TOLERANCE ASSESSMENT OF POLYJET DIRECT 3D PRINTING PROCESS EMPLOYING THE IT GRADE APPROACH

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ABSTRACT: International Tolerance (IT) grade approach was applied for tolerance assessment of the PolyJet Direct 3D printing process (PJD-3DP). Linear sizes of parallel opposite surfaces as well as the diameter of cylinders were measured eight (8) times each one, at eight (8) different test parts which were, all of them, printed using the same optimized parameter design. It was concluded that parts with an IT grade of eleven (11) or even better were possible to build with PJD-3DP process. This IT grade make PJD-3DP process suitable not only for concept modeling but also for fix and assembly applications.

KEY WORDS: PolyJet, 3D printing, IT grade

1 INTRODUCTION

PolyJet Direct 3D printing (PJD-3DP) process uses an Ultraviolet (UV) light to cure (solidify) a photopolymer resin, which is sprayed in a form of tiny droplets similar to ink in an inkjet printer. PJD-3DP is included to the "Additive Manufacturing" Technologies.

Additive Manufacturing is "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies" (Kitsakis et al, 2015). It is a key technology for the future, with strong impact on the addition of business value for manufacturers, over the next decade (Gibson et al., 2015), (Cotteleer & Joyce, 2014).

3D printing invented and patented by the Massachusetts Institute of Technology in 1993 (Chandler, 2011). In 2009, the technology patent for the material extrusion process called Fuse Deposition Modeling (FDM) expired, so the technology became much cheaper and available to a much broader cross section of producers.

The 3D printing process begins with a representation of an object as a 3D model in computer-aided design (CAD) based software. That model can be created directly in the software, or it can be input into the software, through the use of a laser scanning device, that will take a physical object and bring it into the system.

Once that the 3D model is created, the 'STereoLithograph - STL' file is generated by the software. STL is the most popular file format for Additive Manufacturing. It is also known as 'Standard Triangle Language" and "Standard Tessellation Language'.

To tessellate something, means to break it down into a series of polygons -and to be more specific in triangles- to represent not only its external structure, but also its internal structure, too. Once that file is created, the system slices it into many different layers and passes that information to the Additive Manufacturing device (Yan & Gu, 1996).

The Additive Manufacturing system automatically creates the object, by definition layer by layer, until we have a finished object. Very often, post processing is required, that might be the removal of excess material.

Although, machining has its advantages and is preferred when producing very high volumes of similar objects, when we need a diversity of different materials to choose from and when we want to create large parts, 3D printing is preferred when there is high design complexity, the need for rapid production and the necessity for restriction of the material waste (Cotteleer et al., 2014).

Additive Manufacturing processes which are used today includes the following seven groups (Cotteleer et al., 2014): (i) Vat Photo polymerization (Stereolithography-SLA, Digital Light Processing -DLP) (ii) Material Jetting (Multi-jet Modeling-MJM), (iii) Material extrusion (Fused Deposition Modeling-FDM, Fused Filament Fabrication-FFF), (iv) Powder Bed Fusion (Electron beam melting-EBM, Selective Laser Sintering-SLS, Selective Heat Sintering-SHS, Direct Metal Laser Sintering-DMLS), (v) Binder Jetting (Powder Bed and Inkjet Head 3D printing-PBIH, Plater-Based 3D printing-PP), (vi) Sheet Lamination (Ultrasonic

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Consolidation-UC, Laminated Object Manufact-uring-LOM), (vii) Direct Energy Deposition (Laser Metal Deposition-LMD).

In Poly-Jet direct 3D printing technology, a print head selectively deposits material on the platform. These droplets are most often comprised of photopolymers with second materials, such as wax, used to support structures during the building process. At the next step, an ultraviolet light solidifies the photopolymer material to shape the cured parts. At the final pass, the planerizer levels the material to create a nice flat surface (Figure 1). When the parts have been printed, a post-building process is required to remove the support material.

The advantages of PJD-3D printing technology are the high accuracy and surface finish (Kechagias et al., 2014), the capability to use multiple materials and colors on the same part and the hands-free removal of support material. The disadvantages are the limited range of materials and the relatively slow build process (Cotteleer et al., 2014).

