] are cropped.

Dieline	Pickup
	 
"A longitudinal depression or protrusion formed on the surface…. Die lines are present to some degree in all extrusions…" [15]	"Particles of metal and oxide adhering to the surface…at irregular intervals." [15]
	
"A die line is a longitudinal depression or protrusion… ." [19]	"pick-ups,…defect 'adhered',…signs of 'galling'. …the form of a comma or a comet, which are oriented in the pressing direction. … looks like broken lines of grooves (scoring), which often [but not always] end in a lump of aluminum particles (sticky), which rises above the surface…." [16]

An online catalogue of surface defects of aluminium profiles is found on an aluminium information portal [16], where names (in English, German and Russian), details and schematics/photos of common defects are listed. Further information about defects (mainly for 6xxx aluminium) can be found in [22]. [23] focus on pickups as they are the source of severe surface damage occurring inside the process window. A physical model (based on contact and friction models) was developed to be able to propose a surface quality predictor to be implemented in production.

3. Round-robin assessment

The round-robin study was performed at seven aluminum companies representing all stages of the production chain of an extruded aluminum profile. The respondents, most of them with more than 15 years of experience within the field, were selected with the criteria of being close to the product specification, either as a part in defining the quality level of the product, as sale support with customer complaints, or as part of the production (in ch. 3.1 referred to “within the field of quality, sale, and production”, respectively). The samples were chosen in collaboration with the participating industry, where the most common and noteworthy effects and defects for extruded profiles were considered. Both acceptable and un-acceptable samples were included as well as deviations originated at different stages of the production chain. In total, 22 samples were visually inspected by 41 respondents that completed a beforehand prepared protocol (see figure 4) including photos of all samples with surface deviations clearly marked (in total 66 pre-marked deviations).

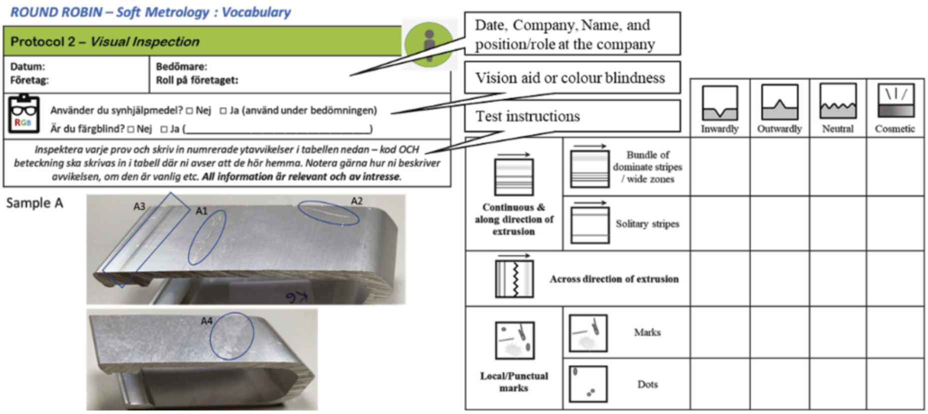


Figure 4. The protocol for sample A; the respondents were asked to complete the table to the right (e.g. A2 – scratch, placed in square: Inwardly/Marks). Test instructions were only in Swedish, here translated to English: *“Inspect each sample and enter the number of actual surface deviation in the table below - code AND term must be entered in the table where you consider it belongs. Please note how you describe the deviation, if it is common, etc. All information is relevant and of interest.”*

The responder was told to inspect the sample and write down the term for the actual defect in one by them selected table category. The table categories are shown in figure 4; rows intend to indicate lateral dispersion, columns the extent in vertical direction. The category ‘cosmetic’ meant that there was no significant height difference compared to the surrounding. Examples of the type of surface deviations (which were also to be found in the literature study), are shown in figure 5. As seen in the photos, both coated, anodized and as-extruded profiles were included.

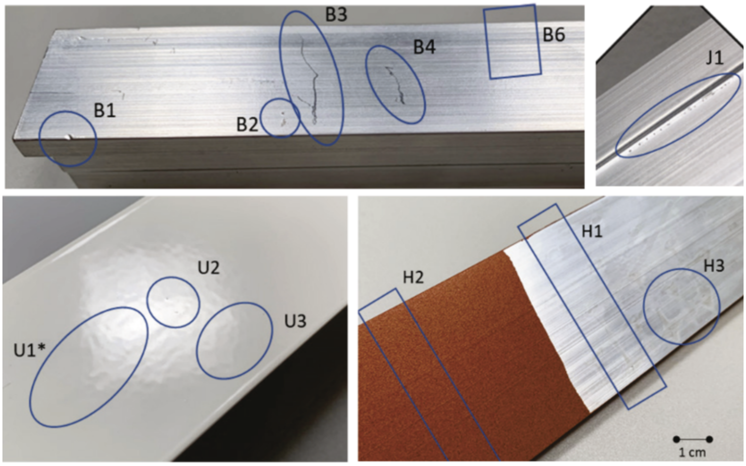


Figure 5. Examples of typical surface deviations included in the round-robin, of which 29 Inwardly (B1-3, U1*), 11 Outwardly (J1 & U2), 15 Neutral (H1-2, U3), and 11 Cosmetic (B4, B6, H3).

