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# FUNCTIONAL REQUIREMENTS AND DESIGN PARAMETERS IN THE MANUFACTURING OF DAMASCUS STEEL

BY

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**Abstract.** According to the information identified in some bibliographic sources, Damascus steels are obtained by hot forging some strips of steel with different carbon contents. The forging is carried out until the strips are solidified after welds of short length have partially solidified them. To obtain samples of Damascus steel, the functional requirements for the manufacturing process of such samples have been formulated. Defining the sequence of manufacturing operations of Damascus steel test samples and equipment to materialize each functional requirement was carried out using axiomatic design principles. Appropriate ways of materialization have been identified for each of the operations included in the technology of manufacturing test samples. The practical implementation of the technological operations confirmed the possibilities of manufacturing test samples from Damascus steels with the proposed technology.

**Keywords:** Damascus steel, axiomatic design, operations, functional requirements, design parameters.

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## 1. Introduction

Alloys containing as main alloying elements iron and carbon are called *steels*. They have a carbon content of less than 2.11%, while alloys with more than 2.11% carbon are called *cast irons*. From the category of metallic materials, steels are the most widespread metallic materials in all industrial fields. Due to the properties of high mechanical strength and good wear resistance, steels are mainly used in the manufacture of various mechanical components and subassemblies. To improve the mechanical properties, other alloying elements are introduced into the steels, in different proportions.

According to the content of alloying elements of the steels, there are two categories of steels:

- *non-alloyed steels* (called *ordinary steels* or *carbon steels*), which are composed only of iron and carbon and contain very small percentage amounts of other alloying elements;

- *alloy steels*, in which, in addition to the main elements, iron and carbon, there are also other alloying elements, such as chromium, manganese, vanadium, nickel, tungsten, etc. An alloy steel is considered to contain more than 1% silicon, 0.8% manganese, 0.1% aluminum, and alloying elements such as chromium, nickel, molybdenum, tungsten, vanadium, titanium, etc.

*Damascus steel* is a steel made from strips of different steels and which, on macroscopic examination, has the appearance of a network of fine wavy lines, darker in color, representing steel with high carbon content, on a light gray background, corresponding to low carbon steel.

Regarding the emergence and expansion of the use of Damascus steel, it is known that in the middle of the 1st millennium (approximately between 500 and 300 BC), in India or Persia, the production of Wootz steel began, through a unique method of melting in a crucible lumps of iron and parts of organic materials rich in carbon. The process lasted from a few hours to a few days, taking place in a well-sealed crucible. Molten iron absorbed enough carbon, about 1.2 – 1.6%, at a fairly low temperature, around 1400°C. Damascus steel was then obtained from the resulting ingot, by free forging very slowly, at a relatively low temperature. Conditions were thus ensured for breaking the cementite dendrites ($Fe_3C$) into small fine particles. The process led to a significant reduction in steel brittleness, an increase in toughness, and a certain combination of cementite fragments with ferrite lamellae.

Later, there appeared objects (mainly weapons in the category of swords) made of Damascus steel, manufactured by twisting bundles of strips of different steels, solidified between them by using forging processes.

The last decades have shown increased interest in studying the mechanical properties of Damascus steels (Criado *et al*., 1997; Wadsworth, 2007; Černý *et al*., 2012; Özkan *et al*., 2014; Sukhanov and Plotnikova, 2019; Strobl *et* al., 2019; Pacchioni, 2020; Kürnsteiner *et al*., 2020; Židzik *et al*., 2021; Papadatu *et al*., 2023). It can be noted that nanotubes were identified in parts made of Damascus steel several hundred years ago, which would justify some of the high values of some mechanical properties of this category of steel (Reibold *et al*., 2009).

The existence of some aspects of current interest in the manufacture of Damascus steels has led to the initiation of attempts to manufacture parts from Damascus steels by additive processes (Hübner, 2020; Kürnsteiner *et al*., 2020; Pacchioni, 2020).

Techniques specific to the methods of obtaining Damascus steels have been studied to highlight the possibilities of their use in the case of other categories of composite metal materials (Strobl *et al*., 2019).

In the present work, the results of experimental research aimed at obtaining a sample of Damascus steel were used, from which later test samples would be separated to be subjected to different mechanical tests.

## 2. Functional requirements and design parameters in axiomatic design

Axiomatic design is a theory whose appearance is aimed at a more systematic approach and design, at first of manufacturing technologies, and later of different categories of mechanical equipment (Suh, 1990; Suh, 2001; Suh *et al*., 2021). Currently, a significant expansion of the use of axiomatic design has been reached, the respective theory being able to be applied to solve design problems in many fields of activity (Dodun *et al*., 2022; Slătineanu, 2019).

The emergence of axiomatic design is related to the work of the American professor of South Korean origin Nam Pyo Suh. At the end of the 70s of the previous century, he published the first results that followed the use of two axioms in design activities. The two axioms referred to the independence of functional requirements (*the axiom of independence of functional requirements*) and, respectively, to the selection of a solution, when several alternatives appeared, starting from the existence of a minimum of information (*the axiom of information*). Appreciating the validity of the two axioms, over the past decades, many researchers have been involved in the research and application of axiomatic design theory for the optimization of various equipment solutions or for the planning of various activities.