Various applications of this technology can be found in some industries (e.g. automotive, medical, aerospace and defense). Applications of this technology are Rapid Prototyping (RP), Rapid Tooling (RT) and Direct Digital Manufacturing (DDM) (Kruth et al., 1998), (Kechagias, et al., 2008). The parts produced for these sectors need to be firm and fit the prospective functionality, but 3D printing for RP, RT and DDM is a relatively new technology and in the literature there are only a few studies related to dimensional accuracy and categorization. Dimitrov et al (2006) provided general IT grades of the 3D powder printing process for parts printed using different materials. Their research is limited to specific materials and equipment. Islam et al (2013) provided experimental results of a preliminary study of dimensional accuracy of parts produced by 3D printing of powder materials. The data showed inherent size errors associated with the 3D printing process, indicating that further investigation is needed. Hirpa et al (2012) investigated the influence of file transfer formats on part accuracy, as well as dimensional and geometrical deviations, and minimum wall thickness limits of a 3d printer by Z Corp (Z510, plastic powders). The research findings indicate that both dimensional and geometrical deviations take place on printed parts and the size of the deviations depends on the type of file transfer format.

The coherence and repeatability of linear and circular dimensions of parts produced by a 3D printer using the PJD-3DP process is studied, at this work. The above dimensions were classified, and categorized according the International Tolerance Grade.
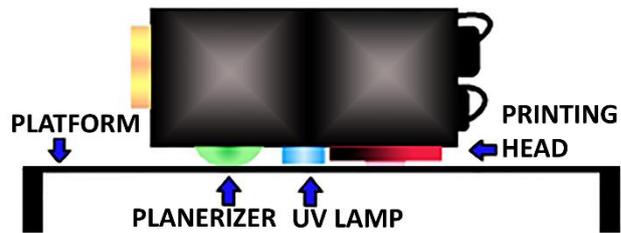

Figure 1. PJD-3DP process

2 SCOPE

The most important applications for the PJD-3D printing technology are any situation in which there is a need for a high fidelity mock up, with complex objects, moving parts, constant service finish, fine resolution, and accuracy. The most crucial aspect for ensuring the dimensional repeatability of the printed parts is the dimensional accuracy, which represents the degree of agreement between designed prescription and the manufactured product dimensions. The current dimensioning and tolerance standards evaluate the dimensional accuracy of a component part through its size and shape (Farmer, 1999).

The variation in size of the manufactured products is very crucial for the applications that this technology is applied for. We examined different linear dimensions in the X, Y and Z-axis and circular dimensions at the top and the bottom of a vertical cylinder to categorize the produced samples according to the ISO 286 International Tolerance Grades table reference.

3 EXPERIMENTAL WORK

For our experiments we designed an 'L' like 3D shape combined with a cylinder near one of its corner, but not tangential to the edges, as shown in Figure 2. This shape gave us the opportunity to examine external linear dimensions (length, width and height of the L shape) and outer circular dimensions (diameter of the cylinder). The dimensions had been chosen so that they belong to different Basic Size ranges of the International Tolerance Grades Table.

Eight (8) independent test parts (Figure 3) were produced from the same STL file using an Objet Eden250 3D Printer. We selected High-speed printing mode (30-micron) and glossy surface at the printing process to have more sleek surfaces and only at the bottom of the parts the FullCure705 support was printed to ground them. For all parts Veroblack Opaque material was used.
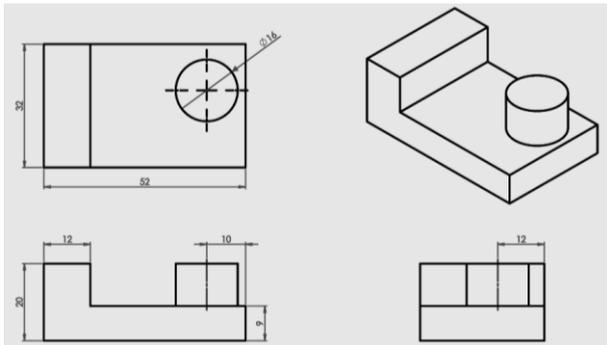
Figure 2. Mechanical drawing of the test part