3.1. Results and discussion

More than 300 different terms or phrases out of 2706 individual answers (of which 1254 within the field of production, 1188 quality, 264 sale, and 639 were 'not named') were used for the 66 surface deviations marked. Most of the answers were in Swedish, although few loanwords in English occurred as 'dieline' and 'pickup' which were technical terms and therefore used as they were. All other terms and phrases discussed in this text are translated by the authors to the best of their ability, however aware on that the exact meaning of a term can be lost as well as that the respondent's interpretation of a term most likely differs from others. In the round-robin procedure, all respondents have assessed the same samples, which made it possible to compare how the companies entitled various surface deviations and to what extent they found them important – e.g. coating companies tend to ignore shallow marks "it will be masked by the coating" and so those deviations were only denoted as cosmetic marks or ok, while extrusion companies named them corresponding to their origin. That is why both adjectives (e.g. patchy or scratchy) and substantives (stain or scratch), or a combination of both (patchy surface or deep scratch), were used; some very precise describing the cause of failure (like 'effect of striped bearing') while others were more general (like 'stripy surface'). The former is important if the information is used as feedback to the production or to determine its origin, whereas the latter is to be used in the communication with end-customers, i.e. for surface perception discussions. This distinction will be considered for the common vocabulary discussed later. Figure 6 shows the frequency of all terms used in the form of a wordcloud, i.e. the larger the word, the more often it was used. If other companies had been included, there might have been a slightly different result since many companies use their own denotations on surface deviations, i.e. it would have added synonyms. Additional surface deviations are to be added as other materials or manufacturing techniques are added.

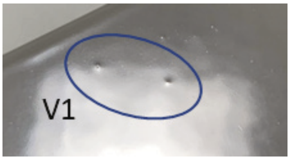
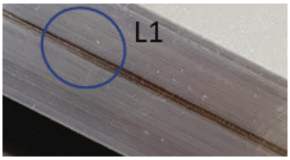
Figure 6. A wordcloud based on the 2067 terms from the round-robin; 'Not named' were excluded from this overview, the term 'ok' is used when no surface deviation was detected. The larger the term, the more frequently it was used; i.e. the term 'repa' (in English 'scratch') was the most frequently term used.

Table 2 highlight some conclusions drawn from the round-robin results:

- E3 *'scratches'*: generic term used and understood by all, and therefore the most frequently used word (see fig. 6), however with severity unspecified (depth, location and direction could be crucial for any attempts to mask the defect in next-coming processes or to assess its visual impression). To add 'handling' to the term indicate its origin, i.e. the material nor the production process have caused the damage. The term was used inwardly/cosmetic marks for both as-extruded samples and surface treated ones.
- V1 *'knobs'*: numerous terms used that in reality 'means the same', i.e. terms describing outwardly directed dots, since the terms link to the origin and/or cause of the dot; e.g. impurity/dust assume it arose during the paint process, while pickup links to the extrusion process. Regardless the term used, this defect is a result of the production somewhere along the process chain unlike handling damages. One respondent answered 'orange peel' which is most likely the term for the overall surface finish rather than a term for the small dots.
- S1 *'sinks'*: indistinct surface aberration causing inconvenience when determining its physical extent since it seemed to create optical illusions. It is also known to be particularly hard to detect before any painting process. Further, both the lighting and the type of paint affect its visibility after coating.
- '*dieline'*: technical term used for various categories of defects (mentioned 40 times for 18 different defects, whereas eight of them are couples, i.e. it is the same defect but painted half (like H1 & H2 in fig. 5). A vague description (se table 1) and a semantic shift (from one clear, deep depression, to a family of shallow lines, depressions as well as protrusions, along the profile) are believed to have provoked this diverse use of the term. Nevertheless, for a consumer, a variation in the surface appearance would simply be referred to as a 'cosmetic defect' or 'stripy surface'.
- *'striped bearing'*: term only used at one company, and strongly related to the production process. The surface was by others perceived as 'stripy' or with 'process lines' (e.g. H1 in fig. 5), to mention some few expressions for this surface deviation/effect, which are more or less visible on all extruded products as a consequence of the manufacturing process.

To form a common vocabulary, all expressions used were sorted by defect type and mapped based on group affiliation; from general terms at stages linked to consumers, designers and sale (i.e. linked to surface perception), towards more technical terms the closer the stage were the origin of the defect is to be found. Figure 7 illustrates the part considering the surface deviation V1, visualized in table 2, from the general term ‘dot’ meaning a small outwardly and local surface defect, to the technical terms that traces back to its origin. The colored boxes (Coating, Machining and Extrusion) are the group affiliation, i.e. were the dot arose, the black boxes (Pickup, Blister etc.) are suggested terms for a specific defect, and the blue text in the role-ups are the expressions from the round-robin surface deviations of type V1.