In principle, the application of axiomatic design requires the specification of the customer's requirement and the subsequent identification of functional requirements, design parameters, and process variables, by gradually decomposing the functional requirements and adequately identifying the design parameters and process variables. It should be emphasized that design parameters mean proper ways of solving each of the previously established functional requirements.

A matrix relationship correlating functional requirements *FRs* with design parameters *DPs* has the form:

$$\{FR\}=[A]\ \{DP\}, \tag{1}$$

where $\{FR\}$ refers to functional requirements, $\{DP\}$ considers design parameters, and $[A]$ is the design matrix, meaning a transfer function between functional requirements $\{FR\}$ and design parameters $\{DP\}$. The analysis of the relationship (1), valid in the case of a proper design situation, allows the evaluation of the extent to which it can be concluded that optimal solutions have been identified or that it is possible to further optimize the previously outlined solution.

## 3. Solving Damascus steel test sample fabrication problems using axiomatic design

The problem addressed was that of manufacturing a sample of Damascus steel from which smaller samples could be separated and which could be subjected to different mechanical tests (tensile, torsional, wear, etc.).

It is intended that the structure of the test sample includes strips from different categories of steel that could give Damascus steel parts special properties in the operation of those parts. Strips of different steels could thus be considered, such as:

1. Tool steel, able to provide high hardness;
2. Manganese steel, to obtain high wear resistance;
3. Spring steel, so that the object made of Damascus steel has superior elasticity;
4. Plain carbon steel to ensure good toughness of the part.

It will be considered that the client's need could take a form derived from the very problem addressed in this chapter. In this case, the need of the client (a Ph.D. student who has to go through the specific stages of doctoral training) could take the form: *CN*: Ensure the manufacture of a sample of Damascus steel from which smaller test samples can be separated and which could be subjected to various mechanical tests.

To the need of the *CN* customer, the zero-order functional requirement could be formulated:

*FR*0: Design a sequence of operations to make a sample of Damascus steel.

To reach the functional requirements of the first order, it is necessary to decompose the technological process of manufacturing the Damascus steel test samples into operations. A simplified graphic representation of the operations that must be materialized to obtain a sample of Damascus steel is shown in Fig. 1.

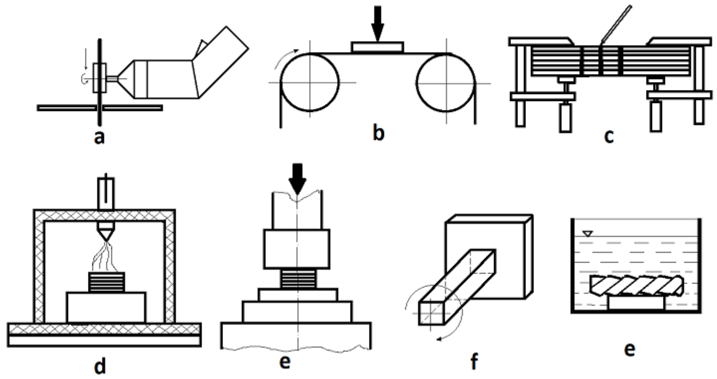


Fig. 1 – Schematic representations of the main operations for making a sample of Damascus steel: a – cutting; b – removal of oxides; c – welding of the strip package; d – heating in the oven; e – free forging; f – twisting; g – passivation.

This decomposition could lead to the following first-order functional requirements:

*FR*1: Cut strips from steels with different carbon contents to predetermined sizes;

*FR*2: Remove oxides from strips;

*FR*3: Wrap and bond the strips together by welding;

*FR*4: Heat the strip pack;

*FR*5: Forge the bundle of strips for their welding;

*FR*6: Twist the strip pack;

*FR*7: Passivate the side surfaces of the forged and twisted blank.

For each of the *FRi* first-order functional requirements, it is necessary to identify one or more pieces of equipment that enable the realization of that functional requirement, which means defining some *DPi* design parameters.

Thus, for example, the fulfillment of functional requirement no. 1 could be done using one of the following equipment: 1. Portable device with abrasive disc; 2. Disc cloth saw; 3. Guillotine for cutting sheet metal.

Taking into account the possibilities of purchasing, manufacturing, or accessing the mentioned equipment, the use of a portable device with an abrasive disc was preferred for cutting strips made of steel with different carbon contents.

As previously exemplified, the *DPi* design parameters were established for each of the *FRi* first-order functional requirements.

A synthetic representation of the functional requirements *FRi* and the design parameters *DPi* that were gradually established can be seen in Table 1.

It can be noticed that for each of the *FRi* functional requirements, only one *DPi* design parameter is called. There are no situations in which the same equipment (design parameter) is used to fulfill several functional requirements, nor any functional requirement whose materialization makes it necessary to use two or more of the identified equipment for the entire manufacturing process.