The decision of taking these parameters levels were taken after process optimization that explained at previous studies (Kechagias et al., 2014), and (Kechagias et al., 2014).
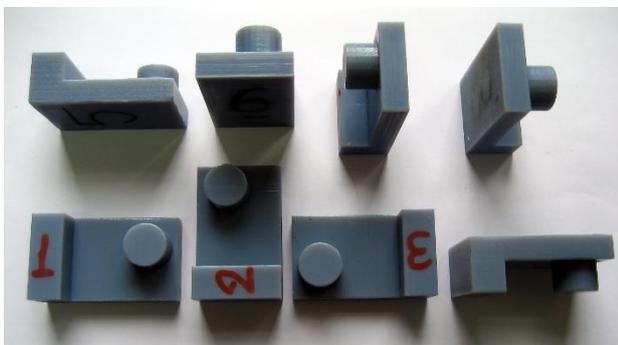

Figure 3. Physical test parts manufactured by Eden 250

The Eden 250 printer (Figure 4) is an ultra-thin-layer, high-resolution 3D printer for rapid prototyping and rapid manufacturing.

Figure 4. EDEN 250 3D printer

Some technical specifications of the printer are: Net build size 250mm X 250mm X 200mm, Build resolution at X-axis: 600dpi, at Y-axis: 300dpi, and Z-axis: 1600dpi, Horizontal build layers down to 16 micron at High Quality and down to 30 micron at High speed printing mode, 0.1-0.2mm typical accuracy varying according to

geometry, part orientation and print size, Materials supported: FullCure 720 Model Transparent, VeroWhite Opaque, VeroBlue Opaque, VeroBlack Opaque and Support type FullCure705 Support (Anon, 2010).

The printed parts were measured by three micrometers, with measuring ranges of 0-25mm, 25mm-50mm and 50mm-75mm each. We measured:

- The height (Z-Print Axis) at ten measurement points on the upper top surfaces (rectangle and circle surface) and at nine measurement points on the lower top surface (points HA1-HA10, HB1-HB9 - Figure 5)
- The length (Y-Print Axis) at six measurement points on the upper rectangle and at six measurement points on the lower rectangle (LA1-LA6, LB1-LB6 - Figure 6)
- The width (X-Print Axis) at ten measurement points (W1-W10 - Figure 7) and the dimeter at four measurement points (D1-D4 - Figure 8).
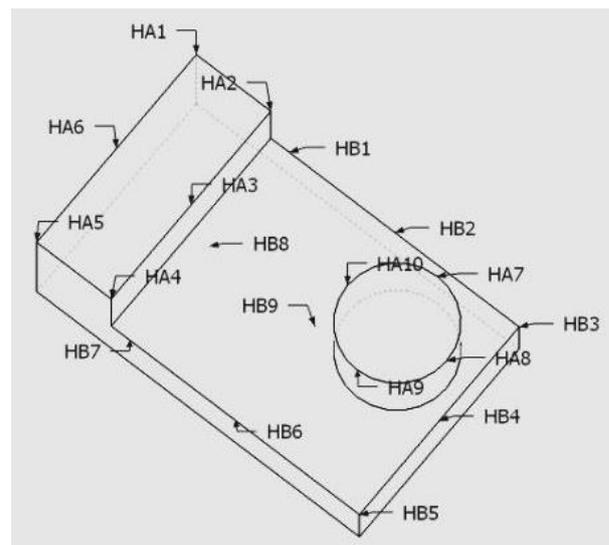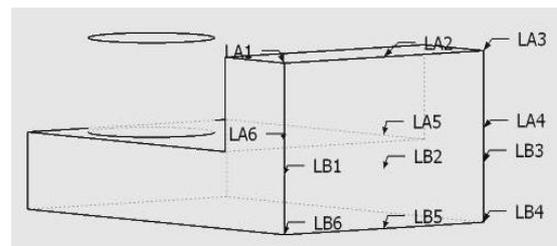

Figure 5. Measured Height points

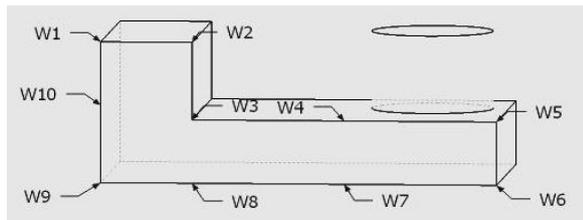
Figure 6. Measured Length points
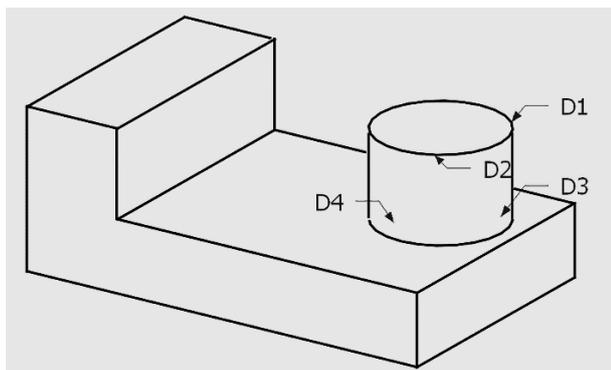
Figure 7. Measured Width points