Table 2. Examples of some of the marked defects and the variations of used terminology. **Term of the defect* (the number of times the term occurs in the round-robin for the actual defect).

Marked defect	Terminology used*
	*Scratches* (27) – alone or in combination with small/micro/superficial/cross/assorted/handling /scraped *Rub/Scuff mark* (3) *Handling damage* (4) *Mark* (1) Not named (6)
	*Knobs* (8) (covers two words in Swedish) *Blister/blow/paint bubble/dot* (6) *Impurity/dust(particle)/dirt/chip* (8) – five had added ‘*or pickup’* *Pickup/stickup* (8) *Paint damage/defect/splash* (3) *Indent mark/Mark* (2) *Orange peel* (1) Not named (5)
	*Sinks (11)* (covers two synonymous words in Swedish) *Press damage/stripe* (6) *Raising/Dirt in paint* (3) *Heat zone / Streak* (5) *Gloss / Matte surface / Discolouration* (3) No defects found (6) Not named (6)
	*Dieline (2)* *(Deep) Press/Process/Tool- Stripe/Line/Scratch/Damage/Error (21)* *Mark/Scratch/Scuff (10)* *Graphite line (2)* *Tearing (2)* *Sinks (1)* Not named *(3)*

Ongoing studies, including another three companies, will build on this mapping aiming to link category, based on surface perception, and group affiliation to ease the communication along the supply chain. The relationship between manufacturing and possible surface quality is important for discussions with customers in terms of expectations and cost, but also in terms of sustainability aspects. Today, far too much is scrapped due to surface related issues, products with perfect function but with minor surface blemishes. Thus, this work is two folded – to develop a common tool for an objective surface assessment along the production chain as well as a communication package to add and highlight sustainability aspects to customer discussions.

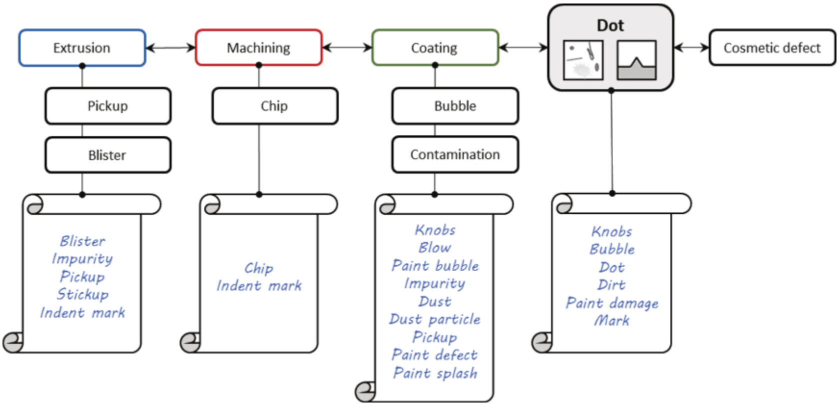


Figure 7. Mapped expressions (blue text in the bottom of the figure) for outwardly and local surface deviations related to 'dots' sorted under the stage of the production chain to where they belong.

4. Conclusions

The literature study showed that most attempts to catalog and categorized various types of defects on commercial aluminum extrusions are based on the origin of defects and how to prevent and/or reduce them, thus the vocabulary is production-oriented and most terms are not useful, nor needed, from the customers' or designers' point of view. From the round-robin assessment more than 300 terms and phrases were used for the included 66 surface deviations, confirming the large variation of terminology used, and that defects were judged differently also within the same company due to experience and field of work. Even though precise definitions are needed as feedback to the production or to determine the origin of the defect, a new way of approaching customer satisfaction is needed in the communication with suppliers and end-customers. Such *surface verification tool* should include both how the surface "should be" and what it "should not be", i.e. expressed design intention vs. surface deviations that cannot be tolerated (e.g. related to how the end product should be used), and how the surface quality should be assessed and controlled along the production chain.

Further investigations of the round-robin results together with the industry (e.g. in workshops to sort and group terms) are needed to suggest a vocabulary agreed on and understood by all. The suggested backtracking of relationship between various surface deviations is one way to build up a vocabulary hierarchy to match the need at all stages in the value chain for a product. It should also be used as a tool to communicate desired surface effect with customers to highlight how their choice of surface quality affect sustainability aspects. E.g. highly shiny and 'defect free' surfaces require cleaner raw material, more accurate processes and handling (and commonly more scrap) that will be far more expensive – both for the customer and for the environment – but will probably not affect the product quality.

Acknowledgement

The project (2019-03568) is carried out with financial support from the Strategic Innovation Programme Metallic Materials, a joint venture of Vinnova, the Swedish

Governmental Agency for Innovation Systems, Formas and The Swedish Energy Agency. The authors would like to thank all persons involved in the project for sharing their experience in fruitful discussions.

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