**Table 1**

*Design matrix containing FRi first-order functional requirements and related DPi design parameters*

| Line no. 1 | Design parameters | | Zero-order design parameter ***DP*0** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2 | | | **Technological process for the manufacture of a sample of Damascus steel** | | | | | | |
| 3 | | | **DP design parameters corresponding to the first level** | | | | | | |
| 4 | **Functional requirements** | | *DP*1: Portable disk drive abrziv | *DP*2: Abrasive belt sander | *DP*3: Welding inverter | *DP*4: Gas stove | *DP*5: Hydraulic press | *DP*6: Forging vise and wrench | *DP*7: Tank with aqueous solution of acids |
| **5 Co-lumn no. 1** | **2** | **3** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| **6** | **Zero order functional require-ment** | **1st order FR functional requirements** | **Highlighting the *DPi* design parameters corresponding to each *FRi* functional requirement** | | | | | | |
| 7 | *FR*0: Design a manufacturing technology of a Damascus steel test sample | *FR*1: Cut strips from different steels | X | | | | | | |
| 8 | | *FR*2: Remove the oxides from the strips | | X | | | | | |
| 9 | | *F*R3: Wrap the strips by welding | | | X | | | | |
| 10 | | *FR*4: Heat the strip pack | | | | X | | | |
| 11 | | *FR*5: Forge the bundle of strips for their welding | | | | | X | | |
| 12 | | *FR*6: Twist the test sample | | | | | | X | |
| 13 | | *FR*7: Passivate the side surfaces | | | | | | | X |

The specific requirement of the first axiom (the one related to the independence of functional requirements) is therefore found to be fulfilled.

As a result of the previously mentioned aspects, it is noted that in Table 1 "$X$" symbols have been placed only along the descending diagonal.

The mentioned arguments lead to the conclusion that up to this design stage, there is a decoupled design, which allows the formulation of an assessment that the process design is optimal or close to optimal.

The further application of axiomatic design principles makes it necessary to identify second-order functional requirements and, respectively, the same-order design parameters.

The matrix equation corresponding to the design matrix in Table 1 will be:

$$\begin{Bmatrix} \boldsymbol{FR1} \\ \boldsymbol{FR2} \\ \boldsymbol{FR3} \\ \boldsymbol{FR4} \\ \boldsymbol{FR5} \\ \boldsymbol{FR6} \\ \boldsymbol{FR7} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{X} \end{bmatrix} \cdot \begin{Bmatrix} \boldsymbol{DP1} \\ \boldsymbol{DP2} \\ \boldsymbol{DP3} \\ \boldsymbol{DP4} \\ \boldsymbol{DP5} \\ \boldsymbol{DP6} \\ \boldsymbol{DP7} \end{Bmatrix} \tag{2}$$

The analysis of the structure of the design matrix (the first factor in the second member of equation (2)) highlights its decoupled character, which means that, from the point of view of axiomatic design, an acceptable solution of the sequence of operations necessary for the manufacture of some Damascus steel test pieces.

a b

Fig. 2 – Equipment designed and made to manufacture test samples of Damascus steel: a – equipment for removing oxides from strips; b – furnace for heating the samples in order to forge the package of strips solidarized between them by means of short welding cords.

In Fig. 2 it can be seen two of the equipment designed and made for the materialization of some operations in the technological route for the manufacture of Damascus steel samples.

## 4. Conclusions

In the present work, problems related to the use of axiomatic design principles for the design of the technology for the manufacture of a Damascus steel test sample were addressed. The different operations that must be included in the technological route of manufacturing the test sample were taken into account and the related design parameters were identified. A valid design matrix was devised for first-order functional requirements and design parameters. The analysis of this matrix highlights the fact that there is a decoupled design, which means an optimal or close to optimal design, from the point of view of axiomatic design. Research could be continued by analyzing second-order functional requirements and design parameters, as well as addressing process variables specific to the technology being investigated.

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## CERINȚE FUNCȚIONALE ȘI PARAMETRI DE PROIECTARE LA FABRICAREA UNOR EPRUVETE DIN OȚEL DE DAMASC

(Rezumat)

Conform informațiilor identificate în unele surse bibliografice, oțelurile de Damasc se obțin prin forjarea la cald a unor benzi din oțeluri cu diferite conținuturi de carbon. Forjarea se realizează până la obținerea solidarizării benzilor, după ce acestea au fost unite parțial prin cordoane de sudare de mică lungime. În vederea obținerii unor epruvete din oțel de Damasc, au fost formulate cerințele funcționale valabile pentru procesul de fabricare a unor asemenea epruvete. Definitivarea succesiunii operațiilor de fabricare a epruvetelor din oțeluri de Damasc și a echipamentelor pentru materializarea fiecărei cerințe funcționale s-a efectuat folosindu-se unele principii din proiectarea

axiomatică. Pentru fiecare dintre operațiile incluse în tehnologia de fabricare a epruvetelor, au fost identificate modalități adecvate de materializare a lor. Realizarea practică a operațiilor tehnologice a confirmat posibilitățile de fabricare a epruvetelor din oțel de Damasc în conformitate cu tehnologia propusă.