Figure 8. Measured Diameter points

4 RESULTS AND ANALYSIS

In Chart 1 and Chart 2 the values of height or Z-Print Axis is presented and although the mean is very close to the designed dimension, the variation of errors (±3σ) sometimes extends the printer's nominal accuracy of 0.2mm given by the constructor. The measurement points 7-10 of HA, which correspond to the top face of the cylinder have even better median values, but larger variation values too. We used the High Speed print mode and probably at High Quality print mode this phenomenon could be eliminated, so further investigation has to be done with another experiment.
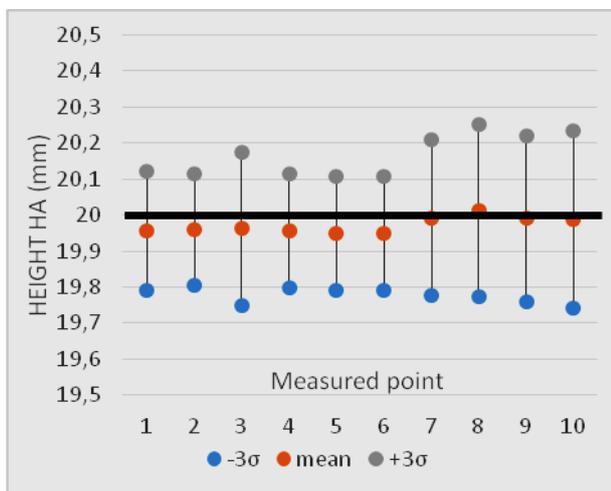

Chart 1. Variations of Height HA
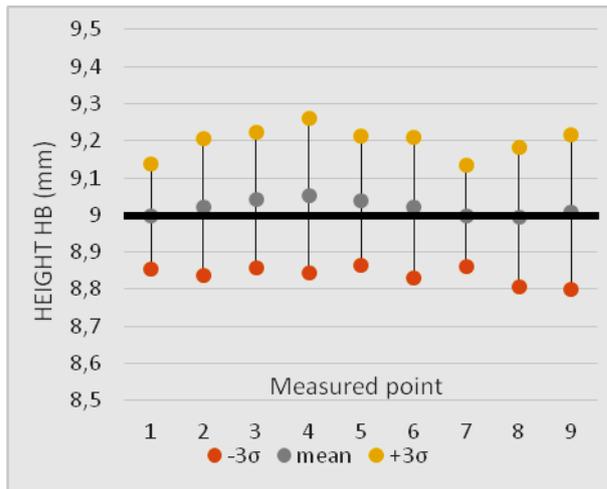
Chart 2. Variations of Height HB

By examining the Y-Print Axis with dimensions LA and LB, values of which are represented in Chart 3 and Chart 4, we note that length is oversized and the variation of errors is very small, excluding measurement points 4, 5 and 6 of LB, which are at the lower layer.

Chart 3. Variations of Length LA

Chart 4. Variations of Length LB

This observation occurs also in Chart 5, for measurement points W6 – W9 of width dimension,

which represents the X-Print Axis. The oversizing of the base layer dimensions is thought to be caused by the support material layer which is pr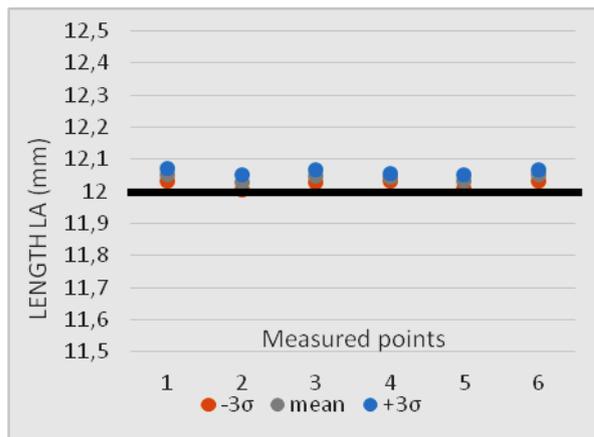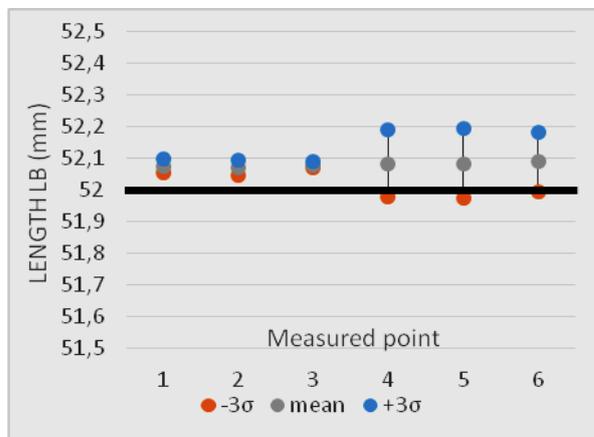inted prior to the main printing process of the part. The Support material is less compact and causes partial diffusion into the lower levels of the printed parts.
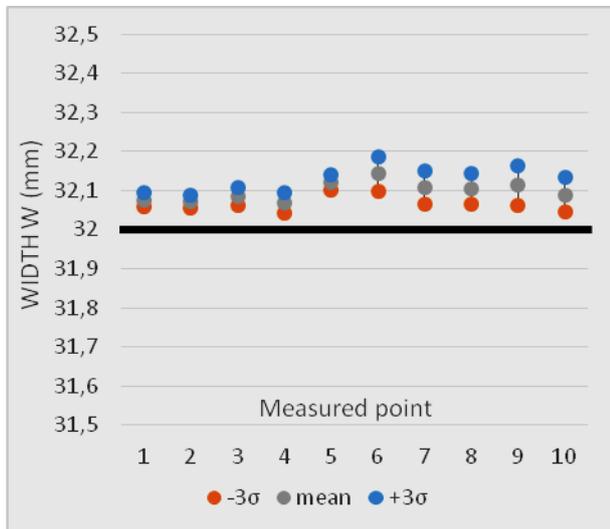

Chart 5. Variations of Width W

The medians and the variations in diameter of a cylinder at four different measurement points, two on the top and two on the bottom are represented in Chart 6. From the results we ascertain that the bottom of the cylinder is undersized, while the top face is oversized and with bigger variation. This finding confirms that geometry is a very basic aspect considering the variation of accuracy and more investigation about the geometry error is required.
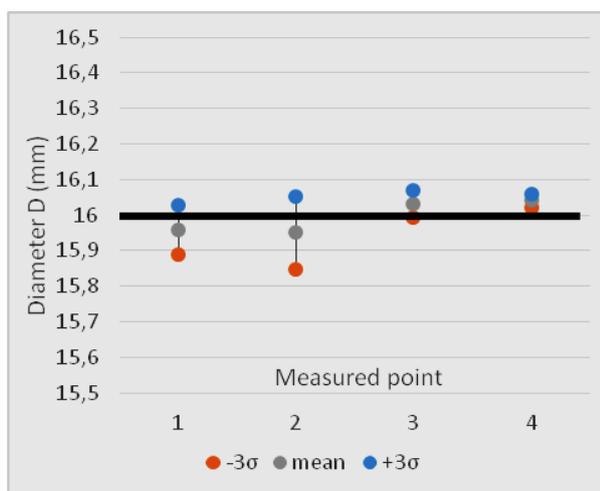

Chart 6. Variations of Diameter D

The International Tolerance Grade (ITG) specifies tolerances with associated manufacturing processes for a given dimension. It indicates how

precise an industrial process is and according to ISO 286-1:2010 for sizes up to 3150mm there are twenty values, IT01, IT0, IT1..IT18. The lower the IT grade number is, the higher is the precision of a machining process. For measuring tools IT01-IT7 is required. IT7-IT11 are grades for Fits and IT12-IT18 for Large Manufacturing Tolerances (Conway , 1966) (Farmer, 1999).

The process Tolerance T can be calculated by the following function:

$$T = 10^{\frac{ITG-1}{5}}(0.45\sqrt[3]{D} + 0.001D) \qquad (1)$$

where ITG is the IT Grade category value (for IT5-IT18),

and D is the Geometrical mean dimension in mm:

$$D = \sqrt{D_{min}D_{max}} \qquad (2)$$

where Dmin and Dmax are the limits of the dimension range.

There are twenty-one ranges for sizes up to 3150 mm and the values of standard tolerance grades according to IT grades and Nominal size are shown in Table 4 (Kverneland, 1996).

To specify the IT grade for the size of two parallel opposite surfaces we examined the shaft through all LA values for one dimension (Y-Axis) and W values 1,2,3,10 for the second dimension (X-Axis). The size of cylinder type was examined with all the values of D. Table 1 -

Table 3 show the minimum and the maximum values for the examined measurement points and the difference of these values (in μm).

Table 1. Tolerance of the Y-Axis

LA	MIN mm	MAX mm	(MAX-MIN) X 1000 μm/mm
1	12.04	12.06	**20 μm**
2	12.02	12.04	**20 μm**
3	12.04	12.055	15 μm
4	12.04	12.05	10 μm
5	12.02	12.04	**20 μm**
6	12.04	12.06	**20 μm**

Table 2. Tolerance of the Y-Axis

W	MIN mm	MAX mm	(MAX-MIN) X 1000 μm/mm
1	32.07	32.085	15 μm
2	32.06	32.08	20 μm
3	32.07	32.09	20 μm
10	32.07	32.11	**40 μm**

Table 3. Tolerance of the cylinder

D	MIN mm	MAX mm	(MAX-MIN) X 1000 μm/mm

1	15.93	16.00	70 μm
2	15.91	16.00	90 μm
3	16.01	16.05	40 μm
4	16.03	16.05	20 μm

For every size, we located its value at the first column of Table 4 and with the maximum value of the above tables, we assigned the corresponding IT grade. Analytically:

- For LA size, Y-Print Axis, with the nominal value of 12 mm and maximum difference of 20 μm we assign the IT8 grade.

- For W size, X-Print Axis, with the nominal value of 32 mm and maximum difference of 40 μm we assign the IT9 grade

- For D size, cylinder type, with the nominal value of 16 mm and maximum difference of 90 μm we assign the IT11 grade.

All three sizes are categorized to IT11 grade at maximum which means that they belong to the Fits area of IT grades.

5 CONCLUSIONS

From the experimental values and the analysis performed, the main conclusions drawn are summarized below:

- Dimensions, both in the X and Y axis, are always oversized.
- The accuracy of the base of the produced parts is poorer in both X and Y axis.
- The accuracy in Z-axis is smaller than that in the other two axes and it depends on, both the geometrical shape, rectangle or cylinder, and the height of the layer.
- The cylinder diameter is undersized at the top, oversized at the base and with less accuracy at the top level.
- The X, Y and cylinder size belong to the Fits area of IT grades.

Note that the present work is the first step in the study on the IT grade specification for the MJM 3D-print process. Further research examining the tolerance of holes and channels in 3D printed objects by this technology is underway.

Table 4. Values of standard tolerance for nominal sizes up to 120 mm

Nominal size mm		Standard tolerance grades																			
Above	Up to and inclu-ding	IT01	IT0	IT1	IT2	IT3	IT4	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16	IT17	IT18
		Standard tolerance values																			
		μm													mm						
—	3	0,3	0,5	0,8	1,2	2	3	4	6	10	14	25	40	60	0,1	0,14	0,25	0,4	0,6	1	1,4
3	6	0,4	0,6	1	1,5	2,5	4	5	8	12	18	30	48	75	0,12	0,18	0,3	0,48	0,75	1,2	1,8
6	10	0,4	0,6	1	1,5	2,5	4	6	9	15	22	36	58	90	0,15	0,22	0,36	0,58	0,9	1,5	2,2
10	18	0,5	0,8	1,2	2	3	5	8	11	18	27	43	70	110	0,18	0,27	0,43	0,7	1,1	1,8	2,7
18	30	0,6	1	1,5	2,5	4	6	9	13	21	33	52	84	130	0,21	0,33	0,52	0,84	1,3	2,1	3,3
30	50	0,6	1	1,5	2,5	4	7	11	16	25	39	62	100	160	0,25	0,39	0,62	1	1,6	2,5	3,9
50	80	0,8	1,2	2	3	5	8	13	19	30	46	74	120	190	0,3	0,46	0,74	1,2	1,9	3	4,6
80	120	1	1,5	2,5	4	6	10	15	22	35	54	87	140	220	0,35	0,54	0,87	1,4	2,2	3,5	5,4

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